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HVDC with Voltage Source Converters – A Desirable Solution for Connecting Renewable Energies

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***Abstract*–When connecting a wind park (WP) to the main grid (MG) by way of an HVDC Light transmission system, the WP becomes decoupled from the MG, which results in several technical and economical benefits, on a variety of aspects, for transmission system operators (TSOs), WP developers and WTG manufacturers. Perhaps most important for TSOs is that an HVDC-Light connected WP becomes comparable to a normal power plant; the MG-side HVDC Light converter can be directly connected to a control or power dispatch center. A desirable consequence is also that AC faults appearing in the WP or MG grid will not be propagated by the HVDC Light transmission system, which has several desirable consequences such as possibly reduced mechanical stresses on the WTGs. In addition, grid code compliance mainly becomes the responsibility for HVDC Light, which results in that WTG and WP developers may place more focus on reliability, efficiency and cost reduction issues. Furthermore, the inherent HVDC Light voltage- and frequency-control capability simplifies WP black starts and WP energization transients will not transfer to the MG. An HVDC Light transmission system, being environmentally friendly with very low electromagnetic fields, oil-free cables and compactly dimensioned converter stations, also allows for more freedom to select the "right" connection point to the MG, which may avoid that the WP introduces grid "bottlenecks" and undesirable new load-flow paths.**

***Index Terms*–HVDC transmission, VSC, wind power, grid connection.**

I. Introduction

In order to reach the goal of climate change mitigation, the interest in renewable energy, recently wind power in particular, has been growing fast. The increased penetration of wind power into AC networks has presented more challenges for TSOs to maintain power quality, which has resulted in stricter grid codes [1], [2]. The grid codes have had a significant impact on the development of WTG technologies [3] as well as the progress of expanding wind power [4]. One consequence of the stricter grid codes has been increased cost for individual generation units and sophisticated communication systems for the control and protection functions of a regional WP. The grid codes have also made it more difficult for WTG manufactures to focus on the optimization related to cost-efficiency, and to design and produce standard products, since many countries have adopted different grid codes. Furthermore, the process of achieving grid code compliance may be challenging for a WTG manufacturer, since it involves time-consuming multilateral discussions between TSOs, WP developers, WTG manufacturers and other regulators. To add further complexity, a TSO or regional grid operator may have to begin projecting the grid connection before a WP developer or WTG manufacturer has even been selected.

The above discussed issues can be resolved by introducing an HVDC interface for decoupling the WTGs from the MG and, consequently, take over the responsibility for grid code compliance from the WP. The voltage source converter (VSC) based HVDC, also referred to as HVDC Light, is an excellent candidate for such an interface, as will be the topic of this paper. The paper will be organized as follows:

- Section II gives a brief description about the HVDC Light technology that is specially suited for connecting a WP to the MG.
- Section III demonstrates grid code compliance for an HVDC Light transmission system and some other possibilities, which are gained from an HVDC Light interface, are analysed from a TSO perspective.
- Section IV describes benefits, resulting from the HVDC Light interface, from a WP and WTG perspective.
- Section V deals with HVDC Light benefits from a TSO perspective.

II. HVDC and HVDC Light

When HVDC is considered for grid connection of a WP, an HVDC Light transmission system is normally required. A conventional line-commutated HVDC system is considered to be unfeasible for at least the following reasons:

- Both the rectifier and the inverter of a conventional HVDC system need sufficiently strong AC grids for valve commutation.
- There is no inherent black start capability, which is normally needed for energizing a WP.
- Moderate control bandwidth for the AC voltage and reactive power, which may create problems for stable WTG operation and grid code compliance.
- Continuous operation of at active power below 5 % may not be possible, which complicates WP energization and operation at low wind speeds.
- Higher degree of complexity for a multi-terminal system, for at least two reasons. Firstly, the DC current can only flow in one direction through a thyristor valve and the polarity of the DC pole has to be recharged from positive to negative, or vice versa, during a power reversal. Secondly, high-speed communication between all terminals will be required for control purposes.

