STATCOM Technology for Wind Parks to Meet Grid Code Requirements

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1 Summary

The continuous increase of installed wind power seen during recent years has forced the transmission system operators (TSO) to tighten their grid connection rules – also known as Grid Code - in order to limit the effects of power parks on network quality and stability. These new rules demand that power plants of any kind support the electricity network throughout their operation. Key issues are steady state and dynamic reactive power capability, continuously acting voltage control and fault ride through behavior.

Some commonly used turbine designs have some limits in terms of achieving Grid Code compliance in several countries. For parks based on such turbines, additional equipment is needed.

This paper presents the medium voltage STATCOM (Static Synchronous Compensator) technology which adds the missing functionality to wind parks in order to become Grid Code compliant. The STATCOM as a pure static device with no switched passive components provides outstanding performance for both steady state and dynamic operation. Especially, the fast dynamic voltage control and the behavior during balanced as well as unbalanced grid faults (fault ride-through) are highlighted.

Based on medium-voltage converter platforms widely used for industrial applications, ABB has successfully supplied STATCOMs to the wind power industry in order to integrate wind parks into grids with demanding connection requirements.

2 Problem Description

2.1 Growing Wind Parks

During recent years, the sizes of installed wind parks have grown in a way that they can no longer be looked at as small single distributed power generators. Their effect to the connecting grid can no longer be neglected. The behavior of wind parks does matter in normal operation as well as in case of voltage dips in the grid. The following questions are more and more of interest: What is the steady state performance of the wind park? Is it able to contribute to voltage control by injecting or absorbing reactive power? What is the dynamic performance in case of balanced or – even more important – unbalanced voltage dips? In some countries – especially those with an already large amount of installed wind power – Transmission System Operators (TSO) and Distribution System Operators (DSO) are aware of these topics and have been modifying their connection rules, the Grid Codes. The particular properties of wind parks have been considered. Nevertheless, the wind parks are required to behave in principle like other generators, e.g. conventional generating units.

For wind parks, the following main topics are therefore of interest:

- Frequency dependent active power supply (frequency control)
- Voltage dependent reactive power injection/absorption, steady state and dynamic
- Voltage control, steady state and dynamic
- Fault ride-through

Besides other utilities, German E.ON was among the first to modify its Grid Code [1]. British National Grid Company as another example has been modifying its Grid Code as well [2]. In addition to the main Grid Code document, guidance notes for power park developers were issued [3]. This document is a helpful tool that guides the user along the Grid Code requirements. Other countries already did or will introduce similar requirements.

Developers of wind parks for said countries or regions have been confronted with requirements that are often beyond the capabilities of their equipment. While frequency control and fault ride-through requirements can often be met, steady state and dynamic reactive power requirements can traditionally not be fulfilled right away by some wind park concepts.

As a consequence, these wind parks need appropriate “add-on” equipment to get Grid Code compliance and therefore the release for operation and power production.

2.2 Reactive Power Compensation Equipment

There are a couple of principles to achieve reactive power compensation. The simplest solution is without any doubts a combination of switched passive elements, i.e. switched capacitors and inductors. Figure 1 shows qualitatively the reactive current versus connected voltage of such a solution. The reactive current depends linearly on the grid voltage and as a consequence the reactive power changes with the square of the grid voltage. Depending on the amount of switched component branches, the reactive current can only be altered in more or less large steps. Due to the limited switching time of capacitors, the dynamic performance of this solution is reduced. Furthermore, switching transients have to be accepted with this solution as well as regular maintenance of the breakers.

