Q-Flex Project: Reactive Power Technology Catalogue

For: National Grid Electricity Distribution

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1. Overview

The Reactive Power Technology Catalogue is developed by Power Systems Consultants UK Limited (PSC) as part of the Q-Flex Network Innovation Allowance project. The Q-Flex Network Innovation Allowance project seeks to demonstrate that reactive power flexibility is technically possible and determine whether it can form a key component in the transition to net zero 2050.

The Reactive Power Technology Catalogue provides:

- A summary of the reactive power capabilities of different existing and emerging technologies connected to the National Grid electricity distribution (NGED) network.
- The P-Q capability plots of the existing and emerging technologies.
- The common reactive power control methods of the existing and emerging technologies.

The data and the information provided in this catalogue are based on:

- Assessing the responses received from a number of stakeholders (i.e. owners, operators, asset managers and manufacturers) who have connected technologies to the NGED network. PSC in cooperation with NGED have developed two questionnaires – available in **Appendix A** and **Appendix B** - and arranged a number of workshops to ask stakeholders to provide more information about the reactive power capabilities of their technologies.
- A literature review of the reactive capability and controllability, trial results, and control systems for the current and emerging technologies connected to the distribution grid.

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2. Existing and Emerging Technologies Covered

The Reactive Power Technology Catalogue covers the following existing and emerging technologies:

- **Existing Technologies**:
    - Wind generation
    - Solar generation
    - Conventional generation
- **Emerging Technologies:**
    - EV charger
    - Battery Energy Storage System
    - Domestic Heat pumps
    - Medium Voltage DC (MVDC) links
    - Soft Open points

2.1. Conventional Generation technology

Under the reactive power service, synchronous Distributed Energy Resources (DERs) will follow a voltage droop control scheme to regulate their terminal bus bar voltage in order to provide reactive power support. Note the reactive power transfer in either direction is proportional to the difference between the actual measured voltage and a desired voltage target.

Synchronous generators providing a reactive power service must be capable to change the reactive power supplied to the distribution system. It is embedded to contribute to voltage control. An automatic voltage regulator (AVR) is required to provide constant terminal voltage control of the synchronous generating unit without instability over its entire operating range. An AVR is a continuously acting automatic excitation control system. A voltage control through a droop characteristic is also required for participation in the reactive power service.

2.1.1. The P-Q capability plot of the conventional generation

Every synchronous generator has its own P-Q capability curve, and this information should be available with the machine documentation or from the manufacturer. The capability curves define the operating characteristics of the generator in terms of kW and KVAR. The reactive power capability of the conventional synchronous generator is typically described by a “D curve” that covers the range from zero to rated output as shown in Figure 2-1. However, it should be noted that synchronous generators are limited by the minimum load capability of the generating plant.

Some conventional generators are designed to operate as synchronous condensers, allowing them to provide reactive power at zero load. The ability to provide reactive power at zero load must be designed into the plant and it is not possible with many larger plant designs.

The capability curve of a generator defines the boundaries within which it can deliver reactive power continuously without overheating. The generator rating is specified in terms of MVA and power factor at a particular terminal voltage. Active power delivered by a generator is only limited by the power-delivering capability of the turbine. But the reactive power which a generator can deliver continuously without overheating is governed by three limits: Armature Current Limit, Field Current Limit and End Part Heating Limit as shown in Figure 2-1.

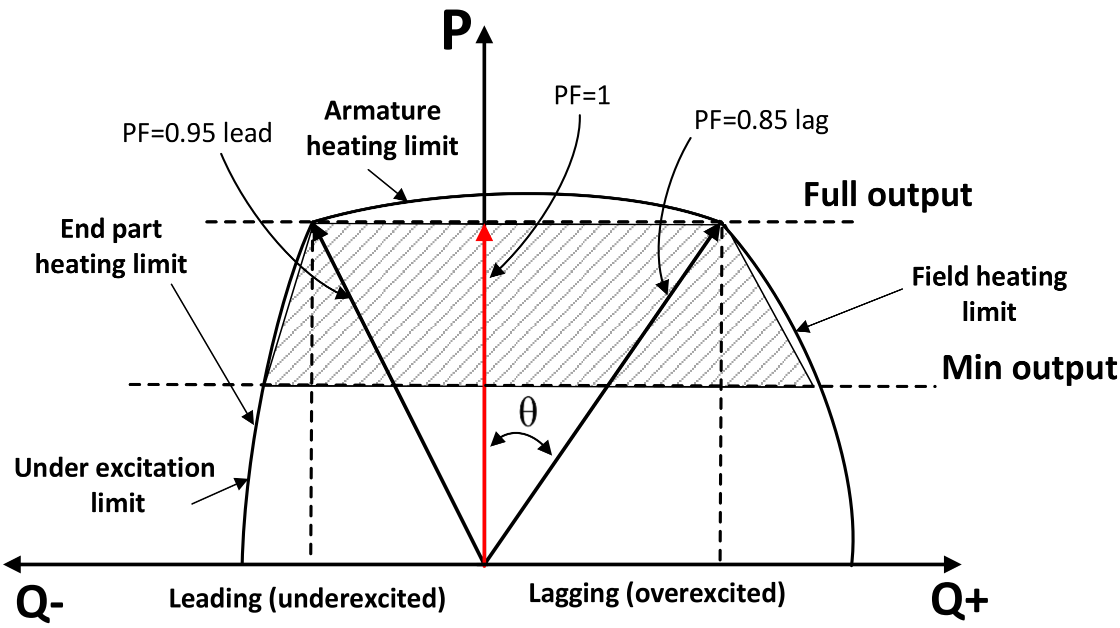

Figure 2-1: the P-Q capability curve of a typical synchronous generator "D curve"

2.1.2. Reactive power control of conventional generation

Conventional synchronous generators can generate or absorb reactive power depending on the excitation. When overexcited, they can supply reactive power, and when they are underexcited, they absorb reactive power. The capability to continuously supply or absorb reactive power is however limited by the field current, armature current and end-region heating limit. The excitation status is changed by controlling the field current.

Synchronous generators are usually controlled using either:

- Voltage control mode: the Terminal voltage of the generator is controlled using an Automatic Voltage Regulator (AVR). The generator absorbs or generates reactive power to keep the terminal voltage of the generator within a certain limit.
- Power Factor control mode: the reactive power can be controlled by setting the required power factor.

Selection of the proper control mode is dependent upon the size of the generator and the stiffness of the connecting utility bus. For large generators where the kVA is significant, these machines are usually terminal voltage regulated and dictate the system's bus voltage. When smaller terminal voltage regulated generators are synchronized to a stiff utility bus, the system voltage will not change as the smaller generator shares reactive loading.

2.1.3. Reactive capability features of conventional generation

- Can provide bi-directional reactive power to the network. When the generators are overexcited, they can absorb power. When the generators are underexcited, they can supply reactive power.
- Can provide bi-directional reactive power at any time of day as long as the synchronous generator is in operation.
- Some conventional generators are designed to operate as synchronous condensers, allowing them to provide reactive power at zero load.
- The ability to provide reactive power at zero load must be designed into the plant and it is not possible with many larger plant designs.
- Most generator reactive capability curves show that most generators are built to and can be operated at lagging power factors well in excess of leading power factor. Meaning, that they are capable of being "over-excited" more than they are capable of being "under-excited".
- Controlling the excitation status of the synchronous generator is achieved by controlling the field current.
- The power factor of the synchronous generator can be controlled.
- The power factor rating of most synchronous generators is typically between 0.8 to 0.95 lagging.
- Power restrictions: The total apparent power (MVA) of synchronous generators is fixed, which means generating more reactive power leads to generating less active power.
- A power factor setpoint could be anywhere "within" the reactive capability curve of the generator.
- Most power plants without any contractual obligation to "produce" MVAr will operate their generators at a power factor of anywhere from 0.95 Lagging to 1.0 (i.e. a very few Lagging MVAr).
- The generation plants can receive control signals to vary their reactive power output while operating in power factor mode, the generator can also participate in reactive power aggregation schemes.
- The generation plant can use external static or dynamic devices such as STATCOM or mechanically switched capacitors to maintain the reactive power of the plant within certain limits.

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2.2. Solar generation technology

PV generators use power converters to control their active and reactive power generation. The reactive capability of PV converters differs from those of synchronous machines because they are normally not power limited, as synchronous machines are, but limited by internal voltage, temperature, and current constraints. Considering PV capabilities for generating reactive power, there is a wide diversity among different products (inverters). The best inverters are capable of generating any reactive power, in accordance with setting the requirements for automatic power factor regulation. But, as a rule, power plant investors/owners want to economically optimize their production, which leads to setting the power factor close to 1.

In principle, inverters could provide reactive power support at zero power, similar to a STATCOM. However, this functionality is not standard in the industry. PV inverters are typically disconnected from the grid at night, in which case the inverter-based reactive power capability is not available at this time. This practice could, of course, be modified, if site conditions dictate the use of reactive capability during periods when generation is normally off-line.

