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Facilitating Bulk Wind Power Integration Using LCC HVDC

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SUMMARY

Many states in the US are experiencing challenges in meeting their renewable energy mandates or goals. Wind energy is the predominant source of such resources with the lowest cost, highest capacity factor wind being located far out from load centers. Existing power transmission infrastructure is simply not capable of integrating large amounts of wind energy for transmittal and delivery towards the end user. HVDC technology is ideally suited for this function providing an efficient and cost effective mechanism for transferring very large amounts of power over significant distances. Indeed HVDC systems are currently being developed across the United States to bring the benefits of wind energy to consumers. Such systems are being used to increase power to load centers in a controlled manner while not increasing the fault level in the target networks. In the past several years the United States has installed several HVDC schemes which have served to strengthen the transmission system and relieve congestion to heavy load areas. The HVDC systems provide the capability to control load flow and to enhance system stability. The Rock Island HVDC project being developed by Clean Line Energy Partners aims at integrating over 3.5GW of wind power from Northwest Iowa to load centers in Illinois and points farther East. This paper analyses some of the technical features of the project and presents some unique challenges associated with it and proposes a novel solution.

KEYWORDS

HVDC, LCC, STATCOM, Stability, Wind power

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INTRODUCTION

Many of the most valuable wind resources in the US are located far away from the biggest load centers [1], this poses a great challenge for wind power plant developers in the US, since it is difficult to deploy the great wind resources available in the area due to a lack of transmission capacity enabling the power delivery to the distant load centers [2].

Developing the necessary high voltage AC transmission lines in order to be able to transmit the wind power to the load centers is a lengthy process, requiring big footprints and therefore complicated right-of-way processes. Additionally, traversing multiple Regional Transmission Organizations and states poses challenging cost allocation and permitting issues under current regulatory paradigms. The use of DC transmission technology has obvious benefits for easing the acquisition of right-of-way and minimizing the land use concern about new transmission. DC transmission technology is also ideally suited to utilize a merchant model for cost recovery as opposed to either regional or inter-regional cost allocation. And finally, the selection of DC technology improves the circumstances around siting by reducing the transmission tower footprints, as well as increasing the power transmission capacity compared with AC lines that would move an equivalent amount of power.

This paper presents a detailed system study investigating the impact of integrating over 3700 MW of wind power using a 500 mile line-commutated converter (LCC) HVDC interconnector. LCC has been selected as the preferred technology due to the following aspects:

- well-proven technology with high reliability / power availability as well as low losses
- fast and stable recovery after AC fault clearing
- capability to extinguish DC line fault currents including a subsequent fast and stable recovery
- power rating using a bipolar scheme with ± 600 kV DC whereas for voltage source converter (VSC) schemes, parallel converter arrangements at high DC voltages would be required

Having such a large amount of wind generation in a relatively weak grid poses a number of challenges such as the need for an optimized reactive power control scheme, operation with low short circuit level conditions as well as the lack of significant inertia associated with wind generation. Within this study the need for communication between the wind power plant controllers and the HVDC converter control was identified. Proper coordination between the HVDC and the central wind power plant controllers has been established to avoid controller interactions. The time domain dynamic simulations of the system were carried out with the PSS®E software.

A number of important aspects have been studied within this project and the following topics are reported in the paper:

- Time domain simulations for different load flow conditions and contingency scenarios in order to verify the impact of the HVDC link in the interconnected power system.
- Analysis of the interactions between the Rock Island HVDC project, the AC power system, and the wind power plants.
- Design of HVDC modulation functions in order to enhance system stability and performance.

THE ROCK ISLAND PROJECT

The Rock Island Clean Line is a 500-mile, ± 600 kV HVDC transmission system that will deliver 3,500 megawatts of wind power from Iowa, Nebraska, South Dakota and Minnesota to Illinois and other states to the east as shown in Figure 1 [6]. The HVDC project and the wind farm collector system are planned to be connected to the 345 kV AC system in north western Iowa. This project is bringing in a number of unique technological advancements in the field of integration of bulk wind power using HVDC LCC.

It is well known that line-commutated converters (LCC) have some technical restrictions. Line-commutated converters require a relatively strong synchronous voltage for the commutation process.

Given the fact that the commutation is driven by the three-phase AC voltages, it requires adequate conditions of the connected AC system. Thus, stable operation under weak AC system conditions (low or very low short-circuit ratio or effective short-circuit ratio (SCR / ESCR) requires very fast control of AC voltage (converter operation in an unstable region of the AC voltage-DC power characteristic). In addition to the voltage stability aspects, low short circuit conditions of the AC system (high AC impedance) increase the demand for reactive supply in combination with the requirement for smaller AC filter or shunt capacitor bank sizes (otherwise the AC voltage change due to (sub-) bank switching exceeds acceptable levels). It is worth mentioning that a large amount of reactive supply increases temporary overvoltages (TOV) in case of large disturbances such as AC and DC faults.

