Abstract:
High-voltage direct-current transmission based on voltage-sourced converters (VSC-HVDC) is an economic connection technology for large remote wind parks. Wind power plants that are connected through a VSC-HVDC link are subjected to the same technical connection requirements as conventional generators. The requirement that these installations have to remain synchronously connected to the network during faults, is particularly challenging. Power electronic converters have no over-loading capabilities and during faults they can only supply a fault current up to the rated current. Since the wind park that is connected to the link does not directly notice the fault, a power imbalance is caused across the link that results in uncontrollability of the direct voltage. Such an uncontrollability might lead to tripping of the link and must be prevented.

Three strategies are described to keep the direct voltage controllable during network faults. The first strategy is formed by over-dimensioning of the GSVSC. The second is formed by dissipation of the excess wind power during the fault in a braking resistor. The third strategy is the fast reduction of the wind power production, and can be achieved by direct communication, voltage reduction and frequency increase. A reliable and cost-effective solution combines over-dimensioning and/or power dissipation with one of the power reduction methods. An optimal system design can be found with the help of an optimization procedure, in which the system costs are minimized.

1 Introduction
For the connection of remote wind power plants to the power system, high-voltage DC (HVDC) transmission is presently being considered as a technology alternative. Especially for large-scale offshore wind parks, where the application of AC cables is restricted by distance and power rating, HVDC may form the single economic alternative. Although both the current source converter (CSC) and the voltage source converter (VSC) technologies have been proposed in literature, the latter is generally considered more attractive for grid connection of wind power plants [1]. Compared to the CSC, the VSC can generate a stable AC voltage, is not dependent on external reactive power sources, and has inherent black-start capabilities.

With a rapidly increasing share of wind generation in their systems, transmission system operators (TSO) have been starting to require equal technical characteristics from wind power installations as from conventional generation [2]. Specifically, wind generators are required to ride through network faults and to provide reactive current during and after faults similar to large synchronous generators. During the last decade wind turbine generators have been continuously improved to comply with these strict grid connection requirements. In the case of remote wind parks that are connected through VSC-HVDC it should be stressed that it is mainly the VSC-HVDC link itself that determines the interaction between the wind park and the power system.

Particularly challenging for VSC-connected wind parks is riding through periods of low network voltage, such as in case of faults in the network. Because of the limited current rating of the grid-side VSC not the full rated power can be fed to the power system during the fault, whereas the wind park keeps feeding the pre-fault power into the link. This results in a fast rise of the direct voltage. To keep the VSC scheme in operation three fundamentally different strategies exist. The first is found in the over-dimensioning of the grid-side converter, such that a higher current can be delivered during the fault. The second is to get rid of the excess energy that is fed to the DC circuit during the fault by dissipation in an external element. The third strategy is the fast reduction of the incoming power from the wind park, for
which different methods have been proposed [3].
This paper elaborates on these fault ride-
through strategies. A practical and reliable
system design will combine the benefits of at
least two of them. The paper describes how
they can work together and proposes a first
approach to find an optimal system design.

2 System outline

2.1 VSC transmission system
A simplified system representation of a VSC-
connected wind park is shown in figure 1. It
consists of a grid-side VSC (GSVSC) and a
wind-park side VSC (WPVSC) that are linked
by a bipolar DC circuit consisting of two cables.
At each VSC a capacitor is present to provide a
stable direct voltage. The VSCs are connected
to the respective three-phase AC systems
through a converter transformer that adapts the
voltage level and provides the necessary
impedance for getting a power flow. The
technology of the VSCs themselves (two-level,
multi-level) is not important for the reasoning in
this paper and the VSCs are therefore assumed
ideal.
The GSVSC is connected to the main
transmission network, which is not represented
here in detail. TSOs require in their technical
codes that generator systems remain
connected when the voltage is low for a defined
period of time. An exemplary voltage profile is
shown in figure 2. If the terminal voltage
remains above the hatched area the generator
is required to remain synchronously connected.
The shape of this curve stems from the typical
voltage recovery process of a network fed by
synchronous generators preventing the voltage
to return immediately. The German TSO E.ON
Netz requires, for example, that the minimum
voltage that the generator has to ride through
$U_0$ is zero for a period $t_1$ of 150 ms, followed by
a ramp with $t_2$ equal to 1.5 s.