2.2.1. The P-Q capability plot of the Solar generation

Figure 2-2 shows the P-Q capability curve of a typical PV inverter. PV inverters have a similar technological design to full-converter wind generators and are increasingly being sold with similar reactive power capabilities. Some PV inverters have the capability to absorb or inject reactive power, if needed, provided that current and terminal voltage ratings are not exceeded. Considering that inverter cost is related to the current rating, the provision of reactive power at “full output” means that the inverter needs to be larger for the same plant MW rating, which comes at a higher cost compared to existing industry practice.

The PV inverter can provide or absorb reactive power as well as provide active power. Controlling the reactive power of the PV inverter affects the active power delivered by the PV inverter. Equation (2.2-1) shows the relationship between active power (P), reactive power (Q) and the S rating (MVA) of the PV inverter.

$$\sqrt{(P)^2 + (Q)^2} \leq S \qquad (2.2\text{-}1)$$

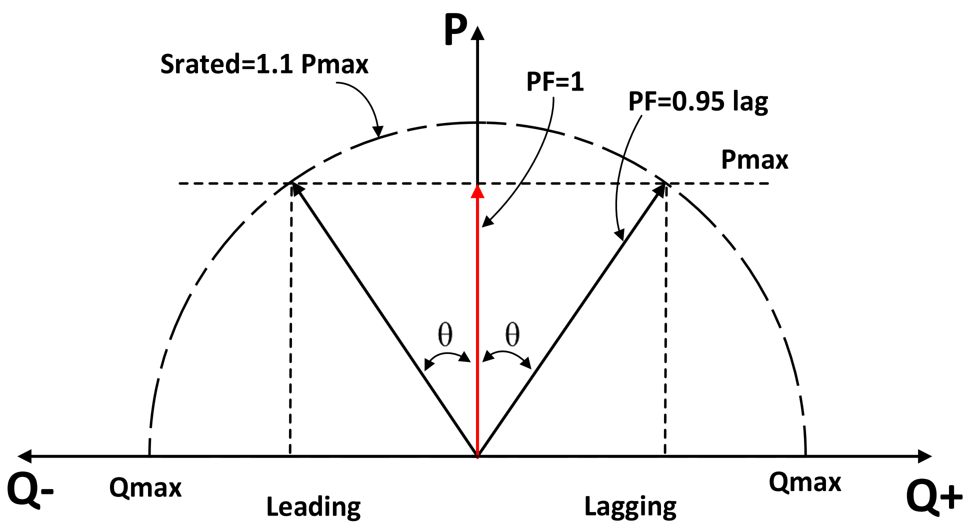

Figure 2-2: the P-Q capability curve of a typical PV inverter

2.2.2. Reactive power control of solar generation

A Power Plant Controller (PPC) is used to regulate and control the networked inverters, devices and equipment at a solar PV plant in order to meet specified setpoints and change grid parameters at the Point of Common Coupling (PCC). Site operators can communicate these setpoints and parameters to the PPC either directly, or more commonly through a SCADA system. A PPC is a means to control plant behaviour in terms of production levels, revenue, compliance and grid stability. Though the specific requirements vary by system, most PPCs can regulate these parameters: voltage, frequency, reactive power, active power, power factor, and ramp control

Modern solar inverters can operate and control reactive power using any of the following modes:

- Maintain a constant power factor: Usually, inverters operate with a power factor equal to 1, but they can be programmed to keep a lower ratio (on the condition that parameter values must be within the operational range of the model).
- Keeping a constant reactive power: regardless of active power produced by the system.
- Voltage-Dependent Reactive Power Control (Volt-Var Control). In this mode, the PV inverter is operated either to inject or to absorb reactive power as a function of the voltage at the PCC.
- Dynamic control of operating values. The inverter adjusts operating values for the power factor or reactive-power rate according to the operator’s commands.

2.2.3. Reactive capability features of solar generation

- Can provide bi-directional reactive power to the network.
- Generally, can provide or absorb reactive power during the day only. During the night, some PV plants can only provide reactive power according to their design [1]. The reactive power delivered or absorbed affects the active power delivered or absorbed by the PV inverter as shown in $\sqrt{(P)^2 + (Q)^2} \leq S$.
- Solar power plants can provide reactive power depending on the revenue from providing this service, compared to providing only active power. High transformer loading values is the main constraints if the Solar power plant operates at high reactive power for a long time.
- SMA company has confirmed, for one of its SMA solar inverters [2], that the Reactive Power in "Q at Night" operation mode should be limited to protect the transformer. The maximum possible reactive power is limited in "Q at Night" operation and set to 30% of the inverter's nominal power that can be fed in. The corresponding limits are permanently set in the control parameters of the inverter.
- Domestic PV generation can participate in reactive power aggregation schemes. It is advisable to have a MW/MVAr meters at the interface point.
- The generation plant can receive control signals to vary their reactive power output while operating in power factor mode, the generation plant can also participate in reactive power aggregation schemes.
- The generation plant can use external static or dynamic devices such as STATCOM or mechanically switched capacitors to keep the reactive power of the plant within certain limits. However, most of solar farm developers prefer to address the problem of keeping the reactive power of the plant within limits by proper design and control of the solar inverters with reactive power capabilities [3].

- Some solar generation plants can provide reactive power while generating zero active power [4], [5]. This is a positive feature so they can generate reactive power at night, when there is no generation on the DC side.
- PV inverters are capable of generating any reactive power, in accordance with setting requirements for automatic power factor regulation. However, as a rule, power plant investors/owners want to economically optimize their production, which leads to setting of power factor to 1 at the PCC.
- Controlling the reactive power of the PV inverter affects the active power delivered or absorbed by the PV inverter as shown in Equation (2.2-1).

2.3. Wind generation technology

Wind generators can be classified into two types: (a) Doubly fed or full converter interface wind turbine generators, and (b) Induction-based wind generators without converters.

- **Doubly fed or full converter interface wind turbine generators**. The reactive capability of converters differs from those of synchronous machines because they are normally not power limited, as synchronous machines are, but limited by internal voltage, temperature, and current constraints. Wind generators with converter interface are often designed for operation from 90% to 110% of the rated terminal voltage.
- **Induction-based wind generators without converters** are unable to control reactive power. Under steady-state conditions, they absorb reactive power just like any other induction machine. Typically, mechanically switched capacitors are applied at the wind generator terminals to correct the power factor to unity. Several capacitor stages are used to maintain a power factor near unity over the range of output. This type is unlikely to be used nowadays by wind farm developers due to its disadvantage as mentioned in [6].

2.3.1. The P-Q capability plot of the Wind generation

Doubly fed and full-converter wind generators are often sold with a “triangular”, “rectangular”,’’ U shape” or “D shape” reactive capability characteristic as shown in Figure 2-3. This represents the reactive power capability of individual wind generators.

