FACTS to facilitate AC grid integration of large scale wind integration

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Summary

Ideally, wind farms should be connected to stiff grids in order not to influence stability or power quality in a detrimental way. This is usually not the case, however. Particularly when the grid is weak, unacceptable voltage gradients may occur. A centrally placed FACTS device such as an SVC or a STATCOM can provide the necessary functionality and be used as an alternative to complex and expensive equipment in each wind turbine generator. This is sometimes also the only option to be compliant with the Grid Code.

When wind penetration becomes a significant fraction of the load, added regulation is required for good grid stability control to compensate the fluctuations in generated wind power. Dynamic Energy Storage may provide a valuable option for such compensating capacity. Dynamic energy storage will also prove useful as a means for storing wind power during low demand, and releasing it into the grid during high demand.

The paper is treating typical challenges in AC grids powered by wind, as well as demonstrating several examples of safeguarding dynamic grid stability and availability. Some salient design features of SVC and Dynamic Energy Storage are also presented.

Three recent cases of real life experience are highlighted:

- Several 69 kV directly connected SVCs for grid stabilization in conjunction with a high degree of wind penetration
- An SVC for integration of large wind clusters in a 400 kV grid
- A Dynamic Energy Storage pilot plant for wind integration into an 11 kV distribution grid.

Introduction

When connecting wind farms to power grids, consideration needs to be given to the ability of the wind farm to produce energy while not impairing grid stability and reliability. As more and more wind farms are connected to the grid, transmission system operators are strengthening Grid Code requirements, specifically related to reactive power, voltage control, and fault ride-through capability. Wind farms often require dynamic reactive power compensation to comply with Grid Code requirements. This is especially relevant within the EU, due to the work of ENTSO-E of creating a uniform Grid Code for the entire EU.

Ideally, wind farms should be connected to stiff grids in order not to influence stability or power quality in a detrimental way. This is usually not the case, however. Quite the contrary, wind power is usually connected far out in the grid, at sub-transmission or distribution levels, where the grid was not originally designed to transfer power from the system extremities back into the grid. Particularly when the grid is weak, unacceptable voltage gradients may occur. To keep system voltages within limits, FACTS is a powerful means.

FACTS (Flexible AC Transmission Systems) is a family of devices based on state of the art, high power electronics operated in conjunction with highly intelligent control systems. Two types of FACTS devices are treated in the paper: SVC (Static Var Compensator) and STATCOM, the latter operated in conjunction with a battery storage, making up a Dynamic Energy Storage system (Also known as DynaPeaQ®).

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Studies as well as recent experience indicate that a centrally placed FACTS device such as an SVC or a STATCOM can provide the necessary functionality and be used as an alternative to complex and expensive equipment in each wind turbine generator. This is sometimes also the only option to be compliant with the Grid Code. Thus, the combination of large wind farms and centralized, high power dynamic compensation of reactive power constitutes a powerful option for the integration of large-scale wind power into power grids.

FACTS is also useful as a means for increasing the power transmission capacity of existing grids, thereby aiding in congestion management and making room for additional power transfer from wind farms over existing grids.

When wind penetration increases to the point where it becomes a significant fraction of the load, added regulation is required for good grid stability control to compensate the fluctuations in generated wind power. DynaPeaQ may provide a valuable option for such compensating capacity.

Dynamic energy storage will also prove useful as a means for storing wind power during low demand, and releasing it into the grid during high demand.

WTG and grid stability

The dominating kind of wind turbine generator (WTG) is asynchronous, utilizing the doubly-fed rotor concept (DFIG). To keep this technology within reasonable cost margins, however, rotor converter ratings must be kept limited mostly to steady-state requirements. During transient occurrences in the grid, the performance of DFIGs may well prove inadequate to maintain primarily voltage stability of the grid, possibly even with a necessity to crowbar the rotor converters to protect them from overload. In a situation like that, the DFIG may basically be reduced to a common induction generator, which is a substantial absorber of reactive power [1]. Here, dynamic reactive power support from FACTS at the point of common coupling (PCC) can improve the situation greatly.

Grid requirements

Grid Codes are issued by grid companies, spelling out the rules that apply for anyone who wishes to connect a wind farm to the grid. Main requirements involve:

- Reactive power supply
- Fault ride-through capability
- Voltage control
- Power quality control (flicker, harmonics)
- Frequency control,

some or all of which may require FACTS at the PCC to satisfy the demands.