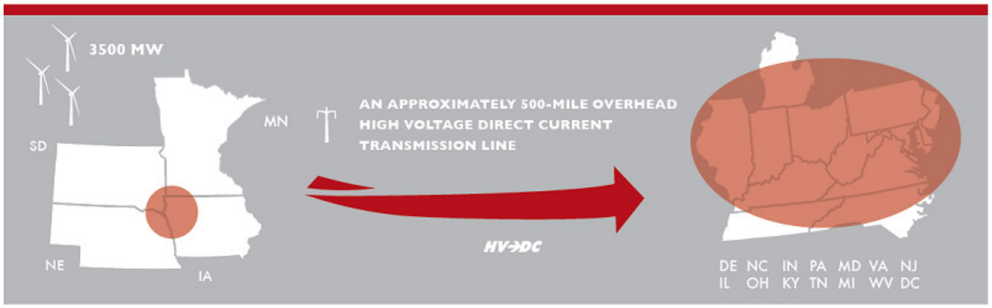

Figure 1: Rock Island Clean Line Project

The combination of LCC schemes with fast and optimized converter controls together with incorporation of STATCOM and / or synchronous condensers facilitate the integration of renewable energy as well as ensure stable operation under weak AC system conditions by removing some of the technical obstacles as discussed below.

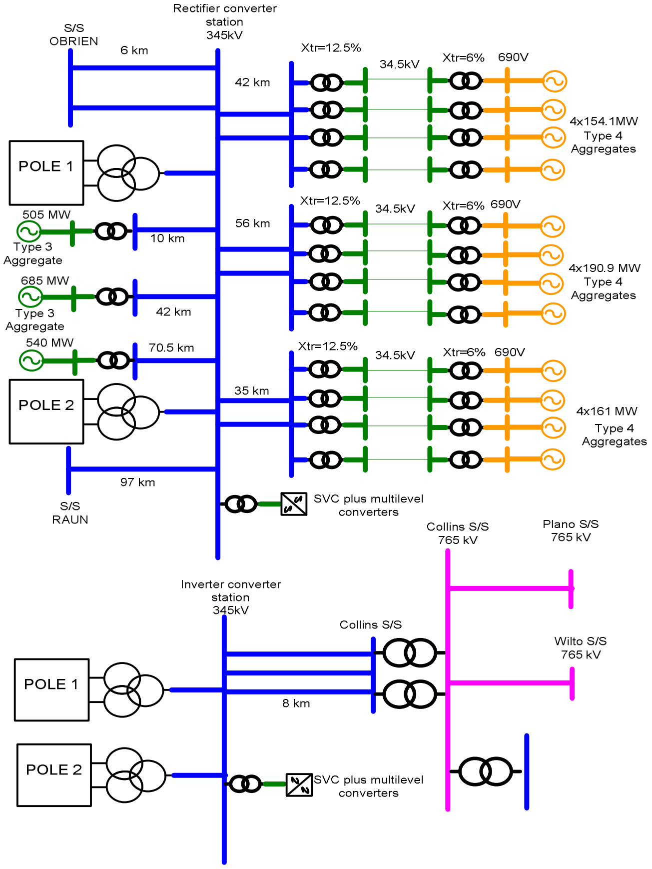

Figure 2: Single Line Diagram of HVDC Stations

One of the major challenges is that the AC system on the rectifying side is quite weak relative to the converter size and the associated wind generation cannot provide substantial short-circuit capability and inertia. Over 3.7 GW of wind power are clustered into six different wind parks ranging between 500 to 800 MW each. Considering the vastness it is obvious that multiple types of wind turbine technology will be used to build such large wind parks. Therefore as a rule of thumb within this study 50% of the wind turbines generators (WTG) are modelled as type 3, i.e. doubly fed induction generator (DFIG). Generic models of type 3 WTG are used from the PSS/E standard library. The other 50% is represented with user-written WTG type 4 models, i.e. full converter WTG. Each wind park is modelled with four equivalent machines. All the wind parks are connected to the 345 kV AC bus of the rectifier station through 345 kV single or double circuits. A single line diagram of both HVDC converter stations is shown in Figure 2.