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As shown in Fig. 1, an HVDC Light transmission system suitable for WP grid connection broadly consists of a DC cable, a DC chopper, two VSCs together with auxiliary equipment in each converter station including transformer, filters, reactors and DC capacitors. The DC chopper enables the possibility to transiently decouple the active power exchange between the WP and the MG. The duration of decoupling is decided by the energy rating of DC chopper or additional energy storage/dissipation system.

Due to the self-commutated properties of the VSC IGBT valves, the VSC can be controlled to create an AC side voltage with desired magnitude, phase angle and frequency. By varying the amplitude and phase angle for the MG-side VSC voltage, the active and reactive power exchanged between the converter and the MG can be controlled. Disregarding losses, the active power exported to the MG is controlled to equal the on-line produced wind power by maintaining constant direct voltage. By way of a swing-bus control system mode for the WP-side VSC, the active and reactive power exchange between the converter and the WP will be automatically determined by the WP, and the small local island grid with WP will have sufficient strength in the voltage and frequency independent of the size of the local island grid. This implies that the WP-side VSC can provide a quality AC source for WP energization.

III. Grid-Code Compliance

The grid codes of different TSOs may significantly differ [2], but usually include at least the following:

- Fault ride-through capability
- Reactive power capability
- Power modulation capability
- Frequency response capability
- Various power quality characteristics

Below, it is shown how some of the most challenging parts of the above list can be fulfilled by using an HVDC Light transmission system for WP grid connection.

A. Fault Ride-Through Capability

The fast switching capability of a VSC and intelligent control systems make it possible for an HVDC Light transmission system to sustain essentially any AC fault or disturbance. Furthermore, a VSC can also control the fault supply current to the desired value within the ratings of the semiconductor devices. After fault clearance, the active and reactive power can be restored to the pre-fault values both quickly and smoothly. To exemplify, Figs. 3 and 4 show simulations of the HVDC Light transmission system in Fig. 1 during three-phase and single-phase faults, respectively. For both simulations, the HVDC Light control system is tuned to not let the phase currents exceed 1 p.u. continuously.

As shown in Fig. 3, the large AC voltage dip results in a significant reduction in active power exported from the direct link to the MG but the WP-side active and reactive powers remain constant. The surplus active power at the direct link is dissipated by the DC chopper. During the fault, the reactive current to the MG is increased, which can be observed from reactive power. Despite some transients in the direct voltage at both DC terminals, the WP-side AC voltages are not influenced by the MG AC fault. After fault clearance, t>0.25 s, the active and reactive power smoothly recover to the pre-fault operation condition.

Fig. 4 shows simulation waveforms for a single phase fault in the MG, which results in a 50 % reduction for the voltage in phase a. The AC voltages and the active and reactive power at the WP side are decoupled from the MG disturbance. The reactive power to the MG is increased during the fault while the active power is only slightly reduced, which results in that the DC chopper does not have to operate continuously. From Fig. 4, it can be seen that the DC chopper is activated when the direct voltage exceeds 350 kV. Once the DC chopper operates, the direct voltage begins to decrease towards 300 kV, which is the turn-off threshold for the DC chopper. The process repeats until the MG fault clears at t=0.85 s.

B. Reactive Power Capability

The reactive power capability of a VSC is determined by the current rating of switching devices, the direct voltage rating, the allowed transformer tap-changer interval, the AC voltage rating and the static stability limit. Fig. 2 shows the reactive power capabilities of a typical VSC, 400 MVA base, and for comparison the capability curve of a 400 MVA hydrogen-cooled steam turbine-driven generator [5] is also included. In Fig. 2, it is clearly shown that the VSC reactive power capability is comparable or higher compared to the synchronous generator.

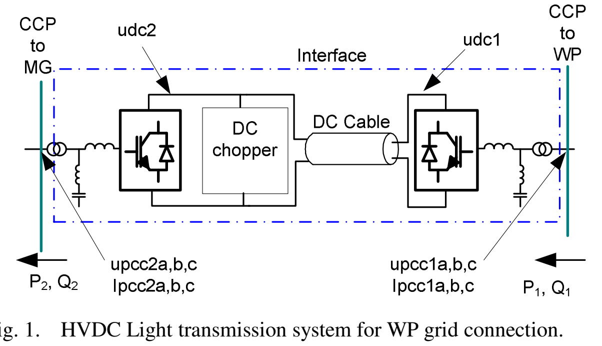

Fig. 1. HVDC Light transmission system for WP grid connection.

