21, rue d'Artois, F-75008 PARIS
http : //www.cigre.org

CIGRE US National Committee
2012 Grid of the Future Symposium

The Role of HVDC for Wind Integration in the Grid of the Future

W. GALLI, P.E.*, A. LANDON
Clean Line Energy Partners LLC
N. J. BACALAO
Siemens Industry – Siemens Power Technologies International
M. KORYTOWSKI
University of Pittsburgh
U.S.A.

SUMMARY

Growing demand for renewables and the shift of the generation fleets toward cleaner forms of energy will require the future grid to be designed to efficiently handle large amounts of renewable generation located far from load centers and whose variability can have important impacts on both the security and economics of the power system. The large body of work performed on integration of renewable generation indicates that wind integration costs are minimized when the number of plants and the geographical diversity increases thus introducing compensation of both the variability and the forecasting errors.

One common problem in achieving the benefits of geographical diversity is that fairly large control areas are required so that the key functions of unit commitment, load following and economic dispatch of the large area's conventional generation can take full advantage of the geographically reduced variability of the renewable generation.

The corollary of the situation above is also a challenge to the industry. A large concentration of otherwise excellent renewable resources can introduce both operational and costs issues if it is to be integrated into the local grid or a relatively small balancing authority.

This paper introduces two projects that are designed to take advantage of the controllability and inherent efficiencies of high voltage direct current (HVDC) to transfer power across long distances. These projects are designed to take large amounts of wind turbine generation from some of the lowest cost wind resource areas in the United States and transmit it to distant higher demand areas whose energy resources respond to a completely different set of meteorological variables. Thus, these projects not only provide the receiving areas with economically priced renewable energy, but also with the means of effectively integrating this generation with other renewable resources, local or imported, through the AC grid. Additionally these projects help the sending areas by allowing development of resources that would have extreme integration issues if integrated locally and potentially providing an additional outlet for the native resources variability. In the paper, the challenges to implementation are also described because there are few examples of developing this type of projects that are designed to have neutral impact on the sending end host areas under normal operating conditions and look like a generator to the receiving end areas.

KEYWORDS

HVDC, Wind Integration, Smart Grid, Planning, Implementation

*wgalli@cleanlineenergy.com

DESCRIPTION AND RATIONALE OF THE GRAIN BELT EXPRESS AND PLAINS & EASTERN CLEAN LINE PROJECTS

The Grain Belt Express Clean Line Project (GBX) and the Plains and Eastern Clean Line Project (P&E) both share the common thesis of delivering 3,500 MW of high capacity factor wind via +/-600 kV HVDC links from the lowest cost, most reliable wind resources in the United States to the load centers in the Midwest, East, and Southeast. GBX is currently being designed as a multi-terminal device rated to deliver 3,500 MW from western Kansas to the 765 kV system in PJM. A 500 MW terminal is also planned to connect to the 345 kV system in the Midwest ISO (MISO), making this project one that connects three major Regional Transmission Organizations and their associated markets; namely, Southwest Power Pool (SPP), MISO, and PJM.

P&E is currently envisioned as being able to deliver 3,500 MW from the panhandle of Oklahoma to the 500 kV network in eastern Tennessee. Effectively, this line would provide a very strong interconnection from the far western portion of the Eastern Interconnection to the robust 500 kV grid in the Southeastern portion of the Eastern Interconnection.

The high quality wind resource in the Great Plains states coupled with modern wind turbine technology results in high net capacity factors means that each project can deliver approximately 15,000,000 MWh of energy per year, helping to satisfy renewable demand in PJM and the Southeastern United States as shown in Figure 1.