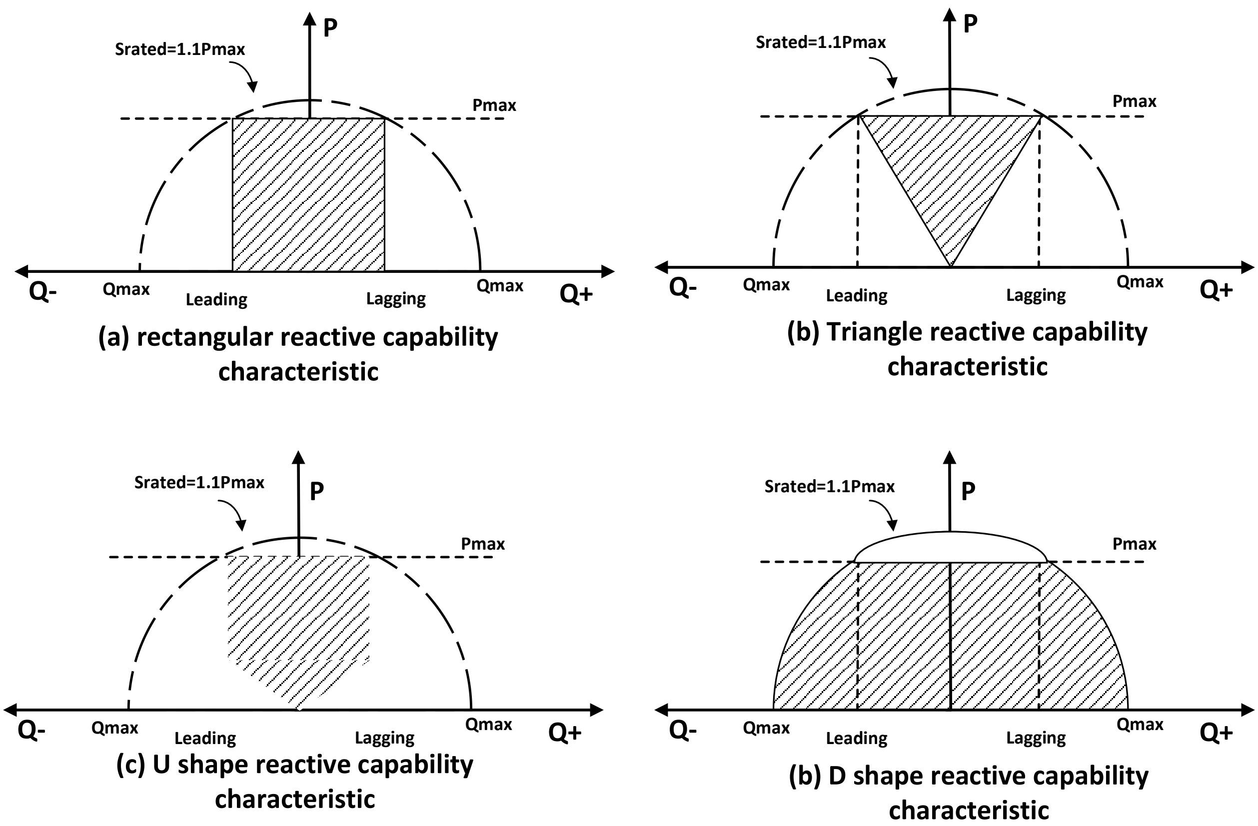

Figure 2-3: the P-Q capability curve of typical wind turbines

2.3.2. Reactive power control of the wind generation

Figure 2-4 shows the control system of a typical Wind turbine. Wind generation technology has the following control modes:

- Voltage control mode
- Current control mode
- Power factor control
- Volt-var control mode

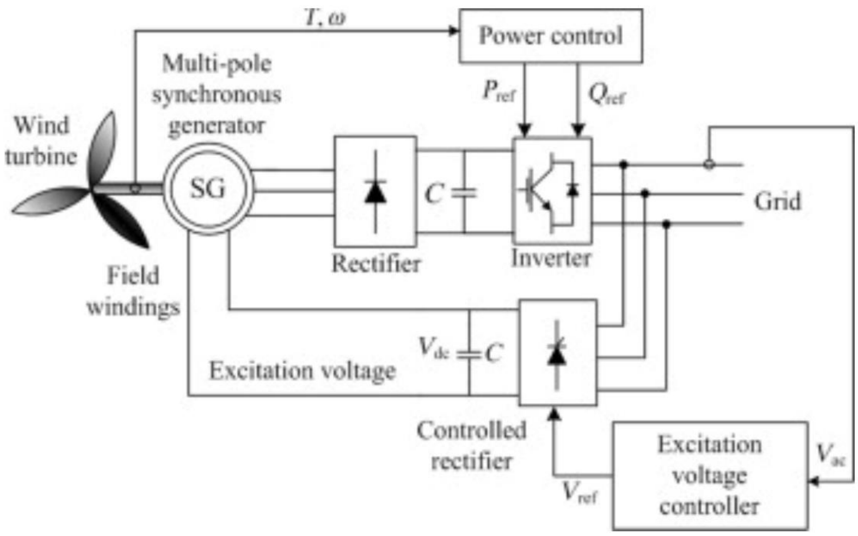

Figure 2-4: The control system of a typical Wind turbine.

2.3.3. Reactive capability features of the Wind generation

- Can provide bi-directional reactive power to the network
- Can provide or absorb reactive power at any time depending on the turbine configuration, Wind speed, and faults (if existing).
- There are real power restrictions caused when providing/absorbing reactive power, and this depends on the turbine configuration (i.e. the PQ curve of the turbine).
- The turbines can operate on a fixed power factor (e.g. 0.95 or any other fixed value) or can be controlled through an external signal to determine the required power factor setting.
- The applicable range of changing the power factor of the turbine depends on the turbine platform itself.
- The technology can receive local and/or remote control signals/schedules to vary their reactive power output. The response time depends on the controller core parameters chosen but generally, we can meet the common requirement of 90% of the required change in 1 second.
- Reactive power may be generated while generating zero active power only on specific wind farm configurations and technology.
- The lagging capability of full converter interface wind turbine generators may reduce as terminal voltage increases because of internal voltage constraints and may reduce as terminal voltage

decreases because of converter current constraints. Leading capability normally increases with increasing terminal voltage.

- Machines with a rectangular or D-shaped reactive capability characteristic may be employed to provide a voltage regulation service when they are not producing active power (e.g., a low-windspeed condition for a wind resource or at night for a PV resource, or during a curtailment) by operation in a STATCOM mode. However, this capability may not be available or may not be enabled by default.
- For smaller turbines, reactive power capabilities will be low.
- Wind generation technology has the following control modes: voltage control, current control, power factor control and volt-var control mode. The control mode of the wind generation power plant can be changed via the converter's control topology.
- The SCADA system in the wind park overview enables start/stop actions across the entire wind farm, groups of turbines, or separate wind turbines. Moreover, the park control is used for setting energy production limits for the entire wind farm. The aim of wind park control is to maximize energy production for the wind farm while reducing operating costs. More details are shown in Figure 2-5.
- The Wind farms can use external static or dynamic devices such as a STATCOM to keep the reactive power of plant within a certain limit. With the STATCOM option, the inverter takes some P from the grid to cover its losses and produces or absorbs Q.
- Some Wind turbines also have a STATCOM feature (i.e. an inbuilt STATCOM option in their turbines.) to provide reactive power at zero-wind. The presence or not of this feature depends on the project.

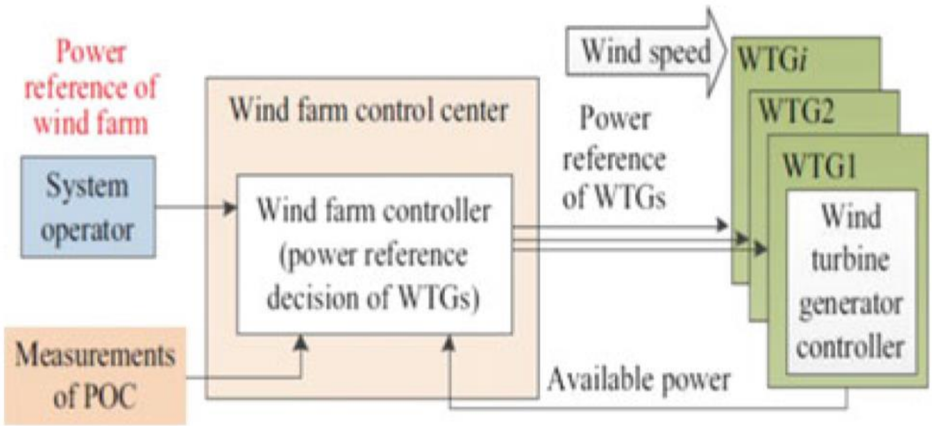

Figure 2-5: Overall control framework for power system and wind farm [7]

2.4. Battery Energy Storage Systems technology (BESS)

The BESS can provide or absorb reactive power as well as active power. Reactive power is used to control voltage levels, keeping them at a safe and efficient level for electricity transportation and consumption. The BESS will absorb or generate reactive power when needed, which will alleviate capacity challenges associated with increased reliance on distributed energy generation.

2.4.1. The P-Q capability plot of the BESS

The BESS can operate in the four quadrants to control the reactive power flow as illustrated in Figure 2-6 both in on-grid and off-grid modes. The BESS has two bidirectional converters (i.e. to perform DC/AC conversions to discharge the BESS into the network and AC/DC conversions to charge the BESS). The BESS converter controls active and reactive power flow, voltage, frequency and ensure that the electricity output meets desired connection requirements.

The BESS can operate in the four quadrants to control the active and reactive power as shown below:

- Quadrant I: Provides active power plus inductive reactive power.
- Quadrant II: Absorbs active power plus inductive reactive power.
- Quadrant III: Absorbs active power plus capacitive reactive power.
- Quadrant IV: Provides active power plus capacitive reactive power.