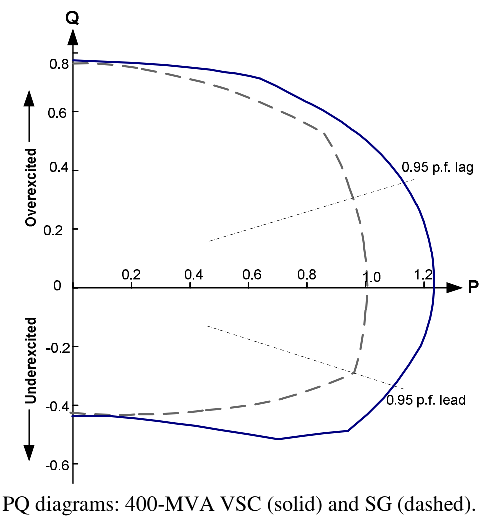

Fig. 2. PQ diagrams: 400-MVA VSC (solid) and SG (dashed).

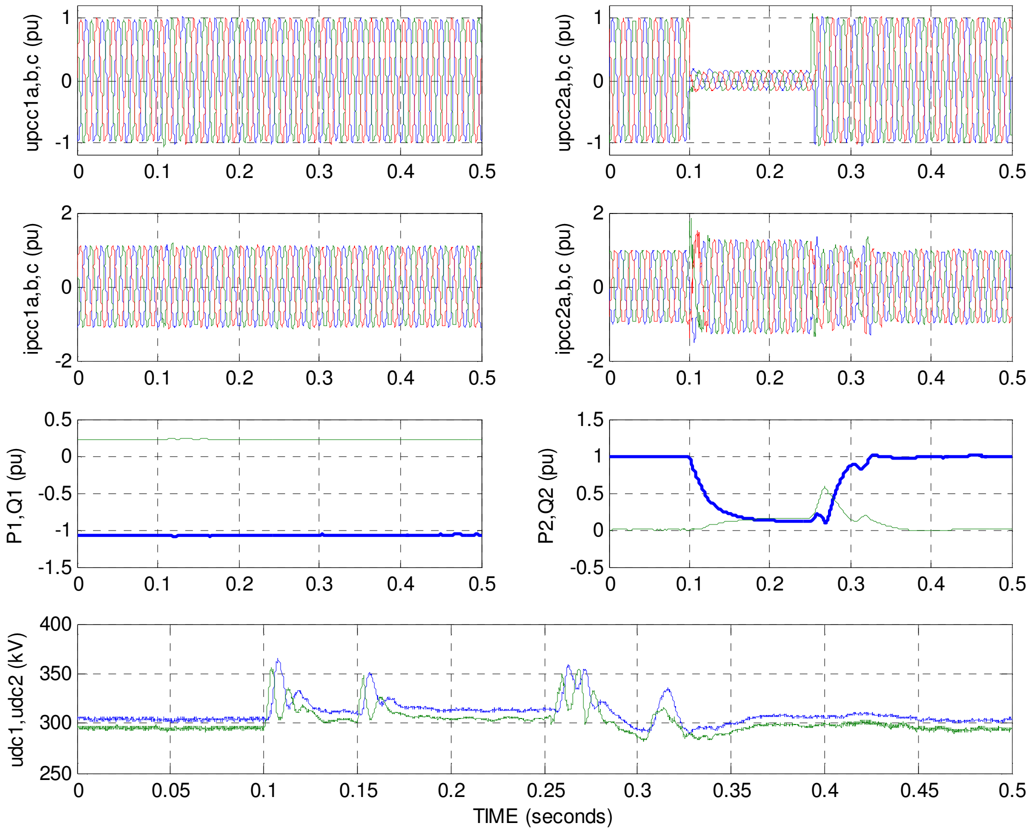

Fig. 3. Three-phase fault close the MG VSC (right) and corresponding waveforms for the WP-side VSC (left): Three-phase voltage at the point of connection (PCC) (row 1), PCC three-phase currents (row 2), PCC active and reactive power (row 3), direct voltages at the WP (blue) and the MG sides (row 4). The y-axis labels conform to Fig. 1.