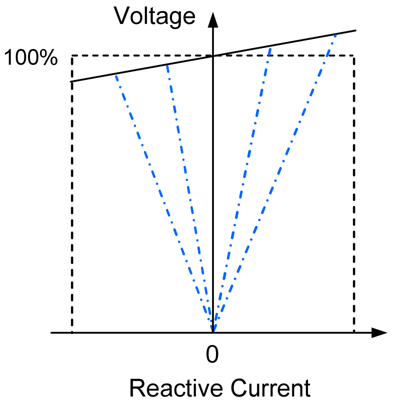


Figure 1: Reactive current versus voltage of switched passive components

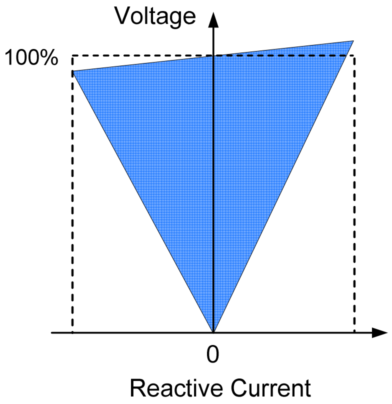


Figure 2: Reactive current versus voltage of an SVC

Figure 2 shows the reactive current versus connected voltage of a well known and widely used reactive power compensator: the SVC (Static Var Compensator). The SVC combines thyristor switched capacitors (TSC) with thyristor controlled reactors (TCR). Doing so, a smooth variation of reactive power over the complete installed power range is possible.

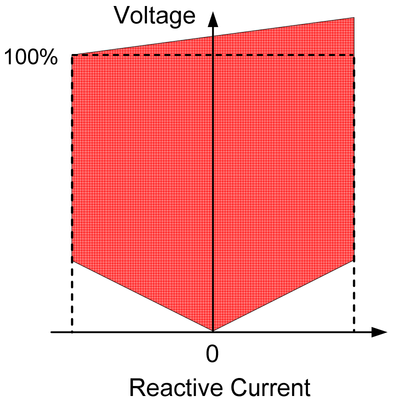


Figure 3: Reactive current versus voltage of a STATCOM

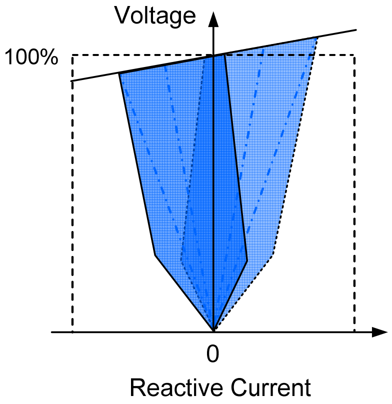


Figure 4: Reactive current versus voltage of mixed solution STATCOM/switched passive components

Figure 3 shows the reactive current versus connected voltage of a STATCOM. The performance is similar to a SVC, i.e. it performs smooth variation of reactive current across its operating range with high dynamics. According to [4], “it has advantages when compared to the Static Var Compensator (SVC), e.g., current injection independent of the system voltage, faster control and less of a space requirement.” The STATCOM is described more in detail further on. Finally, Figure 4 shows a combination of switched passive components with a small-sized STATCOM. This solution still includes disadvantages of switched passive components, e.g. switching transients and the need for regular maintenance of the breakers.

From an operator’s point of view, a solution for reactive power compensation without mechanically switched components is therefore preferred. ABB’s product portfolio includes both SVC and STATCOM. Depending on the project set-up, SVC or STATCOM is the optimum solution.

This paper focuses on the STATCOM (Static Synchronous Compensator) as well suited “add-on” equipment to help wind parks to achieve Grid Code compliance.

3 The STATCOM Solution

3.1 The Principle of a STATCOM

A STATCOM is in principle a voltage source converter (VSC) connected via an inductance to a grid. The concept has been known for many years and is described in detail e.g. in CIGRE publication no. 144, see [4]. Figure 5 shows an example of a STATCOM connected to a grid; Figure 6 shows the simplified single line diagram. The inductance can represent a reactor or a transformer. Reactive power can be altered by modifying the voltage amplitude of the VSC.