Controlling the reactive power of the BESS affects the active power delivered or absorbed by the BESS. Equation (2.4-1) shows the relationship between active power, reactive power and the S rating (MVA) of the BESS.

$$\sqrt{(P)^2 + (Q)^2} \leq S \qquad (2.4\text{-}1)$$

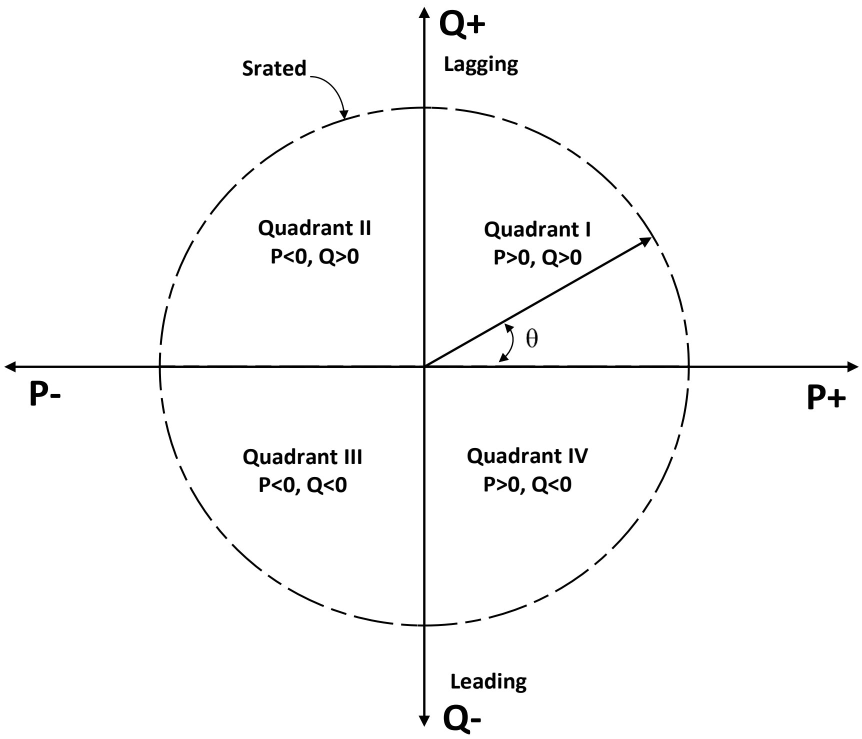

Figure 2-6: The P-Q capability curve of the battery energy storage system

2.4.2. Reactive power control of BESS

The controller is the brain of the entire BESS. It monitors, controls, protects, communicates, and schedules the BESS's key components, called subsystems. As well as communicating with the components of the energy storage system itself, it can also communicate with external devices such as electricity meters and transformers, ensuring the BESS is operating optimally. The controller has multiple levels of protection, including overload protection in charging and reverse power protection in discharging. The controller can integrate with third-party SCADA and Energy Management System (EMS) for complete acquisition and energy management.

The BESS can operate in both grid-connected and islanded modes. Active and reactive power control (P-Q Control) is used in grid-connected mode, while constant voltage and frequency control (V-F Control) is employed in islanded mode. These two control strategies are commonly used and are detailed below [8]:

- **P-Q control mode**: When a reference voltage and a constant frequency are supplied by another source (usually the grid operator). The BESS inverter in this case can change the active and reactive power.
- **V-F control mode:** V-F control mode occurs when, regardless of the varying inverter power, the amplitude and frequency of the output voltage are constant. The inverter with V-F control can provide voltage and frequency support to the microgrid during island operation. The inverter acts as a voltage source. This control mode is usually used in isolated systems.

2.4.3. Reactive capability features of BESS

- Can provide bi-directional reactive power to the network.
- The BESS could generate/consume reactive power at any State Of Charge (SOC) level without impacting the lifecycle of the batteries, only some active power is needed for switches' losses [9], [10]. The inverter of the BESS is usually designed to be (MVA_rating = 1.1 * P_max) to leave a margin to import or export reactive power Q. In Tagenergy's response to the questionnaire, they stated that one of their BESS systems is sized for (Pmax =20 MW) and (MVA_rating = ~22.25 at the PCC), so the BESS can provide/absorb reactive power up to 9.75 MVAr.
- The BESS can support reactive power and voltage control applications in the power grid.
- Reference [11] pointed out that there is no battery degradation in the reactive power market.
- The BESS can provide only reactive power to the network, while operating at zero active power. High transformer loading values and/or BESS heating up are the two main constraints if the BESS operates at high reactive power for a long time (e.g. 24 hrs, without stopping).
- The BESS can provide or absorb reactive power at any time as long as there are no faults or capacity constraints (e.g. cooling).
- The technology can receive local and/or remote-control signals/schedules to vary their reactive power output. The response time depends on the controller core parameters chosen but generally, can meet the common requirement of 90% of the required change in 1 second.
- The small domestic BESS cannot participate by itself in providing reactive power support to the network. Domestic BESS of small size should participate in aggregation schemes to be able to

provide reactive power support services (Ancillary services). For instance, a minimum of 100 kW or 1 MW is necessary to bid in the frequency regulation market [12].

- There are real power restrictions caused when providing/absorbing reactive power, and this depends on the PQ curve of the BESS and the inverter rating, refer to equation (2.4-1). For example, if the system is sized for 20 MW and ~22.25 MVA at the PCC, so if the reactive power is more than 9.75 MVAr = [$\sqrt{(22.25\,)^2 + (20\,)^2}$], then the active power has to be reduced due to physical limitation of the inverter.
- The BESS can operate at a fixed power factor (e.g. 0.95 or any other fixed value) or can be controlled as per the grid code requirements. The applicable range of changing the power factor of the BESS depends on the BESS itself (e.g. can be -1 to +1 (full power factor range)).
- Some systems have a BESS meter at the Point of Connection (MW/MVAr). The participation in aggregation schemes would affect the end user: system was only sized for required reactive power to meet grid code requirements. There is no free reactive power capacity of the system (nor free capacity at the connection point) that can be used without limiting the operation and participation in markets of the asset. Reactive power can be dispatched, however, if the installed power limit is reached, then the priority may not be for the reactive power.
- Some BESS manufactures (e.g. Tesla) allows to send direct reactive power commands to the Megapack BESS system (direct control), to define a power factor charge/discharge set point (power factor control), or to define a Volt/VAR curve (voltage control). Communication protocols supported by the Tesla Site Controller are Modbus/TCP, DNP3 and REST API.

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2.5. EV charger technology

The Electric Vehicle (EV) chargers could participate in the reactive power market to maximize the potential revenue for EV owners or EV charger's aggregators subject to remaining within local voltage limits. EV charging/discharging can take place in any P-Q quadrant, which means EVs could inject or absorb reactive power to/from the grid while charging the battery. In controlled management schemes, distribution system operators (DSOs) can coordinate the charging process of EV chargers to ensure grid's operating constraints are not violated. In fact, this refers to the DSO setting upper bounds on power limits for EV charging. Active and reactive power setpoints are set by a higher energy management system (i.e. usually the DSO), the higher energy management system is responsible for calculating and sending a reactive power setpoint Q to each individual EV charger. It is possible to provide voltage support at the point of common coupling (PCC) to which the EV charger is connected, or a proper reactive power management of the EV charging station, which can improve Volt-Var Optimization solutions for the distribution network.

2.5.1. The P-Q capability plot of the EV chargers

The EV chargers can operate in the four quadrants to control the reactive power flow as shown in Figure 2-7. However, EVs are assumed to operate in charging mode only (Quadrant I and Quadrant IV) to improve the EV's battery lifetime.

The following Q modes are the typical reactive power operating modes of EV chargers.

- **<u>Grid to EV charger - Q mode (Quadrant I and Quadrant II):</u>** when the EV charger absorbs reactive power from the grid (Q > 0).
- **<u>EV charger to Grid - Q mode (Quadrant III and Quadrant IV)</u>**: when the EV charger injects reactive power to the grid (Q < 0).

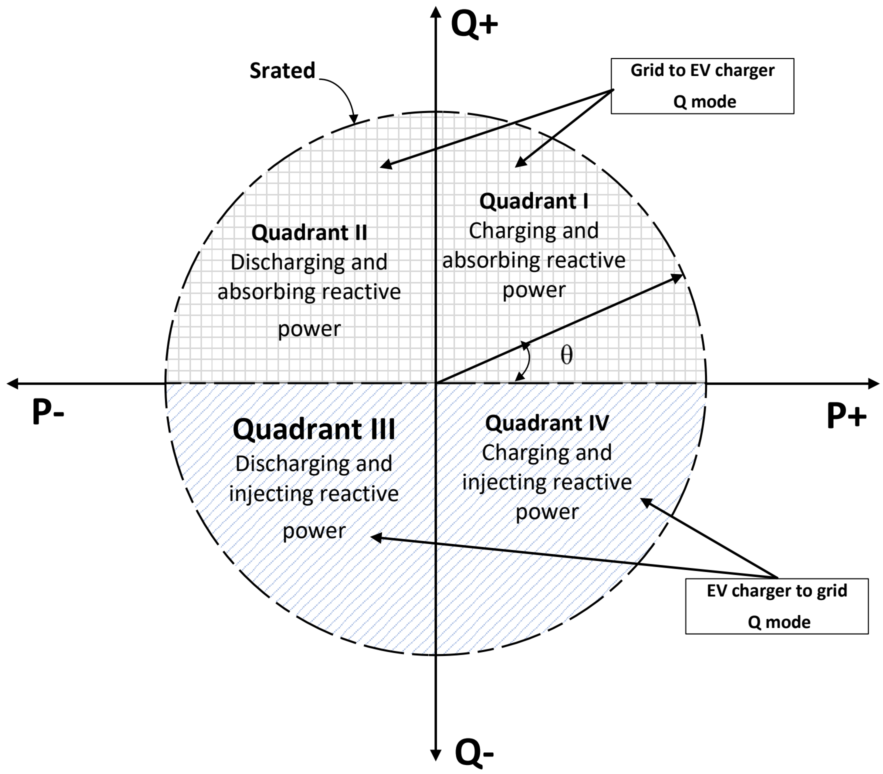

Figure 2-7: The P-Q capability curve of the EV chargers

The EV charger can provide or absorb reactive power as well as absorb active power. Controlling the reactive power of the EV charger affects the active power delivered or absorbed by the EV charger. Equation (2.5-1) shows the relationship between active power (P), reactive power (Q) and the S rating (MVA) of the EV charger.