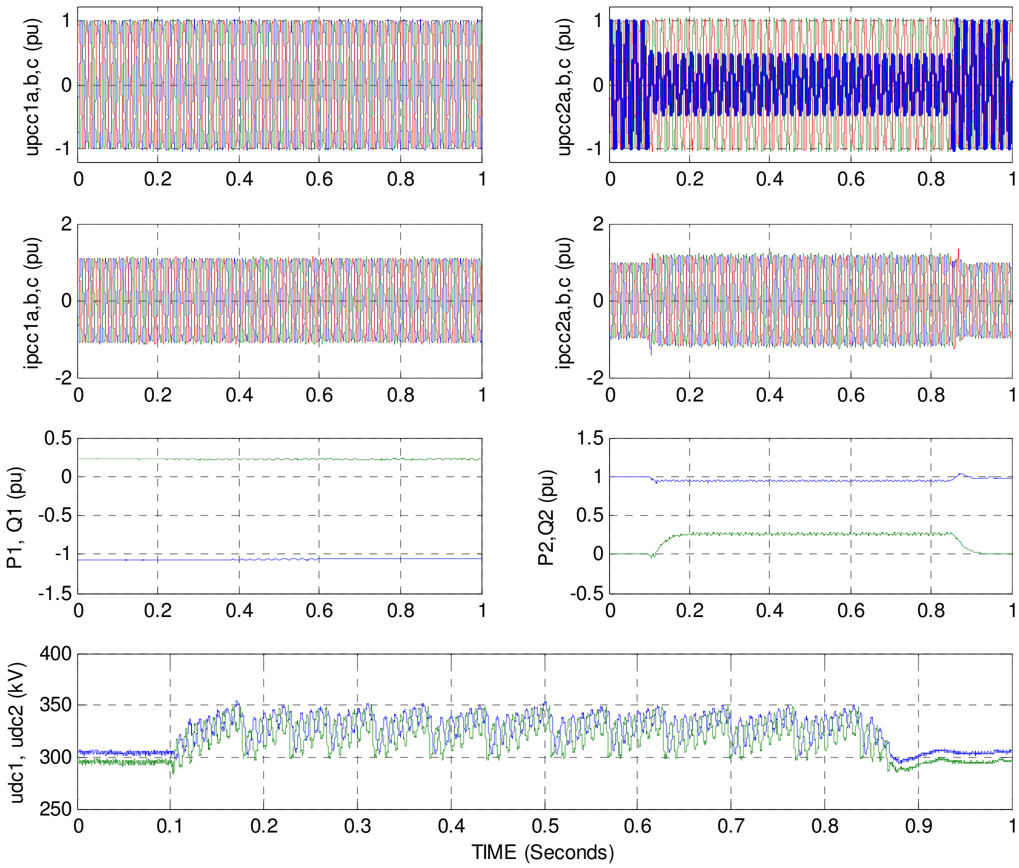

Fig. 4. Single-phase fault close the MG VSC (right) and corresponding waveforms for the WP-side VSC (left), see Fig. 3 for captions.

C. Power Modulation Capability

Many grid codes include power modulation capabilities for WPs, in order to adjust generation according to the on-line load. The power modulation cannot be implemented by the HVDC Light transmission system alone, since it during normal operation simply exports whatever active power that is being produced by the WP. In order to control the active power to the desirable power modulation setpoint, two different strategies may be used:

1) The power modulation order is sent to the WP master controller, which distributes a power order to each WTG.
2) The WP-side VSC "signals" to the WTG to modify their power production by changing the AC frequency in the WP grid. Sophisticated communication systems for sending a power order to each WTG are not needed.