2.2 Control system overview
The VSC has the ability to control the active
and reactive power that is exchanged with the
network independently. An arbitrary voltage
space vector can be created at the converter
terminals by using a suitable pulse-width
modulation algorithm. The voltage difference
across the converter impedance (formed by the
converter transformer leakage inductance and
sometimes an additional reactance) determines
the current (magnitude and angle) and
therewith the power that is exchanged with the
network. Power can therefore be controlled by
controlling the modulation signals for the
converter voltage.
The control of the WPVSC works differently. In
this network no external reference voltage is
present to exchange a defined amount of
power. The WPVSC is required to absorb all
power that is generated by the wind park. This
can be achieved by operating the converter as
a voltage source with a defined amplitude and
frequency (‘slack node’). The WPVSC thus
serves as the voltage reference for this local
network.
The power that is exchanged with the wind-park
network is transferred to the DC network. Since
the direct voltage can vary only slowly because
of the capacitance on the DC side, the power
injections exhibit themselves mainly as current
injections. If the power that is injected into the
DC circuit is not equal to the power that is taken
out by the GSVSC, the capacitors will charge or

Figure 1: VSC transmission scheme for a wind park (WP), consisting of wind-park side VSC (WPVSC)
and grid-side VSC (GSVSC). An optional braking resistor (BR) is also shown.

Figure 2: Exemplary fault ride-through curve
discharge and the direct voltage will fluctuate. Thus, the direct voltage is a measure of the power unbalance across the link. The direct voltage can be maintained by a control loop that regulates the active power exchange of the GSVSC. This control loop automatically balances the VSC transmission scheme.

A typical capability diagram of a VSC is shown in figure 3. The power limits of the converter are dependent on the current rating of the converter. The VSC has no over-loading capability; even a slightly too high current might permanently damage the power electronic components. The controller will therefore enforce these current limits at all times. In case of a fault the system voltage is low and only limited power can be delivered. This limits the capabilities of the direct voltage control. The WPVSC does not notice the fault and keeps injecting the pre-fault power into the DC circuit. The resulting power imbalance causes a steep rise of the direct voltage. This particularly holds for three-phase faults in the AC network. In the case of unbalanced faults, which are more common, the equivalent residual voltage is higher than for three-phase faults. The unbalance, however, results in an oscillation in the power exchange, which might further complicate the control of the direct voltage.

This effect is made worse by the fact that some grid codes, such as the aforementioned E.ON Netz grid-code, require an additional reactive current to be fed into the network during and after the fault [2] to support the voltage restoration of the network. In this case the GSVSC needs to give precedence to the reactive current, meaning the maximum possible active power exchange being decreased further. If no countermeasures are taken for situations like these, the VSC link will trip and the grid code requirements with regard to fault ride through are not fulfilled. Different options exist to keep the scheme operational during network faults. These are described in the following sections.

### 3 Converter dimensioning

A prerequisite for the basic design of a VSC transmission link is the ability to supply the rated power at the minimum continuous system voltage, $U_{\text{min}}$. A typical value for $U_{\text{min}}$ is 0.9 p.u. The corresponding current limit is 1.11 p.u. A straightforward solution to enhance the fault ride-through capability of the VSC-connected wind park is therefore found by increasing dimensioning of the GSVSC current limit.

The required over-dimensioning factor $k$ to supply the rated power even at very low voltages at the network terminals of the converter can be estimated as

$$k \approx \frac{1}{u_k}$$

in which $u_k$ is the converter transformer short-circuit impedance in per unit. The power electronic converter then needs to be able to withstand $k$ times the rated current.

For a typical value of 14% for short-circuit impedance of the converter transformer the over-dimensioning factor amounts 7.1. To realize this over-loading capability, power electronic switches with a higher current rating need to be selected, or multiple switches need to be installed in parallel. This also puts higher requirements to secondary equipment, such as the valve cooling system because of the higher converter losses. Taking into account these disadvantages, over-dimensioning alone is not considered as an economical solution to the fault ride-through problem.

### 4 Energy dissipation

If the GSVSC is not able to deliver all power to the power system, another approach to keep the direct voltage controllable is found in dissipating the excess power that is fed by the WPVSC during the fault. This can be achieved by including a variable dissipative device in the DC circuit, which is often referred to as ‘braking resistor’ (‘BR’ in figure 1). This braking resistor should be suited to dissipate any amount of power up to the rated power of the GSVSC (for the case that no power can be delivered to the grid) for the duration of the voltage dip.