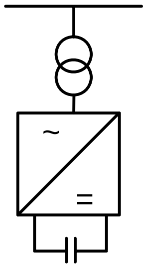


Figure 5: STATCOM, a VSC connected to a grid

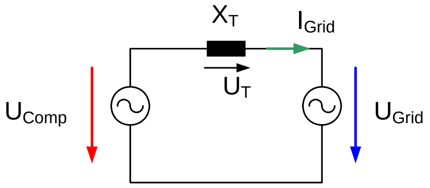


Figure 6: Simplified single line diagram of a STATCOM

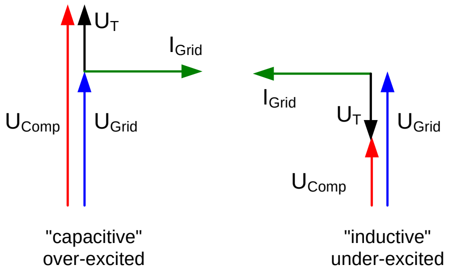


Figure 7: Vector diagram for capacitive and inductive STATCOM operation

The phasor diagram in Figure 7 helps to understand the principle of the STATCOM. For this purpose, a transformer with a turns-ratio of 1:1 or a reactor is assumed. In addition, constant grid voltage is assumed. Therefore, the grid voltage vector $\underline{U}_{Grid}$ remains at a constant value. If the value of the compensator voltage vector $\underline{U}_{Comp}$ is higher than the grid voltage vector, the vector of the voltage drop across the inductance $\underline{X}_T$ is in the same direction as the compensator voltage vector. Therefore the compensator current $\underline{I}_{Grid}$ flows in positive direction as per the definition in Figure 6. In this situation, the STATCOM acts like a capacitor. If the value of the compensator voltage vector $\underline{U}_{Comp}$ is lower than the grid voltage vector, the vector of the voltage drop across the inductance $\underline{X}_T$ is in the opposite direction compared to the compensator voltage vector. Therefore the compensator current $\underline{I}_{Grid}$ flows in negative direction as per the definition in Figure 6. In this situation, the STATCOM acts like an inductor. Since in all situations the current $\underline{I}_{Grid}$ is phase shifted by 90° compared the grid voltage $\underline{U}_{Grid}$, the STATCOM power is purely reactive.

3.2 Power Range of Interest

An analysis of the requirements given in the UK Grid Code shows that the required reactive power is approximately one third of the nominal active power of a wind park. Typical wind park nominal power range is between 30 MW and 100 MW for on-shore wind parks. As a consequence, required reactive power compensation is in the range of about 10 Mvar to 35 Mvar.

3.3 Realization of a STATCOM

A voltage source converter as needed for a STATCOM consists of a self-commutated converter and a DC link. ABB’s STATCOM design is part of ABB’s family of PCS 6000 products which are used for a wide range of applications. It uses the same state-of-the-art power technology as the wide spread ACS 6000 range of medium voltage drives. The standardization of these power electronic modules delivers substantial advantages in terms of cost and quality. With many ACS and PCS 6000 sold worldwide this converter has a proven track record and high reliability. The converter units are based on three-level IGCT phase modules. The IGCT (Integrated Gate Commutated Thyristor) is the state-of-the-art semiconductor element for the power range of interest.

For the STATCOM, double-phase modules as depicted in Figure 8 are connected to open windings of a transformer, resulting in the so-called TWIN topology. The phase modules are operated with pulse width modulation (PWM). Using three-level phase modules in TWIN topology results in a five-level output voltage, see Figure 9.

Figure 8: Three-level double phase IGCT module

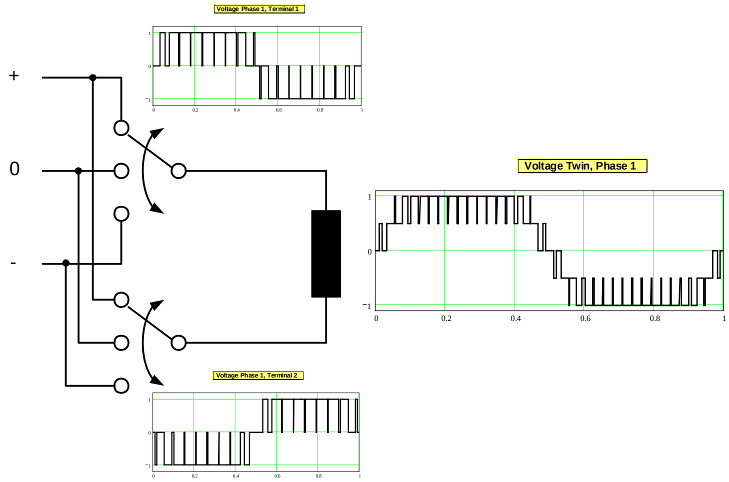


Figure 9: TWIN topology, one phase, PWM modulation

The very compact power electronic modules are placed inside a cabinet structure, see Figure 10. In the same cabinet, other required equipment is placed, e.g. DC link, cooling system, controls. Only a few additional external components are needed, such as STATCOM transformer, grid filter and heat exchanger.