The former method is normally used when a WP is connected to the MG by way of an AC connection, while the latter method is only applicable for an HVDC Light grid connection. When the frequency is changed, the WP power production should automatically be modified within a certain time. Note that unless the WP operates with a reserve before the power modulation intervention, active power can only be reduced, as exemplified in Fig. 5.

D. Frequency Response Capability

Instead of controlling the DC voltage, the MG VSC may during a temporary emergency situation reduce the active power export to the MG to zero or even reverse the active power direction. When this occurs, the excess active power at the direct link will be dissipated by the DC chopper. This allows for considerable faster frequency response and emergency power damping control compared to what is achievable by an AC-connected WP, which typically cannot change the production faster than 0.1 p.u./(m·s). The WP active power production should preferably still be reduced, in order to reduce duration of the DC chopper operation, but the rate of change for the WP power does not have to be significantly high. Furthermore, there is no need to design the WTGs for different rate of power changes for different grid codes.

E. Power Quality Characteristics

Since an HVDC Light transmission system decouples the MG from the WP, and vice versa, AC disturbances at one side of the transmission system will not be transferred to the other side. Furthermore, also the power quality characteristics become decoupled. For instance, voltage flicker will not be transferred to the MG and WP energization transients become isolated from the MG. The power quality characteristics will mainly be determined by the HVDC Light transmission system, which normally conforms to IEC standards with a total harmonic distortion at PCC below 1 %. Furthermore, the HVDC Light control system is normally tuned to provide only symmetrical currents, which provide no phase-unbalance contribution. If desirable, it is also possible to tune the HVDC Light control system to compensate any phase unbalance on behalf of slightly reduced power transmission capability.

Since an HVDC Light transmission system is capable of fast reactive power control within a wide operation range, effective AC voltage controls for both the MG and the WP grid are possible.

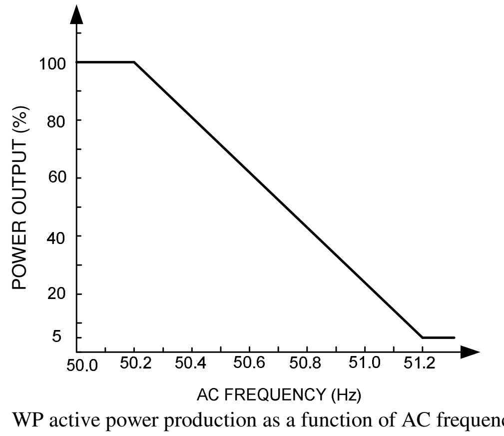

Fig. 5. WP active power production as a function of AC frequency.

IV. Benefits and Minimum Obligation for WP

The decoupling between the MG and WP, introduced by the HVDC Light transmission system, provides at least the following WP advantages:

- Grid code compliance can be relaxed, since this will become the responsibility of the HVDC Light transmission system. Instead, efforts can be placed on improving cost, efficiency and to standardize the WTG design.
- For WTGs with an electrical coupling between the stator and the grid, mechanical stresses will be reduced since the WTGs become isolated from the MG and ride-through operation will occur less frequently. Phase unbalances will be low and the WTG mechanical drive trains will not be subjected to 100-Hz torque oscillations.
- A connection to a weak MG becomes the responsibility of the HVDC Light transmission system, which may allow for simpler WP circuit breakers and protection design within the WP.
- The WP does not have to provide a wide range of reactive power control, so the reactive power setpoint can be chosen to minimize the losses within the WP.
- It may be possible to increase the WP efficiency by letting the WP-side VSC modify the AC frequency depending on the wind speed.
- Problems such as harmonic resonances and transient overvoltages [6] are avoided.