$$\sqrt{(P)^2 + (Q)^2} \leq S \qquad (2.5\text{-}1)$$

2.5.2. Reactive capability features of EV chargers

- Can provide bi-directional reactive power to the network.
- The EV charger can generate or consume reactive power at any state of charge level (SOC) of the EV battery without impacting the lifecycle of the batteries [9], [10].
- EV chargers can support reactive power and voltage control applications in the power grid.
- Most of the ancillary services on which EV chargers can receive a greater benefit impose a minimum power capacity to participate. For instance, a minimum of 100 kW or 1 MW is necessary to bid in the frequency regulation market [12]. Thus, a single EV cannot participate by itself in this type of market as EV chargers are fairly low power. Due to this restriction, an aggregator manages a pool of EVs and coordinates their operation to reach a global goal. For this task, the aggregator gathers some information about the market situation (e.g. prices), some data about the vehicle’s status (e.g. battery SOC, driving preferences, etc.) and some information about the grid infrastructure (e.g. cables and transformer constraints). With these parameters, the aggregator executes an algorithm to decide the operating points of each EV charger it manages.
- This technology can provide or absorb reactive power to the network at any time of the day.
- This technology can provide reactive power while generating/absorbing zero active power.
- A power factor setpoint could be anywhere "within" the reactive capability curve of the EV charger.
- Most power plants without any contractual obligation to "produce" MVAr will operate their EV chargers at a power factor near 1.0 (i.e. a very few Lagging MVAr).
- The EV chargers can participate in reactive power aggregation schemes. It is advisable to have a MW/MVAr meter at the interface point.
- The EV chargers can receive control signals to vary their reactive power output while operating in power factor mode.
- Controlling the reactive power of the EV chargers affects the EV charging status. This means that if the EV charger is required to deliver high reactive power to the network it will charge the EV battery with less active power (P) because the MVA rating of the converter is fixed, see Equation (2.5-1), meaning the charging time will be longer.

The EV charging station can use external static or dynamic devices such as a STATCOM to keep the reactive power of the plant within certain limits.

2.6. MVDC link technology

Medium-voltage DC (MVDC) link can be viewed as acting in the same way as high-voltage DC (HVDC) systems in transmission grids, just on a smaller scale and over comparatively shorter distances or at a specific site. MVDC link can be installed for voltage 132 kVac and below [13]. Such MVDC systems allow much more flexible ways of grid operation beyond the scope of conventional AC systems by flexible power flow control, increased connection capacity on the same infrastructure compared with AC and voltage optimisation and hence a more efficient use of grid resources. Medium Voltage Direct Current (MVDC) technology represents a candidate solution as well to unlock the capacity of existing electrical network assets. It increases transmission capabilities, strengthens the grid infrastructure, helps minimize losses, and provides reactive power compensation and load flow control.

Figure 2-8 shows a schematic diagram of an MVDC link connecting two distribution networks. The MVDC link is constructed via fully controllable power electronic converters. A voltage source converter (VSC) station is used for the conversion between AC and DC at each terminal of the MVDC link. The MVDC link allows for real power exchange between the two terminals as well as reactive power support on both sides.

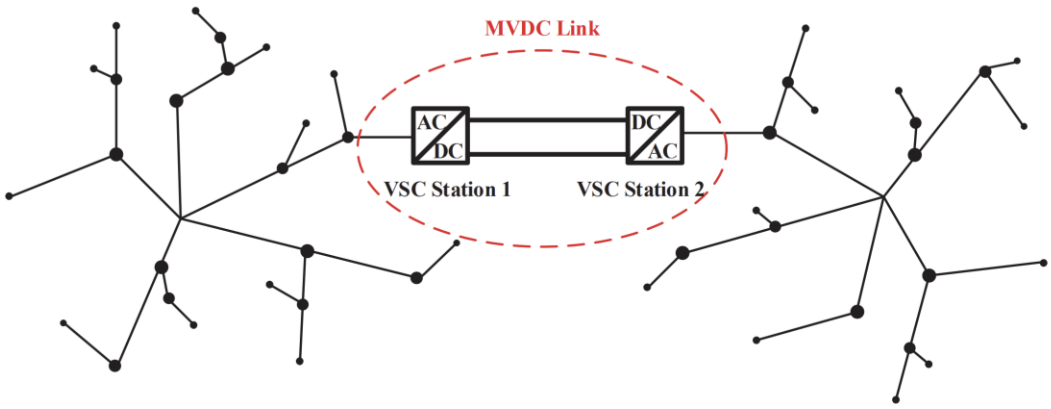

Figure 2-8: An MVDC link between distribution networks

2.6.1. The P-Q capability plot of the MVDC links

The power provided by an MVDC link can be modulated in the four quadrants of the power chart, and each VSC can operate in any region of the four quadrants. Figure 2-9 shows an example of an MVDC's operating point. To fully evaluate the effects of an MVDC link on network operations, the following mathematic power injection model of an MVDC link was used:

- Active power constraints:

$$P_{VSC1} + P_{VSC2} = 0 \quad (2.6\text{-}1)$$

where P_{VSC1} , P_{VSC2} are the active power flow through each VSC

- Reactive power constraints:

$$Q^{min}{}_{VSC,n} \leq Q_{VSC,n} \leq Q^{max}{}_{VSC,n} \quad (2.6\text{-}2)$$

where $Q_{VSC,n}$, is the reactive power at the nth terminal of the MVDC link. $Q^{min}{}_{VSC,n}$ and $Q^{max}{}_{VSC,n}$ are the lower and upper limits of reactive power provided by the VSC at terminal n. $Q^{max}{}_{VSC,n}$ is positive - indicating that reactive power is injected into the network, and $Q^{min}{}_{VSC,n}$ is negative - indicating that reactive power is absorbed from the network.

- Capacity constraints:

$$\sqrt{(P_{VSC,n})^2 + (Q_{VSC,n})^2} \leq S_{VSC,n} \tag{2.6-3}$$

where $S_{VSC,n}$ is the rated capacity of the VSC at the nth terminal of the MVDC link.

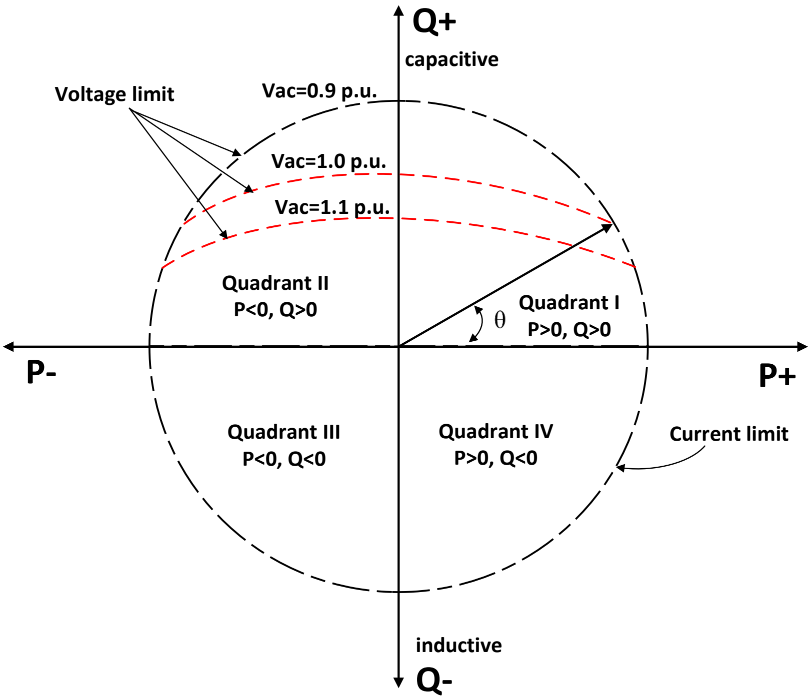

Figure 2-9: The P-Q diagram of VSC power transfer [14]

2.6.2. The common reactive power control methods of the MVDC links

Common reactive power modes of the MVDC links are:

- Power transmission mode: this mode controls both the active power and reactive power according to equations (2.6-1) to (2.6-2), where one VSC station controls the active power flowing through the link, and the other VSC station is used to maintain the DC voltage. In addition, for each VSC station, either the reactive power or the AC side voltage can be controlled. Table 2-1 summarises these operating conditions.
- STATCOM mode: in this mode, the reactive power only is controlled, (i.e. Zero active power). The MVDC links work as if it is a STATCOM that injects reactive power.