![Figure 3: Typical VSC capability diagram (positive power into the network)](image)
A conventional resistor can serve as a dissipative device. To make the dissipated power switchable and variable, the resistor must be connected through a power electronic device that regulates the current. A straightforward chopper circuit can do this. The power electronic switches must be able to carry the full current rating of the link. The amount of switches is approximately one third of one of the VSCs, which directly shows one of the disadvantages of this solution, the high costs of the additional equipment needed. The braking resistor control can be made independent of the main link control. It monitors the direct voltage and adapts the current to keep it at a given level. If this level is set slightly above the control target of the GSVSC (say 5%), a robust control scheme is achieved. When the GSVSC hits its current limit and cannot maintain the direct voltage, the direct voltage rises and the braking resistor is activated automatically. As soon as the network voltage is restored and the GSVSC can continue power injection, the GSVSC and the braking resistor operate in parallel drawing more power from the DC circuit than is injected, causing the direct voltage to fall below the threshold level. The braking resistor is then deactivated.

The thermal capacity of the resistor limits the applicability of this method. In the power range of hundreds of MW, a compactly built resistor will quickly heat under the dissipation of the full power. If we consider a simple single-body thermal model for the resistor and we assume that the heat radiation to the surroundings is negligible compared to the heating up, we can calculate the temperature rise by

$$\Delta T = \frac{1}{C_p} \int Q \, dt$$

(2)

Here \(C_p\) represents the thermal mass of the resistor and \(Q\) the thermal energy. If the dissipated power is constant, the temperature will rise linearly. Since the temperature of the resistor may not exceed a maximum, there is an upper limit to the total amount of energy that can be dissipated. This also implies that when the braking resistor has been activated for riding through a network fault, it needs to cool to a sufficiently low temperature before it can be used again. Cooling down will take a long time. Hence, if the resistor is to be used for riding through multiple system faults shortly after each other, an appropriate thermal design is required. The costs of this solution will depend on this design to a great extent.

Apart from the thermal design it should not be forgotten that the power electronic converter interfacing the braking resistor with the DC network, is required to carry the full rated current of the scheme. Independent of the dissipative properties of the resistor itself, this significantly adds to the costs of the design.

5 Fast power reduction

The last group of solutions is based on a fast reduction of the generated power in the wind park. If the power fed into the DC link can be reduced fast enough, the excess energy that is stored in the DC capacitor(s) can be limited and the direct voltage remains controllable. To do so, the wind-park side VSC needs to signal a power reduction order to the wind turbines. Three methods to achieve this behavior are described below.

5.1 Direct communication

The first method of fast power reduction is based on communication between the wind-park side VSC and the wind park. Most large wind parks are equipped with a park controller that regulates the active and reactive power output of the complete wind park. The park controller translates the park set points to reference values for the individual turbines. Usually, the cables connecting the turbines have an embedded fiber-optic link that enables fast communication between the park controller and the individual turbines. Such communication is mostly implemented using standardized SCADA\(^1\)-protocols. Through the SCADA-link a high amount of data is sequentially transmitted that is required for remote monitoring and control. Because of the high amount of data the up-dating frequency is normally low, in the order of magnitude of 10–100 Hz. The worst-case communication delay for a power reduction order in a typical wind park arrangement therefore is about 100 ms. Besides the delay, the reliability of direct communication can be problematic. A failure or an additional delay of the communication chain would lead to failure of the power reduction order, taking the complete transmission scheme out of operation in the case of a network fault. In the two methods that are described next the signaling of the power reduction order is contained in the electrical waveforms themselves and this information is always

\(^{1}\) Supervisory Control And Data Acquisition
present. These methods are expected to have a higher reliability.

5.2 Voltage reduction
This method is based on the idea that by lowering the wind park network voltage a power reduction is automatically effected [4]. Since the WPVSC network voltage is highly controllable, a reduction of the wind park voltage amplitude is possible within several milliseconds. However, this method has also several serious drawbacks.

Firstly, the voltage reduction method works best if the wind park consists of wind turbine generators that are variable speed machines employing a power electronic converter, such as the doubly-fed induction generator (DFIG) or various designs with a full-converter interface. The converters in these machines usually have current limits that are close to their rated current; they have hardly any over-loading capability. The concept of this strategy is that at a low network voltage the converters of the wind turbine generators run into their current limit and the power output is changed accordingly.