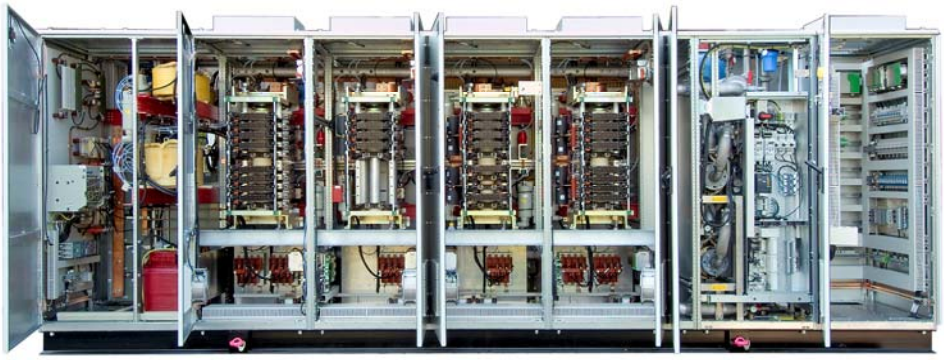


Figure 10: View of a PCS 6000 STATCOM converter cabinet

3.4 Functionality of a STATCOM

The STATCOM has to be equipped with a set of functions in order to help wind parks to fulfill the Grid Code requirements. These functions are listed below:

- Steady state reactive power supply or absorption. This function can be fulfilled by following a reactive power set-point, a set-point for a power factor at the connection point of the wind park or by operating according to a linear reactive power versus voltage characteristic (Q/U characteristic).
- The implementation of the latter case also fulfills the voltage control requirement often asked for in the Grid Codes. The Grid Companies often require certain flexibility to change the basic behavior of the voltage control scheme. A reduced set of changeable parameters has to be available, especially the target voltage and the slope of the linear characteristic. As an example, Figure 11 shows the requirements from National Grid Company (UK).

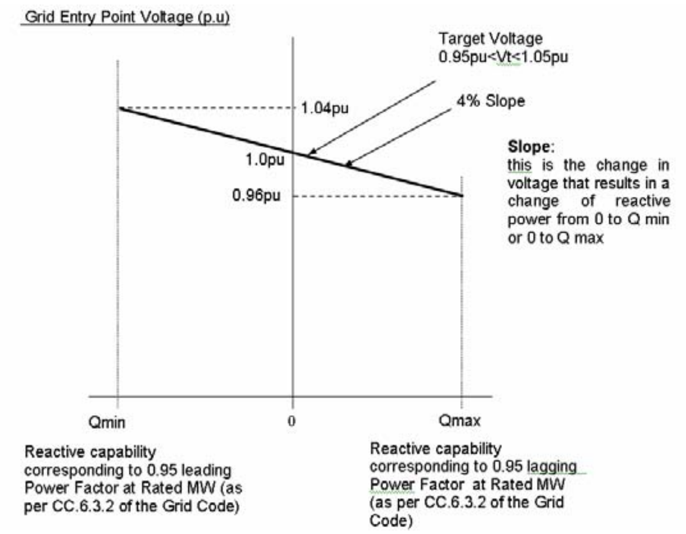


Figure 11: Linear Q/U characteristic as required by the National Grid Company (UK)

- Smoothly follow a set-point ramp. No steps occur as e.g. with solutions based on switched passive components.
- The dynamic requirements of the Grid Codes are met, e.g. a step in the set-point is followed within less than 1s without notable overshoots or oscillations.
- During voltage dips (balanced or unbalanced), the STATCOM injects reactive current in the order of nominal STATCOM current and therefore helps to support the grid voltage.