The type 4 wind turbine models also include park pilot (wind power plant controller) voltage and frequency controller models. The voltage controllers are set to control the 345 kV point of common coupling (PCC) voltage using the reactive power capability of the wind turbines. The park pilot frequency controller is set to support the AC frequency at the 345 kV PCC in case of frequency increase. As a part of the designed reactive power control (RPC) scheme STATCOM units, each rated 125 Mvar, are incorporated in both rectifier and inverter stations. For detailed analysis, user-written HVDC and STATCOM [3] models have been used.

In order to obtain more realistic results regarding over-voltages during contingencies in the substations nearby the converter stations, typical transformer saturation characteristics have been added to the HVDC converter transformers, the two 1800 MVA autotransformers at the inverter station (used to interconnect the 345 kV Rock Island AC bus to the 765 kV system in Illinois), and to the power transformers (345 kV / 34.5 kV) at the wind plants. The 'SAT2' model has been used for this purpose (see Program Operation Manual PSS®E 32 Documentation).

PROJECT CHALLENGES

A project of this magnitude presents many technical challenges that have to be addressed very carefully in a comprehensive manner to ensure a technically feasible and compliant solution. Some of the major project specific challenges are described below.

Temporary / Transient over-voltages: During AC network faults as well as DC line faults, the reactive power consumption of the converter stations changes considerably. For example, during a fault within the AC network at the inverter side, a voltage drop potentially leads to a commutation failure causing the loss or reduction of DC power transfer. After fault clearing, the HVDC system starts to restore power to pre-disturbance levels. However, it takes a few hundred milliseconds to recover to the pre-fault value. The MVAr mismatch between the converter consumption and the AC filter / shunt capacitors connected to the AC bus may result in high transient and temporary AC overvoltages. This can be more important if the fault-clearing weakens the AC system (e.g. trip of important transmission lines or large generators). State-of-the art multilevel STATCOM devices [3] play a key role in this aspect by providing fast dynamic reactive compensation.

Frequency deviations: Due to the weak network conditions and substantial amount of wind power to be installed at the rectifier side, frequency deviations can be significant during contingencies. Therefore it is important to use the DC power modulation features of the HVDC in order to limit frequency deviations [4][5]. If there is an additional need to increase inertia of the AC system the integration of synchronous condensers can be used to strengthen the system. This enables maintenance of AC frequency deviations, under contingency conditions, within predefined levels (e.g. 5%).

Stable DC power recovery: System conditions at the inverter side can also become very weak in case of the trip of important transmission lines, e.g. 765 kV lines. AC fault clearing by tripping of AC lines will weaken the AC system and may cause AC voltage instabilities (voltage drop) during the fast recovery of the HVDC system. Furthermore, commutation failure may occur during the recovery. It is, therefore, very important to provide a robust solution which enables the stable recovery of DC power without subsequent commutation failures for the whole range of operating conditions including certain contingencies / pre-fault conditions. Dynamic reactive compensation by the STATCOM significantly supports voltage recovery under such conditions.

Active power exchange with the AC rectifier network: In order to control the active power exchange between the wind power plants, the HVDC link, and the connected 345 kV AC network, a power exchange controller (PI controller) has been designed and implemented within HVDC station controls. The HVDC control system measures the active power flow into the 345 kV rectifier AC network and adjusts the DC power reference value to control the active power exchange with the network within a predefined, narrow band. Due to the varying nature of wind power, this PI controller will slowly and continuously modulate the DC power in order to keep the steady-state active power exchange to the AC network within a tight band. This ensures that in steady-state conditions the AC network load flow is not altered and all generated wind power is transmitted via the HVDC link.

Controller coordination: The HVDC controller and the wind power plant controllers need to be coordinated to avoid unacceptable disturbances of the connected rectifier AC system in case of HVDC pole trip or initiated power limitation (run-back).

Reactive Power exchange with the AC network: In order to not influence the AC system voltage at the PCC, the HVDC system is operated in "Q-mode" keeping the steady-state reactive power exchange with the AC network within a specified band. Furthermore, if the AC voltage exceeds the specified, normal range, fast voltage control capability of the HVDC system with incorporated STATCOM units will be utilized to minimize AC voltage deviations. Proper coordination between the converters, AC filters, and shunt reactors as well as the STATCOM units ensures optimized operation and sufficient dynamic Var-control capability.