New stringent demands

ENTSO-E, the association for the TSOs in the EU is currently working on new guidelines for the grid codes within the EU. Their pilot network code was released in March 2011 [2] and gave a first indication as to what their guidelines for grid codes will be like.

One of the more stringent demands is the demand on reactive power. For wind farms larger than 10MW (or 5MW for Ireland and the Baltic region) the requirements are according to Fig. 1 (red dashed line)**.** The Figure describes the required reactive power capability (Q) versus the active power produced (P), as a function of the installed capacity (Pmax).

If e.g. the wind farm is 100MW the requirement on production of reactive power is 40Mvar (0.4 p.u.) capacitive and 35Mvar (0.35 p.u.) inductive. It can also be seen that the wind farm will have to fulfill these requirements even if the wind farm is only producing 10% of its rated power.

The grayed area in Fig. 1 corresponds to a power factor of 0.95, a common operational area for several types of wind turbines. As can be seen, the grayed area fails to cover the “Basic requirement” (Red dashed line).

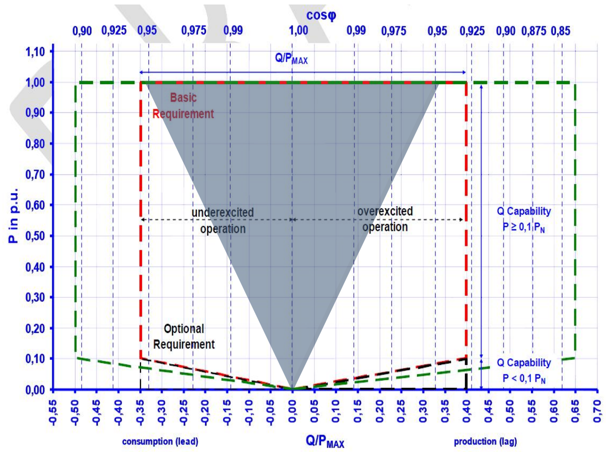

Fig. 1: ENTSO-E requirement on reactive power production

Simulation results for a wind farm in the UK clearly show these limitations and are presented in [3]. In order to comply with the ENTSO-E pilot network code it is necessary to integrate more dynamically available reactive power in the wind farm. One simple and cost effective way of doing this is to place a STATCOM or an SVC directly at the medium voltage busbar of the wind farm.

FACTS

FACTS make up a family of high power devices that are applied in power systems in shunt and/or in series. FACTS solutions are particularly justifiable in applications requiring rapid dynamic response, ability for frequent variations in output, and/or smoothly adjustable output [4]. Under such conditions, FACTS is a highly useful option for enabling or improving the utilization of power systems. FACTS devices treated in the paper are SVC (Static Var Compensator) and STATCOM (Static Compensator)[1].

SVC

An SVC is based on thyristor controlled reactors (TCR) and harmonic filters. An example SLD is presented in Fig. 2. A TCR consists of a fixed shunt reactor in series with a bi-directional thyristor valve. The thyristor switch acts to connect or disconnect the reactors for an integral number of half-cycles of the applied voltage. In this way the thyristor controls the amount of reactive power, generated by the capacitors that will be released into the grid.

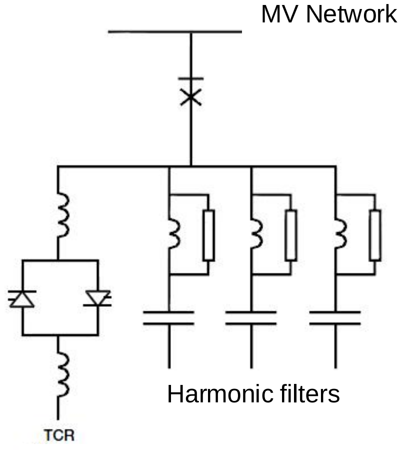

Fig. 2: Example SLD of an SVC

[1] Also known as SVC Light®

A complete SVC may be designed in a variety of ways, to satisfy a number of criteria and requirements in its operation in the grid. In some cases it can also be necessary to add a branch of thyristor switched capacitors (TSC).