4 Case Study: STATCOMs at a Wind Park in Scotland

4.1 Case Description

A developer of the wind park in Scotland was faced with the updated Grid Code requirements of NGET, see [2]. They soon realized that their standard wind park design was not able to fully comply with the requirements. They decided to use a STATCOM solution from ABB to help them fulfilling the requirements in terms of

- Steady state reactive power supply
- Voltage control
- Dynamic reactive power supply

Of course, also the harmonic requirements given in [5] had to be fulfilled.

Since the wind park is connected via two 33kV cable connections to the nearest 132kV/33kV substation, the wind park is split into two parts that can also be connected via a coupling switch. However, both wind park strings are required to run autonomously. Therefore, two STATCOM units are required, see Figure 12.

4.2 Set-up

Both STATCOM converter units are placed inside the wind park substation building as depicted in Figure 14. Both transformers are located outdoors next to the STATCOM converter units, see Figure 13. Although the output voltage waveform of the STATCOM is close to sinusoidal, still a small harmonic filter is needed to fulfill the requirements of [5]. The filter of each STATCOM is located on a steel structure close to the transformer. The heat exchangers of the STATCOM converter cooling system are also located outdoors.

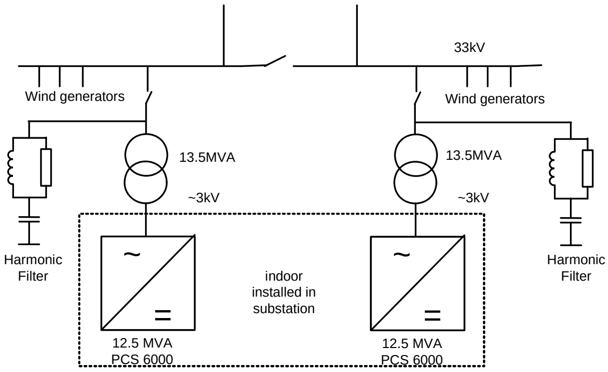


Figure 12: Simplified single line diagram of the STATCOM installation in the wind park.

Figure 13: Substation building with outdoor STATCOM equipment

Figure 14: Indoor installed STATCOM converter units

4.3 Measured STATCOM Performance

The system design of each individual STATCOM was done to comply with the mentioned requirements.

The system performance was tested based on the procedure given in [3].

4.3.1 Reactive Power Capability

During one hour, both STATCOMs were continuously operated at nominal power. Figure 15 shows reactive power capability of one STATCOM unit in function of the grid voltage. In this diagram, positive reactive power means, the STATCOM behaves like a capacitor, it supports the grid voltage. It runs therefore like an over-excited machine. The area within the blue lines is the calculated operation range of the STATCOM. The area within the dash-dotted line is the Grid Code requirement, whereas the customer’s additional requirements are reflected by the area within the grey line. The measurement points (red cross on orange rectangle) clearly show that the requirements are met.