CASE STUDY RESULTS

In order to investigate the stability of the interconnected system and the interactions between the AC systems, the Rock Island HVDC converter stations, and the wind power plants, several contingencies which result in worst case conditions have been considered. Contingencies and fault events which have been studied include:

- AC faults at or in close proximity to the converter stations with the trip of important transmission lines resulting in a weaker AC system (extreme low short circuit levels) after fault clearing
- Faults resulting in loss of generation
- Remote faults in the AC system(s)
- HVDC permanent or partial load rejection

The above described contingencies have been applied to various pre-fault load flow conditions. A few of the most interesting scenarios are presented below showing the dynamic behavior of the Rock Island HVDC Project. Within each of the described scenarios, the HVDC link is affected and the recovery of the link is one of the phenomena under study as well as power exchange with the AC grids and general system stability behavior.

AC fault at the inverter side: A three phase-to-ground fault is applied at the inverter station and the fault is cleared after five cycles by tripping a 765 kV line that was carrying a portion of the transmitted DC power as shown in Figure 3.

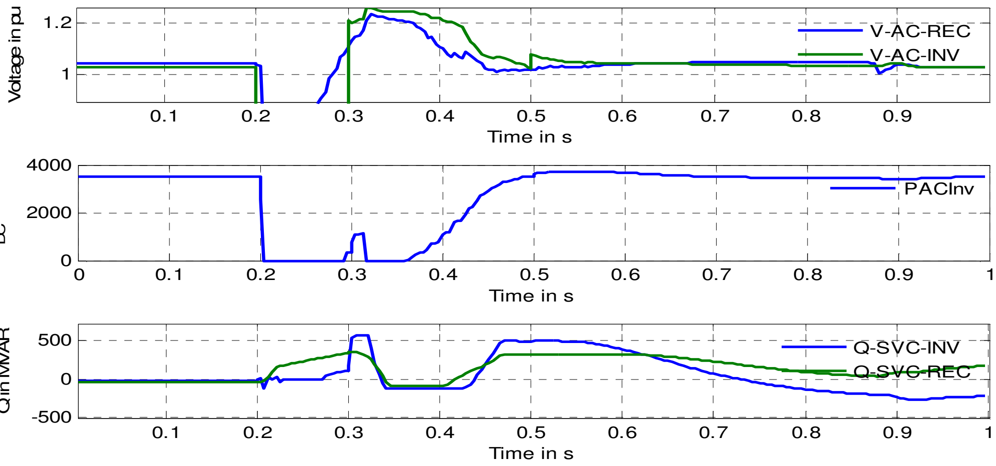

Figure 3: AC fault at inverter side

The STATCOM at the inverter side supports the AC voltage during DC power recovery by supplying maximum capacitive reactive power. This voltage support function of the STATCOM prevents an AC voltage collapse during the HVDC recovery and therefore assists in avoiding commutation failures and voltage instabilities during DC recovery under weak AC network conditions.

AC fault at the inverter side, resulting in an extremely weak system: In this test case a three phase-to-ground fault is applied to an N-1 pre-fault condition, the fault is cleared after five cycles by tripping another key 765 kV line that carries a major portion of the transmitted DC power (see Figure 4). The AC fault is cleared by tripping the most important 765 kV AC line. As a consequence, the AC system was not strong enough to enable a fast recovery of the HVDC system to 100% pre-disturbance levels because of the N-1 pre-fault conditions (recovery under N-2 contingency conditions). In order to maintain system stability under these contingency conditions a DC power limitation (run-back), combined with other advanced control features, is initiated to quickly reduce the DC power to 60% of the rated power (see blue trace "*P-inv*"). This power run-back function is very important to retain system stability and to avoid repetitive commutation failures.

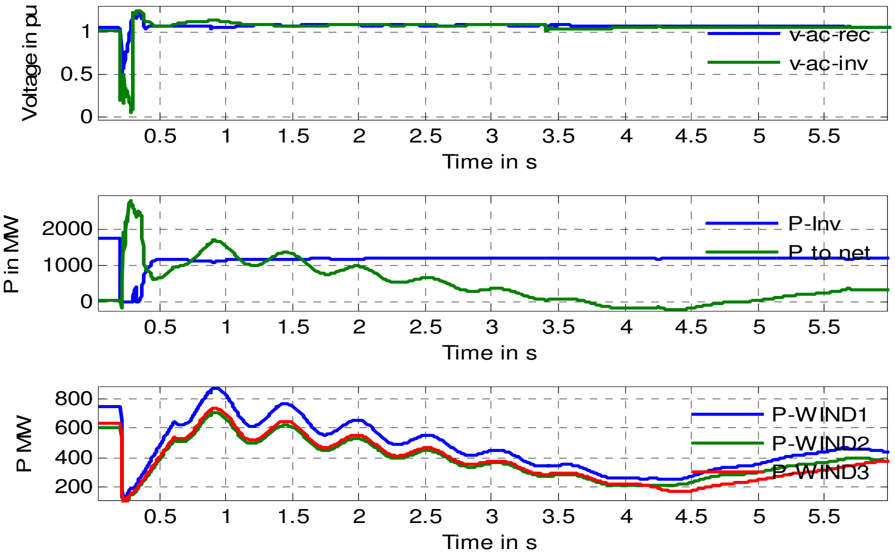

Figure 4: AC fault at inverter side with weakened system (DC power given for one pole)