STATCOM

SVC Light® is a STATCOM type of device, based on VSC (Voltage Source Converter) technology and equipped with IGBTs (Insulated Gate Bipolar Transistor) as semiconductors. A typical voltage-current characteristic of an SVC Light is shown in Fig. 3. It is worth pointing out that the SVC Light is capable of yielding a high reactive input to the grid more or less unimpeded by possible low grid voltages, and with a high dynamic response. This is highly useful to improve the fault ride-through capability of a wind farm, where otherwise the returning voltage upon fault clearing would be depressed.

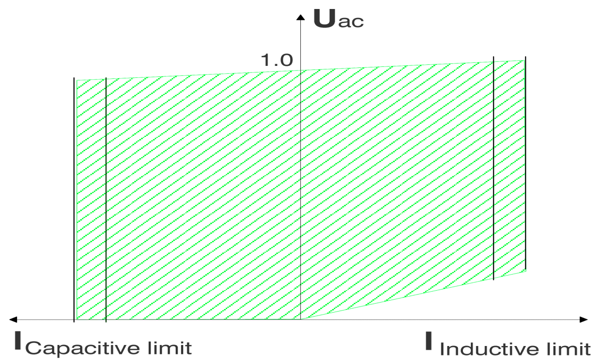

Fig. 3: Reactive power limits of a STATCOM

From a practical point of view, SVC Light brings further benefits such as:

- Reduced area requirements, due to the replacing of passive reactive components by compact electronic converters;
- Modular, factory assembled units, reducing site works and commissioning time and costs;
- Natural relocatability, due to modular, compact design as well as low harmonic interaction with the grid.

Wind integration: voltage control

Often, voltage regulation problems arise as a consequence of grids being made dependent on wind power, a matter of growing concern as wind power gets more important in the power balance. The problem is aggravated as traditional primary power such as thermal generation gets lower priority in the power supply balance, which is often the case due to political and environmental considerations.

To a certain degree, voltage control problems caused by deficit of reactive power in the grid can be, and is, remedied by installation of fixed or mechanically switched shunt capacitors. This will not help on voltage fluctuations, however, caused by varying output of wind generators.

Steady-state voltage control

Distribution networks (and indeed also in many cases, sub-transmission networks) receiving wind power have two distinct characteristics, both influencing voltage stability in the network: number one: resistance is usually not negligible as part of the line impedance, and number two: the network was usually not designed originally to receive and carry this power from wind generation.

The relationship between voltage gradient and the flow of active and reactive power on a radial distribution feeder can be expressed as follows:

$$\Delta U \approx \left(\frac{RP + XQ}{\mathrm{U}} \right) \tag{1}$$

Here, ΔU is the voltage gradient over the feeder due to the infeed of active power P and consumption of reactive power Q of the wind power plant. R and X are feeder resistance and reactance, respectively.

The simple expression shows that the impact of the wind mill on the feeder voltage will be a rise or a drop along the feeder, depending on the X/R ratio. If P and Q were constant, the voltage gradient would be constant, as well, and could be compensated by means of fixed reactive power compensation. To some extent, as mentioned above, this is done, to achieve a no load power factor at the wind power plant usually between 0,95 and 1.

However, the active as well as reactive power flow due to the wind farm in reality also contains fluctuating components, giving rise to corresponding fluctuations of the feeder voltage. This is detrimental to power quality in the grid and needs to be remedied. Switching WTGs in the grid also needs to be taken into consideration. This is where dynamic compensation comes in (SVC or SVC Light).

Further examination of (1) shows that with a high X/R ratio, pure reactive power compensation is efficient for voltage control [5]. For small X/R ratios, adding an active power component to the control will be helpful. This can be achieved by means of SVC Light with energy storage[2].
SVC Light, furthermore, is a superiour flicker mitigator.

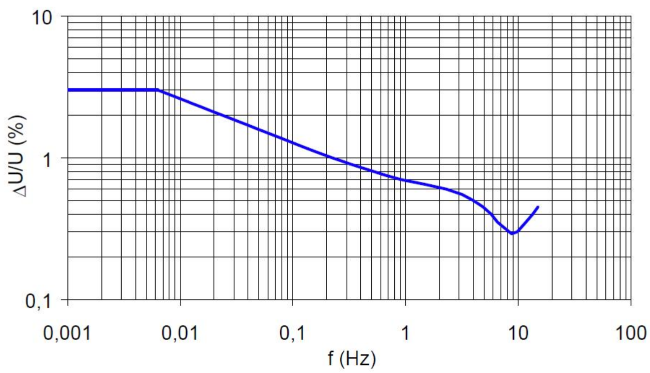

Fig. 4: IEC threshold curve for flicker

The flicker threshold curve according to IEC is illustrated in Fig. 4. According to the curve, a maximum of 3% voltage variations can be allowed for a periodicity of one minute. For more frequently occurring variations, the permitted value decreases to below 0,3% for fast variations (flicker).