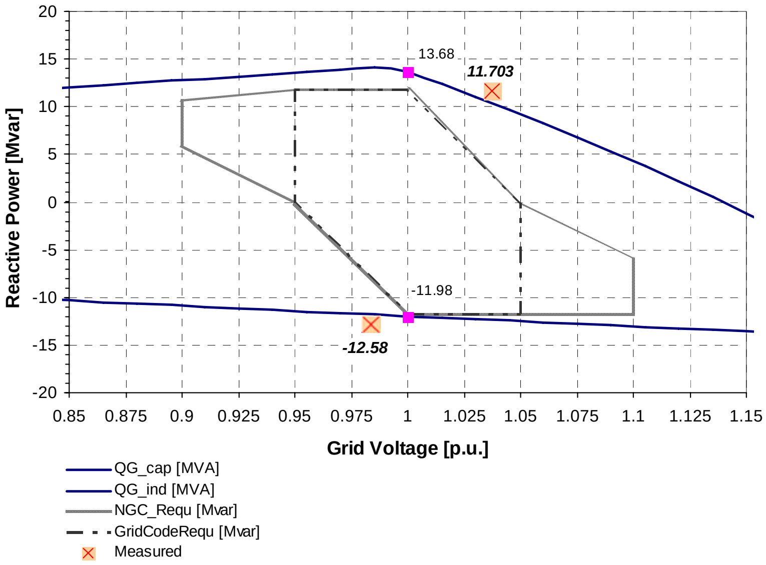
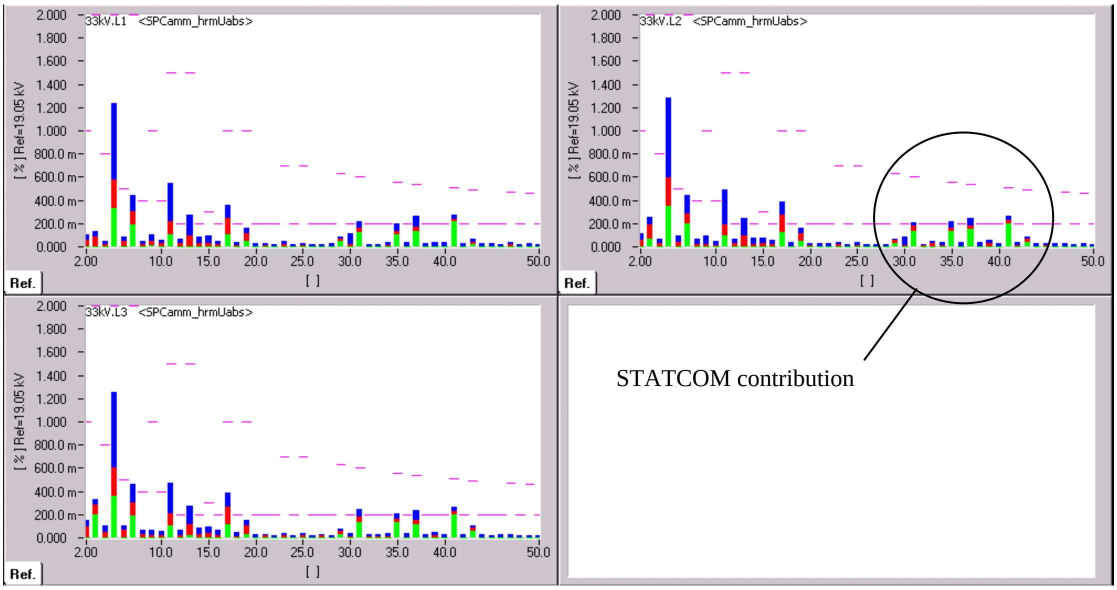


Figure 15 Measured reactive power capability vs. design

4.3.2 Contribution of the STATCOM to the Harmonic Spectrum at the Connection Point

During the continuous operation of the STATCOMs, the harmonics were measured at the connection point.



STATCOM contribution

Figure 16: Harmonic spectrum at the STATCOM connection point

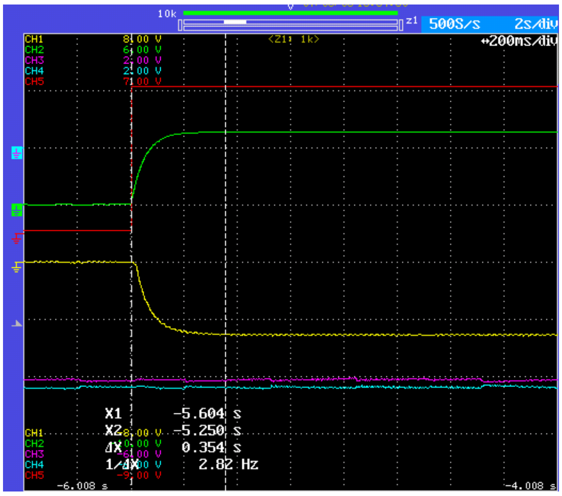
Figure 16 shows the resulting harmonic spectrum for each of the three phases at the 33kV connection point of the one of the STATCOMs. The measurement was done over several hours. On the x-axis, the harmonic number can be found; on the y-axis the voltage level in per cent is shown. The meaning of the graph colors is the following:

- Blue bars: maximum value within measurement period
- Red bars: average value within measurement period
- Green bars: minimum value within measurement period
- Pink dashes: Planning levels given in [5]

The spectrum was measured with and without connected STATCOM. A comparison of the results shows clearly that the STATCOM contributes to the spectrum only in the frequency range between 23 · 50 Hz and 43 · 50 Hz as predicted by calculations done during the design phase. It can clearly be seen that the resulting spectrum caused by the STATCOM is well below the planning levels. The resulting total harmonic distortion is hardly effected by the STATCOM; it is dominated by the pre-existing 5th harmonic.