Table 2-1: Control modes of an MVDC link under normal operating conditions

Control Mode	VSC Station 1	VSC Station 2
1	PQ/PV_{ac}	$V_{dc}Q/V_{dc}V_{ac}$
2	$V_{dc}Q/V_{dc}V_{ac}$	PQ/PV_{ac}

2.6.3. Reactive capability features of the MVDC links

- MVDC couplers and MVDC links provide full control of active power between the grid sections, and reactive power on both ends.
- Control of reactive power flow at both ends of the distribution circuit.
- This technology can provide reactive power while generating zero active power.
- The reactive power provided, or absorbed, by the two terminals of the MVDC link are independent (i.e. the reactive power can be controlled independently).
- A power factor setpoint could be anywhere "within" the reactive capability curve.
- The active power transferred between the two terminals of the MVDC link (i.e. P1 and P2) must be the same, as the sum of the active powers should be equal to zero, assuming a negligible power loss through the DC lines.
- The power factor can be set to a fixed value or can be controlled on both sides independently.
- The technology can receive local and/or remote control signals/schedules to vary their reactive power output. The response time depends on the controller core parameters chosen.
- There are real power restrictions caused when providing/absorbing reactive power, refer to equation (2.6-3).

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2.7. Soft Open Points Technology

A Soft Open Point (SOP) is a new type of power electronic equipment which consists of two back-to-back Voltage Source Converters (VSCs) and can replace the traditional tie switch [15]. SOPs are power electronic devices installed in place of normally-open points in electrical power distribution networks. They can provide active power flow control, reactive power compensation and voltage regulation under normal network operating conditions, as well as fast fault isolation and supply restoration under abnormal conditions [16]. SOPs control load transfer and regulate network voltage profiles by flexibly controlling active/reactive power flow between adjacent feeders. Immediate fault isolation between interconnected feeders as well as fast supply restoration is also enabled using these devices. Therefore, SOPs are able to improve distribution network operation as well as facilitate a large penetration of low-carbon technologies into the distribution network.

Figure 2-10 shows a one-line diagram of an MV distribution network with an SOP connected at the remote ends of two feeders. The two VSCs (i.e. VSC1 and VSC2) are connected via a capacitor. P1 and Q1 represent the active and reactive power that VSC1 provides to Feeder 1, and P2 and Q2 are the active and reactive power that VSC2 provides to Feeder 2. The AC terminal of each VSC is normally connected to an AC network via a coupling transformer. An SOP with two- or multi-level VSCs introduces additional degrees of flexibility for network operation, and the power flow through the SOP can be adjusted within operating limits.

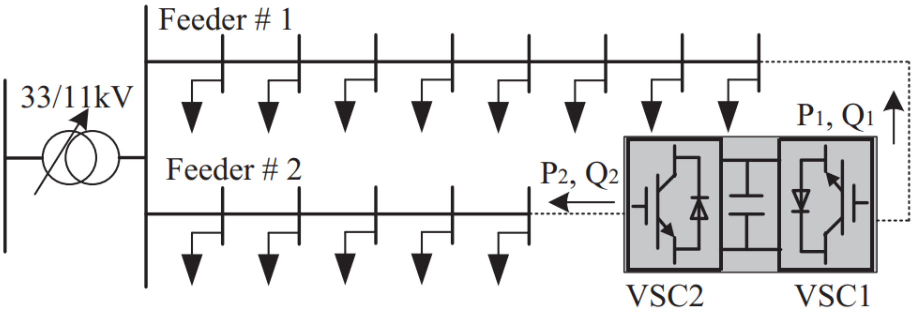

Figure 2-10: MV network with an SOP at the remote ends of two feeders

2.7.1. The P-Q capability plot of the Soft Open points

The power provided by an SOP can be modulated in the four quadrants of the power chart, and each VSC can operate in any region of the four quadrants. Figure 2-11 shows an example of an SOP's operating point where two VSCs operate in regions I and II, respectively. The two axes in Figure 2-11 are for the active and reactive power. Positive values represent the VSC providing power and negative values represent the VSC absorbing power. The circles represent the size (i.e. maximum apparent power, S1, S2) of the corresponding VSC. The power provided by the VSCs cannot exceed their ratings, as shown in equation (2.7-1) and equation (2.7-2).

$$\sqrt{(P_1)^2 + (Q_1)^2} \leq S_2 \qquad (2.7\text{-}1)$$

$$\sqrt{(P_2)^2 + (Q_2)^2} \leq S_2 \qquad (2.7\text{-}2)$$

With appropriate control, both VSCs produce their individual voltage waveforms with the desired amplitude and phase angle. This provides full (four-quadrant) control of the active and reactive power at both AC terminals. It is worth mentioning that the reactive powers provided, or absorbed, by the two terminals, i.e. Q1, Q2, are independent; whilst the active powers, i.e. P1 and P2, are not independent variables, as the sum of the active powers should be equal to zero, as shown in equation (3-3)

$$\sum_{j=1,2} P_j = 0 \qquad (2.7\text{-}3)$$

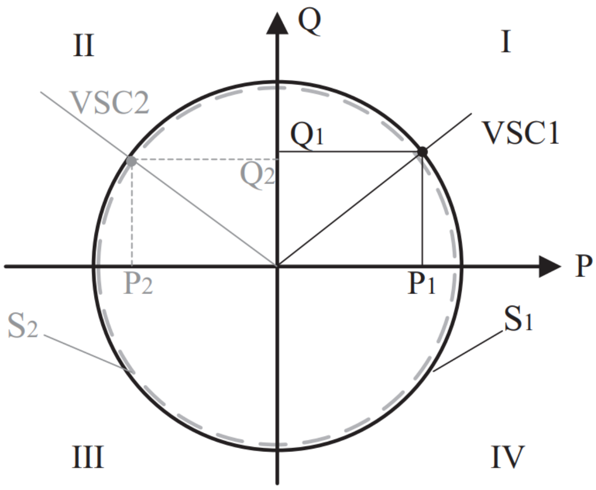

Figure 2-11: SOP's operating point: active and reactive power provided by an SOP with two VSCs having the same rating (for illustration purposes, the circle for VSC2 is smaller than VSC1 in the figure)

2.7.2. Common reactive power control arrangement

The control of SOPs is different than other grid-connected converters as an SOP is connected at least with two feeders. Figure 2-12 shows a basic block diagram of SOP where two converters are controlled in closed-loop control method having multiple loops to achieve optimal performance during normal and abnormal grid conditions. The superscript 1 and 2 represent the left side and right-side converters and their corresponding parameters, respectively in Figure 2-12.

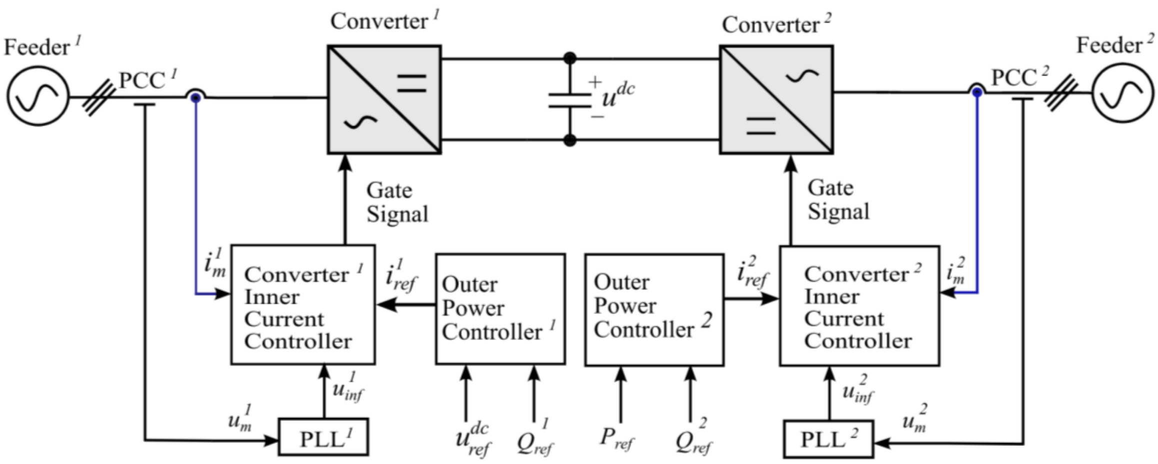

Figure 2-12: Block diagram for the control of SOP in a distribution network

Each converter in Figure 2-12 has mainly three control block, named as outer power control loop, inner current control loop and Phase-Locked Loop (PLL). The PCC voltage (u_m) between SOP and feeder's and line current (i_m) are usually main feedback parameters in multiple loop control method. The outer power control loop takes the power references as active power reference (P_{ref}), reactive power reference (Q_{ref}), dc-link voltage reference ($U_{dc\,ref}$) as input and generates the current references (i_{ref}) for inner current control loop, where P_{ref} and $U_{dc\,ref}$ can be given either of the converters, depend on the control algorithm. Then, information of u_m from PLL is given as input to the inner current control loop, which generally generates the Pulse Width Modulated (PWM) gate signal for the transistors of the converters.