V. Benefits and Possibilities for TSO

The increasing number of installations of renewable energy sources introduces new challenges to maintain power quality and reliability for the electricity supply. One major issue that appears to gain TSO interest is to identify necessary grid reinforcements, in order to maintain acceptable levels for voltage stability, voltage quality, short-circuit currents, and to avoid grid "bottlenecks" and undesirable new load-flow paths. For some of these aspects, an HVDC Light transmission may be a viable alternative for grid reinforcement:

- With fast and continuous control of the reactive power within a wide range, an HVDC Light transmission system may enhance voltage stability.
- If a WP installation results in significantly higher short-circuit currents, it may be necessary to upgrade existing circuit breakers. An HVDC Light transmission system can control the short-circuit current contribution to the desired value within the ratings of the semiconductor valves. Also, the short-circuit current contribution becomes independent of the WP size/ and rating.
- Grid “bottlenecks” and undesirable load-flow paths are results of an uncontrolled active power flow or an unsuitable grid connection point. With an HVDC Light transmission system, the active power flow can be controlled. Furthermore, by way of underground cables and compact converter station design, HVDC Light can tie into the “right” connection point, for instance, to an area with large consumption.
- Flexible active control, or power dispatch, becomes straight-forward. An HVDC Light system that connects a WP to the MG is comparable to a normal power plant. The direct access to the MG-side VSC via a control or dispatch center makes it easy for the TSO to implement regular active and reactive power dispatches and emergency-power and AC-voltage controls. The time delay, due to the communication infrastructure between the supervisory control and data acquisition (SCADA) system and the WTGs, is no longer a problem.

Compared to an AC grid connection of WTGs that use full-power back-to-back converters, a WP connected by way of HVDC Light transmission system may provide the following advantages:

- WP disturbances will not be transferred to the MG.
- No “reactive” power losses and no overhead lines in the transmission path regardless of transmission distance.
- Improved AC voltage control at the connection point to the MG.
- Power dispatch and emergency power controls become straight-forward and can possibly be carried out with less time delay.
- Since the reactive power is controlled at both sides, an HVDC Light system may be considered as a series compensator, which may enable connection to a weaker AC grid than otherwise possible.
- The WP may use WTGs with simpler electrical systems, which may partly or fully compensate for the cost of the HVDC Light system.

VI. Conclusion

An HVDC Light transmission introduces several advantages for all parties involved in a WP grid connection project. The HVDC Light system decouple the MG from the WP grid, which may reduce WTG mechanical stresses, improve power quality and reliability and relaxes the matter of grid code compliance for the WTGs. The combination of the WP and the HVDC Light transmission system can be considered as a normal power plant, which alleviates TSO control and MG VSC may tie into the preferred TSO grid connection point, due to oil-free underground cables and compact converter station design.

VII. Acronyms

HVDC	High Voltage Direct Current
IGBT	Insulated-Gate Bipolar Transistor
MG	Main Grid
PCC	Point of Common Coupling
SCADA	Supervisory Control And Data Acquisition
TSO	Transmission System Operator
VSC	Voltage Source Converter
WP	Wind Park
WTG	Wind Turbine Generator

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IX. Biographies

Ying Jiang-Häfner received her B.Sc and M.Sc Degrees in electrical engineering from Huazhong University of Science and Technology, China, in 1984 and 1987, respectively. She received the Ph.D. Degree in electrical from Royal Institute of Technology (KTH) of Sweden in 1998. During the six years at KTH, she was one of the principal researchers in the ABB-EPRI-Vattenfall joint research project “Evaluation of Performance of Static Condensers” and the ABB-Vattenfall-Elforsk-Svenska Kraftnät joint research project “Evaluation of Performance of UPFC.” She joined the System Development Department of ABB Power Systems in Ludvika, Sweden, in 1998. She has been involved in the development and design of control systems for HVDC Light since she joined ABB. She is now a Senior Specialist in the technical area of HVDC Light control.

Rolf Ottersten received the M.Sc., Licentiate and Ph.D. degrees in electrical engineering in 1997, 2000 and 2003, respectively, from Chalmers University of Technology, Gothenburg, Sweden. When pursuing the Licentiate degree, Ottersten participated in a university-industrial co-operation project, which outcome was a prototype 600-kW variable-speed wind turbine, while his Ph.D. degree targeted applied control engineering for the electric drive systems. Ottersten has been with NFO Controls AB, GM Powertrain Sweden AB, Gothia Power AB and is since 2008 with the Systems Development Department at ABB Power Systems in Ludvika, Sweden. He is mainly involved in system development studies for HVDC Light transmission systems.