4.3.3 Voltage Step Response

In order to check the dynamic performance, a test of the STATCOM response on a sudden voltage step of 2% was done. The STATCOM Q/U characteristic was set to a slope value of 4%, see Figure 11. Accordingly, a reactive power step response of -6.2 Mvar was expected. Figure 17 shows the measurement of the dynamic behavior of one STATCOM unit. The screen shot is a zoom of an event with longer duration. The zoom window is displayed with 200ms/div. The shown traces are explained below.



Red:
Target voltage step (indication)

Green:
Grid Voltage (indication)

Yellow:
Reactive Power (5 Mvar/Div)

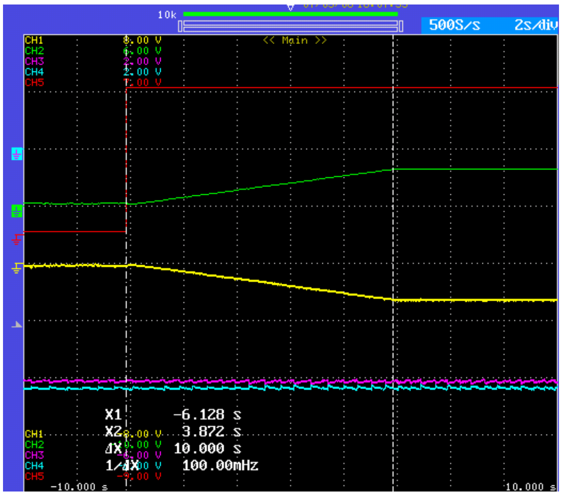
Pink/Blue:
DC link voltages (indication)

Figure 17: Measurement of voltage step response test

It shall be noted that the step response time is around 350ms which is well below the 1s requirement. No overshoot and no noteworthy oscillation can be seen. The expected reactive power is precisely achieved. The requirements are fulfilled.

4.3.4 Slow Voltage Ramp Response

In order to check the control stability as well as the resolution of the STATCOM control, the response of the STATCOM on a slow voltage ramp was done. The target voltage was ramped up by 1% over a period of 10 seconds. The STATCOM Q/U slope was again set at 4%. The final reactive power was measured to be -3.1 Mvar as expected.



Red:
Voltage ramp start (binary signal)

Green:
Grid Voltage (indication)

Yellow:
Reactive Power (5 Mvar/Div)

Pink/Blue:
DC link voltages (indication)

Figure 18: Measurement of slow voltage ramp response test

It can be noted that no instability can be seen. The reactive power output follows the ramp very smoothly with a very high resolution. The requirements are fulfilled.

4.4 Behavior During Grid Faults

The following measurements were performed at a hardware-in-the-loop simulator with original controls and modeled power electronic circuits and a simplified grid model. The voltage was measured at the 33kV equivalent connection point of the STATCOM.

For each of the following figures, the same trace designation applies:

- Green, yellow, pink: grid voltages, 37.93 kV/div
- Orange, red, light blue: STATCOM currents, 269.2 A/div
- Dark blue: ignore
- Grey: reactive power, 12.5 Mvar/div

The upper part of the graphs shows the zoomed fault initiation and the subsequent transient behavior of the STATCOM. The lower part of the graphs shows the zoomed fault clearing and the subsequent transient behavior of the STATCOM. Time resolution is 20ms/div except for the bottom part of Figure 21 where it is 50ms/div.