Two control modes were defined to operate the SOP under both normal and abnormal network operating conditions as follows:

1. The power flow control mode: is used to regulate both active and reactive power flow on the connected feeders under normal network-operating conditions and to isolate faults between the interconnected feeders when a fault occurs on one feeder.
2. The supply restoration mode: is used under post-fault supply restoration conditions to provide power supply for the isolated loads on one feeder through the other feeder.

2.7.3. Reactive capability features of SOP

- Can provide bi-directional reactive power to the network.
- The reactive powers provided, or absorbed, by the two terminals of the SOP (i.e. Q1, Q2) are independent (i.e. the reactive power can be controlled independently).
- The active powers transferred between the two terminals of the SOP (i.e. P1 and P2) must be the same, as the sum of the active powers should be equal to zero.
- The power factor can be controlled on both sides independently.
- Can control/provide reactive power at any time of day.
- A power factor setpoint could be anywhere "within" the reactive capability curve.
- Flexible control of active/reactive power flow between adjacent feeders.
- This technology can provide reactive power while generating zero active power.
- The technology can receive local and/or remote control signals/schedules to vary their reactive power output.
- There are real power restrictions caused when providing/absorbing reactive power, refer to equations (2.7-1) and (2.7-2).

2.8. Domestic Heat Pumps Technology

Heat Pumps (HPs) can be controlled to provide stability to the electrical grid in the form of ancillary services. HPs can provide ancillary services in a similar way to other energy storage devices like electrochemical batteries or pumped hydroelectric storage. HPs can store energy by injecting or removing heat from the building's thermal mass. For example, in summer, a HP can increase its power consumption and charge its storage by removing heat and cooling the building to its lower thermal comfort limit. By doing so, the HP now has the flexibility to reduce its future power consumption and allow the indoor temperature to drift up to its upper thermal comfort limit. This increase or reduction in HP power consumption results in a net removal or injection of power onto the grid, achieving a similar result to a generator lowering or increasing its power output, respectively. The building then acts as a virtual battery, where the indoor temperature relative to the upper and lower thermal comfort limits acts as a state of charge, and the building's thermal mass acts as a measure of the energy storage capacity. It is important to note that when HP operates, it controls both the active and the reactive power at the same time.

2.8.1. The reactive capability of HPs

Based on trial results, laboratory studies and modelling of the effect of HPs on the power quality experienced on an LV feeder carried out by Imperial College London [17], twenty HP installations in a variety (and geographically dispersed set) of domestic dwellings were monitored with 18 yielding useful data. Data for real and reactive power draw and local connection voltage were gathered.

Figure 2-13 shows the maximum, mean and minimum reactive power recorded for each HP. The majority of the reactive power consumption from the HP was negative, which according to the normal load convention is a source of reactive power and a representation of a capacitive characteristic to the network. Most of the HPs have a minimum reactive power which is non-zero but some do reduce to essentially zero for some operating conditions (i.e low power consumption mode) [17]. it is clear that there are significant differences between brands of HP [17].

It can be observed from these results and measurements that the HPs can act as a source of reactive power injection in the network. Aggregation of reactive power might be important on this level to form a bulk reactive power provider to be able to participate in the reactive power market.

2.8.2. Reactive power control of HPs through aggregation

By aggregating together many HPs (i.e. in a range of 100 to 1000) [18], the combined capacity of ancillary services can be greatly increased. However, in aggregate HP control, the detailed parameters of each individual building and HPs are difficult to obtain. Therefore, aggregate control studies often contain high-level control schemes using simplified HP and building models. The main objective in aggregate control is to determine which HPs to modulate to accurately track an ancillary service signal while maintaining thermal comfort and reliability constraints. Note that while these aggregation control studies assume that each HP serves a single building, district heating and cooling systems can also provide ancillary services while serving an aggregation of buildings.

The power consumption of the Variable Speed Heat Pumps (VSHPs) can be dynamically adjusted as a function of the compressor rotor speed. In other words, VSHP's power consumption can be regulated to any point between zero and the full rated capacity by varying its compressor speed; therefore, ancillary services can be provided by using a compressor variable-speed controller.

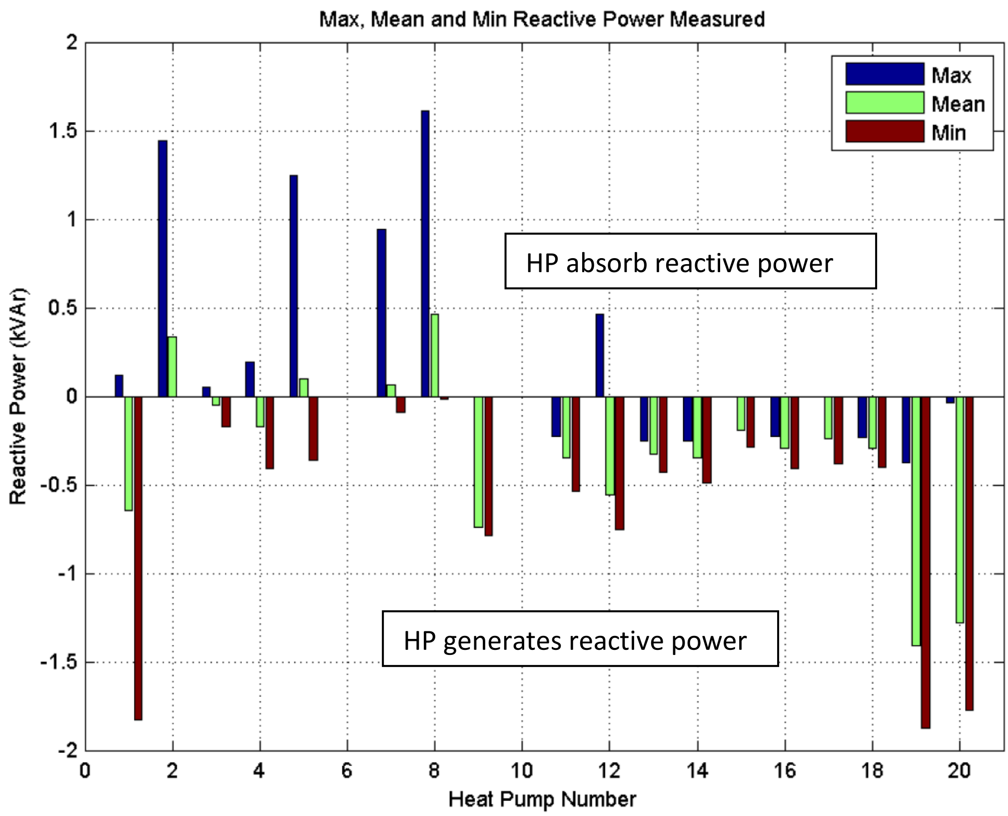

Figure 2-13: Maximum, mean and minimum recorder reactive power [17] for HPs

2.8.3. Reactive capability features of the HPs

- Some HPs can provide reactive power while they are operating, while others import reactive power. This returns to the type and the technology of the HP. There is a large variation between brands and there are indeed many detailed differences in the way the compressor motor of a heat pump might be supplied and controlled that could explain this difference.
- Both articles [19] and [20] have discussed the effect of adding HPs to the LV network on both the thermal and voltage limits of the LV network. Their conclusion is that adding more HPs to the LV network will lead to the network overloading (e.g. if more than 20% of customers install HPs, the network (under investigation) will be overloaded). Also, more consideration should be given for the type of the HPs (i.e. ground source heat pump or air source heat pump), Some HPs may lead to a transient voltage drops which may exceed statutory limits.
- To make a commercial use of the reactive power of HPs, many HPs should be aggregated together to increase the combined capacity of ancillary services.
- The domestic HPs cannot participate by themselves in providing reactive power support to the network. Domestic HPs of small size should participate in aggregations schemes to be able to provide reactive power support services (Ancillary services).
- HPs are much smaller than generators and therefore must be aggregated together to satisfy the 100 kW to 1 MW minimum requirement to participate in ancillary service markets.

- Controlling strategy: When a generator is required to reduce generation, the HP should increase load and vice versa.
- Controlling limits: HPs must not violate indoor temperature constraints and therefore cannot operate above or below their setpoint for an extended period of time.

3. Communication technology and infrastructure

The communication technology and infrastructure used to receive the remote-control signals to vary the reactive power output of any of the previous technologies can be any of the following:

- **Modbus:** Modbus has been around for over 40 years and is open source. This protocol is very widely used for automation components. About 80-90% of plant devices (inverters, trackers, etc) "speak" Modbus protocol, so it is important that the SCADA software and power plant controllers do too.
  - **Modbus TCP, and Ethernet protocols:** With Modbus TCP, the Modbus data is encapsulated inside a TCP/IP packet and uses IP addresses to communicate with slave devices. This enables Modbus TCP devices to connect and communicate over existing Ethernet and fibre networks easily. Therefore, any Ethernet network that supports TCP/IP should directly support Modbus TCP. Also, Modbus TCP allows for many more addresses, including multiple masters and speeds in the gigabit range.
  - **Modbus RTU with RS-485:** Modbus RTU RS-485 is a Remote Terminal Unit (RTU) Modbus over a serial RS-485 connection. Modbus RTU has been in existence for a long time and is supported by many inverters, power meter, and met station/sensor manufacturers.
- **Distributed Network Protocol 3 (DNP3):** DNP3 is a newer protocol that has gained usage over the past 10-15 years. It has some additional features over Modbus, including a timestamp that lets you know exactly when and where data was received. It is primarily used to communicate between different substation devices. It is recommended to use DNP3 for critical devices like substation devices, and Modbus for the rest of the plant.