The impact of wind turbulence on the mechanical input to the turbine is quite heavy, as the wind power transferred to the turbine is proportional to the cube of the wind velocity. Consequently, any fluctuating component in the wind impact will be reflected in a strongly amplified way in the mechanical power transferred to the turbine shaft, and from there on to the output of the generator.

Low voltage ride-through

Main grid requirements on integration of wind farms are treated in Grid Codes [6]. Regarding fault ride-through, the German E.ON grid code stipulates that the WTG must stay connected for

[2] Also known as DynaPeaQ®

a close-up 3-phase fault in the transmission system that is cleared within normal protection operating times (150 ms). Mechanical power output during and after the fault has been cleared must not be significantly reduced.

The WTG must remain stable throughout, which calls for fast re-magnetisation of the WTG when the grid voltage returns after the fault. With SVC, the need for fast injection of reactive power upon fault clearing is readily satisfied. With SVC Light, even faster response is attained.

High voltage ride-through

If a wind powered section of a network is isolated (”islanded”) from the rest of the grid, the wind mills will continue to produce active power, causing unacceptable values of voltage and / or frequency. In such cases, the wind mills are to brake and trip automatically. This, however, cannot happen instantaneously. Consequently, until tripping has been performed, there is an overvoltage risk.

Immediately following upon the occurrence of the islanding condition, the system voltage will rise so as to create a balance between the reactive power production in the grid and the consumption of reactive power of the wind mill(s). The time it takes to reach this balance depends on the electric time constants of the generator(s), i.e. a few cycles.

To prevent unacceptable over-voltages, it is essential that any production of reactive power in the network is very quickly absorbed or interrupted. This can only be achieved by means of dynamic compensation, i.e. SVC or SVC Light.

A sub-transmission multi-SVC case

In Western Texas, there is an abundance of wind power. In one hub, located in the McCamey area south of Odessa, wind production has grown to 750 MW and is expected to grow to well over 1 GW in the next few years. This corresponds to some 80% wind power penetration. In a second hub, the Central area located south of Abilene, 1000 MW of wind power is installed.

The transmission system in the McCamey area is basically two 138 kV lines providing parallel paths for the wind power delivery into the 345 kV system supplying the Dallas-Fort Worth area, a major load center. With either of these lines out, a substantial increase in reactive losses will occur, leading up to voltage stability problems. Correspondingly, the Abilene hub causes a significant power flow across a 345 kV transmission system towards the Dallas-Fort Worth area. Contingencies in the 345 kV network will load up the underlying 138 kV system, which will have to carry a portion of the power diverted from the 345 kV line lost in the outage.

For these situations, adequate dynamic reactive power support is necessary to maintain system operation at acceptable voltage levels. To improve and maintain system voltage stability in the McCamey and Abilene areas, three SVCs have been installed in the system, each rated at 40 Mvar inductive to 50 Mvar capacitive (-40/+50 Mvar). Two of these, located at Crane and Rio Pecos substations south of Odessa, are connected directly to 69 kV without any need for step-down transformers. The third, located at Bluff Creek close to Abilene, is connected to the 34.5 kV tertiary winding of an existing 345/138 kV autotransformer [7].

The concept of medium size SVC units distributed to critical buses in the system was chosen by the grid owner for the ability to apply the dynamic support close to the wind power connection points. This yields effective reactive power support during post fault system conditions and maximizes the power transfer capability out of the wind farm areas during shifting wind conditions.

Each SVC also has the ability to control up to five external mechanically switched shunt capacitors and reactors. In addition to enhancing the overall dynamic stability, this approach also enables implementation of large sized shunt elements, as the number of switching operations is minimized. These factors added together have given an extremely cost effective Static Var System and also helped improve the project´s total cost effectiveness [7]. A site picture of the Crane 69 kV SVC is shown in Fig. 5.