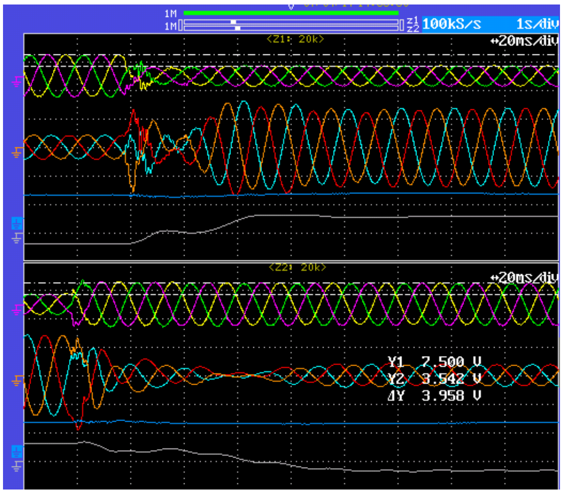


Figure 19: 3ph balanced voltage dip to 47% remaining voltage

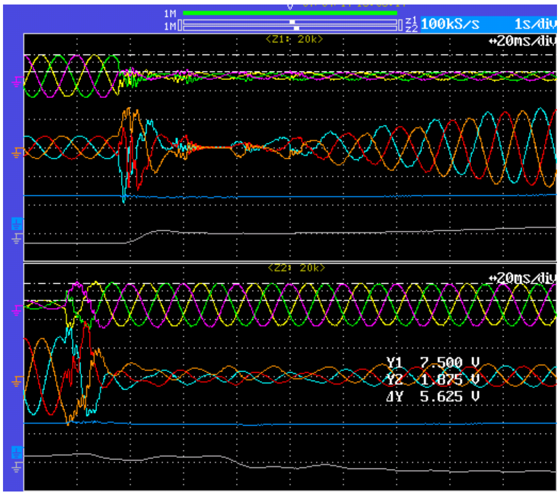


Figure 20: 3ph balanced voltage dip to 25% remaining voltage

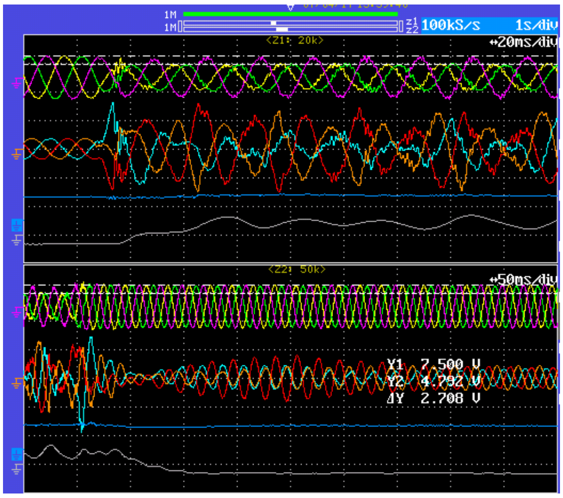


Figure 21: Example of an unbalanced 2ph fault to 64% remaining voltage

It can be noted that the STATCOM supports the wind park during balanced faults: It injects reactive current in such a way that it helps to maintain the voltage. Even during heavy unbalanced faults, the STATCOM supports the voltage. This can indirectly be seen by the behavior of the reactive power: Before the fault, the STATCOM runs slightly under-excited, i.e. it tends to decrease the voltage at the connection point. During all faults, the reactive power changes its sign, resulting in over-excited operation and therefore supporting the voltage at the connection point.

5 Conclusion

This paper describes some challenges for wind park developers in certain countries. Mainly, the steady state and dynamic reactive power injection/absorption requirements are difficult to fulfill with some wind park designs. Therefore, often “add-on” equipment is needed to comply with the Grid Codes.

Different reactive power compensation solutions are mentioned and briefly discussed. The STATCOM principle as well as the ABB STATCOM as a member of the PCS 6000 medium voltage IGCT converter family is presented in more details. Finally, site measurements performed with a STATCOM installation for a wind park in Scotland are shown.

6 References

[1] Grid Code, High and extra high voltage, E.ON Netz GmbH, Bayreuth, Status: 1st April 2006

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[5] Engineering Recommendation G5/4, February 2001, Planning Levels for Harmonic Voltage Distortion and the Connection of Non-Linear Equipment to Transmission Systems and Distribution Networks in the United Kingdom, Energy Networks Association, London W2 2HH