- **IEC 60870-5 protocol:** IEC 60870 part 5 is one of the IEC 60870 set of standards which define systems used for telecontrol (supervisory control and data acquisition) in electrical engineering and power system automation applications.

- **IEC 61850:** IEC 61850 is an international standard defining communication protocols for intelligent electronic devices at electrical substations.

Figure 3-1 shows an example of the Communication system architecture in wind farm SCADA. **Please note:** The communication technology and infrastructure section is a general section and can be applied to all technologies

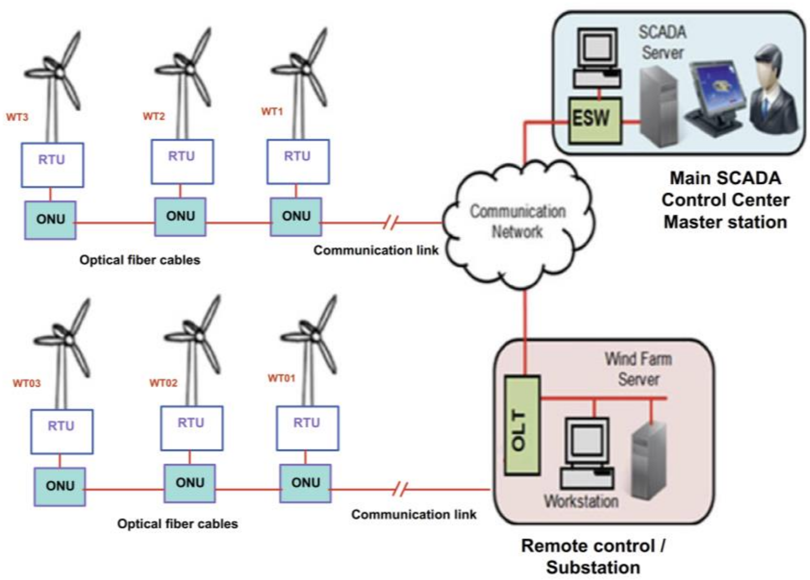

Figure 3-1: the Communication system architecture in wind farm SCADA farm [7]

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Appendices

Appendix A: Existing Technologies Questionnaire

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Existing Technologies Questionnaire

Organization name:	Department:
Responsible Person:	Email address:
Date of the Questionnaire:	

Summary: Power Systems Consultants UK Limited (PSC) has developed this questionnaire in participation with National Grid (NG) to survey the existing connected technologies to their electricity distribution network as a part of Q-Flex Innovation project. The Q-Flex Network Innovation Allowance project seeks to demonstrate that reactive power flexibility is technically possible and whether it can form a key component in the transition to net zero 2050.

PSC asks owners, operators, asset managers and manufacturers who have existing connected technologies to the National Grid electricity distribution network to participate in this questionnaire to provide more information about the capability of their technologies to **provide reactive power to the National Grid electricity distribution network**.

If you have any queries, please contact Mahmoud Elkazaz (power system engineer at PSC) by email mahmoud.elkazaz@pscconsulting.com

Please answer the following questions:

1. Which technology Category (from the following technologies) connected to the distribution network is your company responsible for?
   - Wind generation
   - Solar generation
   - Conventional generation

   Note: please fill a separate questionnaire for each Technology Category

2. What is the connection voltage, rated power, quantity of installations and the installation date (if already connected) of the technology?

3. Can the technology provide reactive power to the distribution network? (Please provide links to manuals or certification)

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4. If the technology can provide reactive power to the distribution network, are there any constraints on the availability through the day? (i.e. can provide reactive power only during certain hours, only during the day, only during the night, anytime of day for a limited duration)

5. If the technology can provide reactive power to the network, are there any real power restrictions caused when providing/absorbing reactive power?

6. If the technology can provide either bi-directional or single directional reactive power to the network, does it operate on a fixed power factor (e.g. 0.95 or any other fixed value) or it can be controlled?

7. If the power factor of the technology can be controlled, what is the applicable range of changing it?

8. If the power factor of the technology can be controlled, what are the existing control systems/interfaces available?

9. What is the control mode of the technology (voltage control, current control, power factor control, volt-var)? Can the control mode of the generation/demand technology be changed?

10. Can the technology receive local and/or remote control signals/schedules to vary their reactive power output? and what is the response time?

11. If the technology can receive control signals to schedule/vary their reactive power output, what is the communication technology/infrastructure used to receive this signal?

12. Can the technology provide reactive power while generating zero active power and if so what is the range of this?

13. If the technology **cannot** receive control signals to vary the reactive power output, can it be adjusted in the future to receive remote control signal to vary the reactive power generation? What are the required devices for this?

14. What is the reactive capability characteristic of the generation technology (e.g. triangular, rectangular, or D shape)? If applicable, can you provide the P-Q capability curve of the generation technology?

15. Does the technology/plant use any external static or dynamic devices such as a STATCOM or mechanically switched capacitors to keep the reactive power of plant within a certain limits?

16. Does the current technology provide any kind of flexibility services to the distribution network? If yes, please explain.

Appendix B: Emerging Technologies Questionnaire

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Emerging Technologies Questionnaire

Organization name:	Department:
Responsible Person:	Email address:
Date of the Questionnaire:	

Summary: Power Systems Consultants UK Limited (PSC) has developed this questionnaire in participation with National Grid (NG) to survey the emerging connected technologies to their electricity distribution network as a part of Q-Flex Innovation project. The Q-Flex Network Innovation Allowance project seeks to demonstrate that reactive power flexibility is technically possible and whether it can form a key component in the transition to net zero 2050.

PSC asks owners, operators, asset managers and manufacturers who have emerging connected technologies to the National Grid electricity distribution network to participate in this questionnaire to provide more information about the capability of their technologies to **provide reactive power to the National Grid electricity distribution network**.

If you have any queries, please contact Mahmoud Elkazaz (power system engineer at PSC) by email mahmoud.elkazaz@pscconsulting.com

Please answer the following questions:

1. Which technology category (from the following emerging technologies) connected to the distribution network is your company responsible for?
   - EV charging
     - Domestic
     - Connected at 11 kV+ (i.e. superchargers)
   - Battery energy storage systems (BESS)
     - Domestic
     - Connected at 11 kV or higher
   - Domestic Solar
   - Domestic Heat pumps
   - Medium-Voltage Direct Current (MVDC) links
   - Soft Open points

   Note: please fill a separate questionnaire for each Technology Category

2. What is the connection voltage, rated power, quantity of installations and the installation date (if already connected) of the technology?

3. Can the technology provide reactive power to the distribution network? (Please provide links to manuals or certification)

4. If the technology can provide reactive power to the distribution network, are there any constraints on the availability through the day? (i.e. can provide reactive power during certain hours, only during the day, only during the night, anytime of day for a limited duration)

5. If the technology can provide reactive power to the distribution network, are there any real power restrictions caused when providing/absorbing reactive power?

6. If the technology can provide either bi-directional or single directional reactive power to the network, does it operate on a fixed power factor (e.g. 0.95 or any other fixed value) or it can be controlled?

7. If the power factor of the technology can be controlled, what is the applicable range of changing it?

8. If the technology can provide reactive power to the network, what control systems/interfaces are available or planned for the future?

9. What is the control mode of the technology (voltage control, current control, power factor control, volt-var)? Can the control mode of the generation/demand technology be changed?

10. Can the technology receive local and/or remote control signals/schedules to vary their reactive power output? and what is the response time?

11. If the technology can receive control signals/schedules to vary their reactive power output, what is the communication technology/infrastructure used for this?

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12. Can the technology provide reactive power while generating zero active power and if so what is the range of this?

13. If the technology can receive control signals/schedules to vary their reactive power output, Can the technology participate in reactive power aggregation schemes? Do the devices have MW/MVAr meters at the interface? Does the participation in power aggregation schemes affect the end user/customer?

14. If the technology **cannot** receive control signals to vary the reactive power output, Can it be adjusted in the future to receive remote control signal to vary the reactive power generation? What are the required devices for this?

15. What is the reactive capability characteristic of the technology (e.g. triangular, rectangular, or D shape)? If applicable, can you provide the P-Q capability curve of the generation technology?

16. Does the technology/plant use any external static or dynamic devices such as a STATCOM or mechanically switched capacitors to keep the reactive power of plant within certain limits?

17. Does the current technology provide any kind of flexibility services to the distribution network? If yes, please explain.

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