Fig. 5: Crane 69kV, -40/+50 Mvar SVC

In the given example, a comparison between the case benefiting from SVC and a base case without SVC suggests that to attain adequate system stability without SVC would most probably require comprehensive reinforcing of the grid by means of building additional transmission lines and/or upgrading the existing system to higher voltages. That would induce far higher costs as well as much longer implementation times. As conclusion, the chosen technology represents an attractive solution to the grid stability problem.

SVC for grid integration of wind power in a 400 kV interconnector

A Static Var Compensator (SVC) rated at 300 Mvar inductive to 300 Mvar capacitive is operated in the 400 kV La Ventosa substation of the CFE (Comisión Federal de Electricidad) power transmission grid in Mexico. The SVC is required to provide high-speed dynamic reactive power generation and/or absorption during certain system outages and loading conditions. The SVC was installed and commissioned in 2010 as a turn-key commitment.

Fig. 6: 400 kV SVC at La Ventosa, Mexico

The SVC (Fig. 6) is located adjacent to a large wind farm cluster, with a generating capacity close to 2.000 MW at the time of commissioning the SVC. Subsequently, there are plans for additionally 1.900 MW of wind power to go into operation in the area. The wind power is fed to La Ventosa substation over a 230 kV collection grid. The SVC fulfils several tasks in conjunction to this:

- Control the 400 kV voltage under steady-state as well as transient conditions;
- Minimize voltage fluctuations in the grid;
- Provide damping of active power oscillations between wind farms as well as between wind farms and the grid. Also, provide damping of active power oscillations over the 400 kV interconnector between Mexico and neighbouring Guatemala.

Main circuit design

The SVC consists of two thyristor controlled reactors (TCR), each rated at 175 Mvar, two thyristor switched capacitors (TSC), each rated at 125 Mvar, and three harmonic filters, rated together at 50 Mvar. The SVC is connected to the 400 kV grid via three single-phase step-down transformers, with one spare single-phase transformer located close to the transformers in operation. The phase-angle control of the TCRs and switching of the TSCs result in a continuous reactive power control over the entire SVC operating range (- 300/+ 300 Mvar).

DynaPeaQ-a dynamic energy storage

By adding an energy storage to SVC Light, not only reactive power can be controlled in a grid, but also active power (DynaPeaQ). The area of operability covers all four quadrants (Fig. 7):

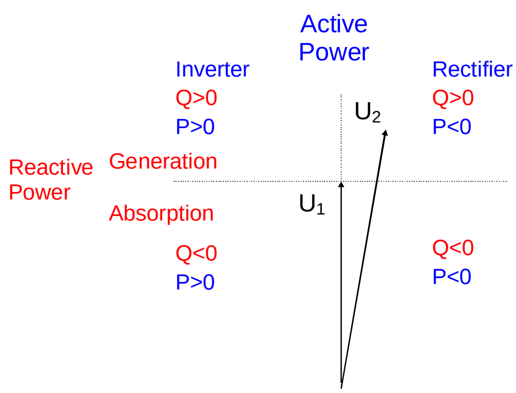

Fig. 7: Four quadrant VSC operating area

DynaPeaQ is based on Li-ion batteries. Since SVC Light is designed for high power applications and series connected IGBTs are used to adapt the voltage level, the pole-to-pole voltage is high. Therefore, a number of batteries are connected in series to build up the required voltage level in a battery string. To obtain higher power and energy, a number of parallel battery strings may be added (Fig. 8).

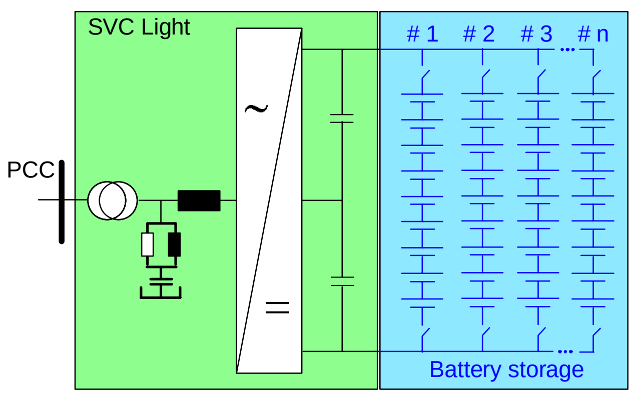

Fig. 8. Basic scheme, DynaPeaQ.