As a result of the DC power run-back, some generated wind power flows into the rectifier AC network. This is counteracted by initiating a signal from the HVDC controls to the wind power plant controllers triggering a proportional MW-output adjustment of the wind turbines. The active power exchange with the AC network is shown above (see green trace "***P to net***"). After receiving the signal from the HVDC controls, the wind power plants start reducing their power output (see third plot in Figure 4) and thereby reduce the active power flow into the rectifier AC network.

AC fault at rectifier side: A three phase-to-ground fault is applied close to the rectifier station resulting in the trip of a 700 MW wind park due to the fault clearing action (Figure 5). Without additional measures, the lost wind power will be drawn from the 345 kV rectifier AC network. Immediately after fault-clearing, the DC power recovers successfully to its pre-fault value (see blue trace "P-Inv"), causing high absorption of power from the AC network (see negative value of "*P to net*"). The HVDC active power exchange controller (see red trace "*P-EX-OUT*") will automatically reduce the DC power transfer level to minimize the active power exchange with the network at the rectifier side. This controller action is based on local measurements and thus does not rely on communication between the wind park controller and the HVDC controls.

The studies carried out prove rotor angle stability of generators, AC voltage stability of the power systems, as well as stable operation of the HVDC Rock Island Project. Transient frequency deviations are quickly reduced by modulating the DC power using a HVDC frequency limitation controller.

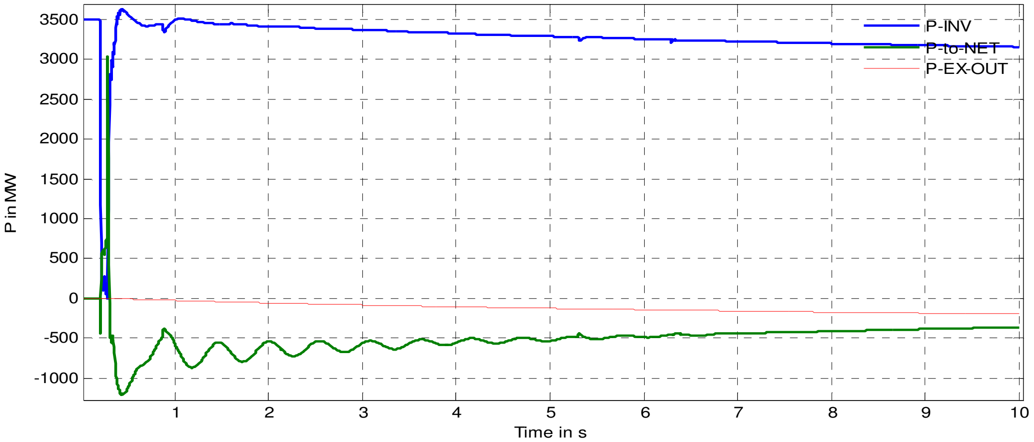

Figure 5: AC fault at rectifier side

Proper coordination between the controllers is required to avoid hunting effects and mal-operation. For example the active power exchange controller shall not counteract the power limitation (run-back) by increasing power transfer levels. In order to solve this potential controller interaction issue, two measures are considered:

- Fast communication between the HVDC control and the wind power plant controllers is necessary in case a runback is activated at the HVDC controls (or in case of a pole trip). A power limitation (run-back) request is sent to the wind power plant controllers, to limit their MW-output accordingly. In the study, realistic signal processing times have been considered.
- The active power exchange controller is designed so that it slowly and continuously modulates DC power without interacting with the very fast power oscillations that could occur during contingencies.

CONCLUSIONS

HVDC systems offer a number of advantages from both a regulatory and technical perspective that can support the growing energy demands and associated infrastructure needs of the US in a sustainable way. The use of LCC HVDC technology to integrate large wind power plants poses a number of unique challenges. By proper system wide control design and coordination it is possible to successfully accomplish such a goal. Within the design and stability studies it is demonstrated that the technical challenges could be addressed by additional control features and proper communication between the wind power plants and the HVDC controls. Furthermore, with the incorporation of STATCOM units within the HVDC converter station(s), voltage stability and overall dynamic performance can be enhanced considerably.

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