Secondly, the controller design of the wind turbines needs to be adapted such that no additional voltage support is enabled, and no additional fault ride-through measures are activated. This especially holds for DFIG turbines, where a steep voltage sag might trigger the so-called crow-bar protection that short-circuits the rotor windings in order to protect the converter. When the crow bar is activated high current peaks will occur, which works adversely on the power reduction strategy.

Moreover, if the wind turbine generators are of a fixed-speed design based on directly coupled induction machines, voltage reduction may have an adverse effect. If the blade pitch controller is slow, or the machine is based on passive-stall control, it would accelerate during the low-voltage period. A high slip would occur and would load to high reactive currents, comparable to the currents that occur at starting of the machine and could be in the range of several times the rated current.

5.3 Frequency droop
A last method for fast power reduction is formed by signaling through the electrical frequency. The very fast control possibilities of the WPVSC enable an almost instantaneous change of the frequency. As long as no synchronously rotating equipment is present that is sensitive to frequency deviations, the frequency can be changed freely in a small range around the rated value. In this control scheme the wind-park side converter could gradually increase the network frequency as soon as the direct voltage exceeds a threshold value [5]. As for the voltage reduction method, the method is mainly aimed at variable-speed wind turbine generators that employ a power electronic converter.

For this method the wind turbine generators need to be equipped with an additional control loop that reacts to the frequency change of the terminal voltage. If this loop would not be included, the output power would not react to a change of frequency. Such an additional control loop reacting on frequency could be based on the design described in [6].

An aspect that is generally not considered in previous works is the fact that frequency measurement is not instantaneous. Controllers of power electronic converters are usually equipped with a phase-locked loop (PLL) circuit that is used to detect the actual angle of the network voltage space phasor. The same PLL circuit can be applied for continuously measuring the frequency. A typical PLL has a first order time response, causing an inherent delay aggravating the speed of response of the frequency-dependent control loop. A typical time delay lies in the range 10–100 ms. Making the PLL faster is possible, but makes the system very sensitive to measurement noise, which is the main reason that a slower PLL is preferred for practical applications.

6 Optimized system design
By applying the described strategies it is possible to design a VSC transmission system for a wind park that complies with the grid code requirements with regard to low-voltage ride through. The first method, converter overdimensioning, and the second method, power dissipation, are on their own able to make a compliant design. Both methods require additional equipment to be installed in the converter stations, which will add significantly to the total system costs.

On the other hand, the methods for the third strategy, power reduction, are all based on changing the control systems of the WPVSC and the wind turbine generators and hardly add costs. However, all the methods described have some disadvantages making it impossible to rely on their functioning alone. A cost-effective yet reliable system design will therefore
combine one (or both) of the first two strategies with one of the methods for power reduction. For instance, if frequency droop is applied as power reduction method, a smaller braking resistor can be applied that only needs to dissipate the excess power that enters the DC circuit because of the slow time response of the frequency measurement.

An optimized system design will comply with the grid code in a reliable way at the lowest cost. Continuing the above example of dissipation and frequency control, an expression can be formulated that relates the required thermal capacity of the resistor $C_p$ to the excess power flowing into the DC circuit caused by the time delay of the PLL. The thermal capacity is assumed to be directly proportional to the costs of the resistor. By finding the minimum value of $C_p$, the optimal design can be found. This can be achieved by standard optimization approaches, such as linear programming. Different boundary conditions can be added to this optimization, for instance the time that is assumed between two consecutive system faults with respect to the cooling of the resistor.

### 7 Conclusion

This paper gives an overview of fault ride-through strategies for offshore wind parks that are connected through a VSC-transmission link. Power electronic converters have no current-over-loading capability and hence only a reduced power can be delivered to the network during faults. This causes the direct voltage to become uncontrollable during the fault which might lead to tripping of the link. To maintain power balance across the scheme during the fault and keep the direct voltage controllable, three strategies have been described. The first strategy is formed by over-dimensioning of the GSVSC. The second is formed by dissipation of the excess wind power during the fault in a braking resistor. The third strategy is the fast reduction of the wind power production, and can be achieved by direct communication, voltage reduction and frequency increase.

A reliable and cost-effective solution combines over-dimensioning and/or power dissipation with one of the power reduction methods. An optimal system design can be found with the help of an optimization procedure, in which a cost function is minimized. Future research will concentrate on the implementation of the fault ride-through strategies in a detailed model and assess different system combinations.

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### References