The battery system comprises rack-mounted Li-ion modules. An array of battery modules will provide the necessary rated DC voltage as well as storage capacity for each given case.

Applications

By means of DynaPeaQ, benefits in conjunction with integrating wind power in grids are enabled:

- Storage of energy during low demand, to be released into the grid during periods of high demand or during periods of more favourable price rates
- Levelling out power fluctuations
- Providing ancillary services such as area frequency control

A pilot case

UK Power Networks has installed a DynaPeaQ dynamic energy storage system at a site in Norfolk in England in collaboration with ABB and Durham University. is located in an 11 kV grid with considerable penetration of wind power (Fig. 9).

Fig. 9: DynaPeaQ installation, Norfolk, UK

Interest in electrical Energy Storage Systems (ESS) is increasing as the electricity supply industry is faced with growing pressures including the accommodation of distributed generation, management of ageing assets and avoidance of network reinforcement. Among other things, energy storage can be expected to help overcome the issues of intermittent power production (such as wind and solar), and in a Smart Grid development perspective, energy storage should come to play a natural part. This is the first time an electrical energy storage device has been installed on an 11 kV distribution network in the UK. Commissioning of the installation was finalized in the spring of 2011. The project was financially supported through GB regulator Ofgem's Innovation Funding Incentive scheme.

The installation will yield dynamic voltage control in the 11 kV distribution system and at the same time enable dynamic storage of surplus energy from wind farms, which can be utilized to level out peaks in grid loading and enable increased grid stability. Using this strategy, it should be possible to enable the power harnessed from the wind to be put to more efficient use than would otherwise be possible.

Test network

A site was selected such that the maximum number of benefits with the ESS could be considered from a single installation. A rural 11 kV distribution network in North Norfolk with a 2.25 MW wind farm connection was selected. The storage device is installed at a normally open point between two primary substations, near the remote ends of 11 kV feeders from the substations. Only one feeder is connected to the ESS at any single moment, but it is easy to switch between feeders, allowing for different operational scenarios. Physical network information such as line and transformer data is provided by the Distribution Network Operator (DNO) as well as half-hourly operational data comprising feeder current and DG output.

A mixture of residential areas, rural areas and seasonally occupied accommodation are supplied by the feeders in this region. The typical load on the feeders is 1.15 MW and 1.30 MW with peaks of 2.3 MW and 4.3 MW respectively. The wind farm with 2.25 MW installed capacity is attached midway along the first of these feeders. This installation has fixed speed induction generators, so there is significant reactive power demand while generating.

Daily load profiles show that the two feeders have quite different characteristics. On the first, the most significant demand occurs during the night, due to a high number of homes heated by night storage heaters. Summer loading is lower than during winter. The second feeder has much less storage heating, and in this case summer loading is higher than during winter. These dissimilar characteristics mean that events requiring ESS support are likely to occur at different times, maximising the utilisation of the ESS.

A range of modelling and simulation work has been carried out by Durham University to evaluate the most effective way to operate the ESS on a distribution network.

Funding for the monitoring and evaluation phase of the work has been secured from the GB Regulator Ofgem as a Tier One Low Carbon Networks Fund (LCNF) project together with matching funding from ABB.

Main circuit design

The size of the energy store was determined by the cost that could be reasonably justified as an R&D project. ABB integrated a battery system with an SVC Light to enable independent sourcing or sinking of real power up to 600 kW and reactive power up to 600 kvar (Fig. 1). The DC side of the VSC is connected to Li-ion batteries with a capacity of 200 kWh. An ABB MACH 2 control system controls both the VSC and the battery system. A dry-type step-down transformer rated at 1 MVA is employed to optimize the VSC voltage.

The VSC has a nominal rating of 850 kVA. A passive harmonic filter rated at 125 kvar and tuned close to the 37^{th} harmonic is installed to satisfy harmonic requirements at the 11 kV PCC.

The DynaPeaQ has a dynamic reactive power range from 600 kvar inductive to 725 kvar capacitive. The battery storage connected to the DC side of the VSC can deliver 200 kW for one hour, or 600 kW for a short period.

The design is based on IEC standards for both outdoor and indoor equipment. The design is also based on the vast experience gathered from other plants utilizing SVC Light.

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