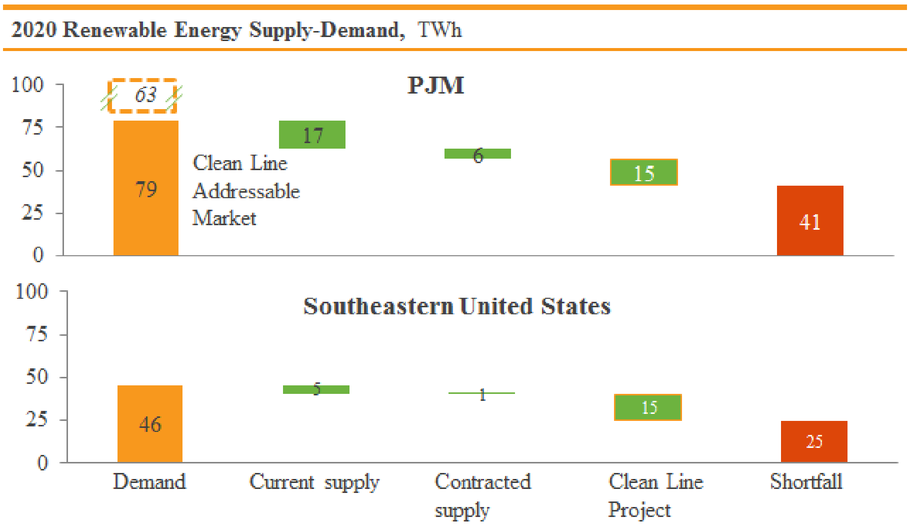

Figure 1: 2020 Demand addressed by GBX and P&E [1]

As the projects are currently envisioned, the interchange with SPP on the windward side will be maintained at some preset value (e.g., 0 MW) and the wind energy transported on the projects will be from radial connections to the AC bus of the converters. Interconnection with the SPP grid is necessary for commutating voltage support; however, this interconnection will also provide additional flexibility as will be discussed later.

IMPACT OF GRAIN BELT EXPRESS AND PLAINS & EASTERN ON INTEGRATION OF WIND TURBINE GENERATORS

Renewable generation integration costs refer to those costs associated with the impact that the variability and uncertainty that this type of generation has on the operational costs and reserve needs of the systems that host them. These costs have been subject to multiple studies in recent years [2,3,4,5,6] and typically include: Frequency Regulation Costs, Load Following Costs, and Unit Commitment Costs. Likewise, in the growing body of work on wind integration several key conclusions can be derived:

a) Integration costs and impacts normally increase with the level of wind penetration.

b) Geographical diversity of the renewable resources reduces the overall variability of the renewable generation.
c) Improved wind power forecasts can significantly reduce integration costs. Wind forecasts aggregated across large areas are more accurate than non-aggregated wind forecasts for individual wind plants or smaller areas.
d) Sustained power increases or decreases of renewable generation (i.e. ramping in MW/min) can stress reserves, introduce large Area Control Errors, and in smaller isolated areas, create significant frequency deviations.
e) A similar issue can arise due to the inherent lack of inertial and frequency response of renewable generation that, unless introduced via controls, makes this generation insensitive to rapid frequency increases due to load drops or reductions due to generation drop.
f) Integration costs are minimized with greater generation flexibility in conventional power plants; however this must be accompanied with intra-hour scheduling (e.g., 5-minute scheduling) to provide access to this flexibility.

As a result of the above, most studies conclude that larger balancing areas make it possible to integrate more renewable generation with reduced integration cost due to a) greater geographical diversity, b) reduced forecast errors, c) reduced probability of large generation ramping with respect to the size of the conventional generation in the area and greater system inertia and d) greater size and diversity of the conventional generation resources. In particular reference [6] indicates in its conclusions that "This and other recent studies reinforce the concept that large operating areas—in terms of load, generating units, and geography—combined with adequate transmission, are the most effective measures for managing wind generation."

It is the authors' opinion that the use of the concepts presented in this paper where large amounts of wind turbine generation (WTG) are collected in one geographical area (Kansas and the Oklahoma and Texas Panhandles) and are shipped via a highly controllable HVDC to other areas (e.g., central MISO, PJM and TVA) will result in a minimization of integration costs to values similar or lower to those found in the references above. The reasons behind this observation are rooted in the nature of the proposed HVDC link that can near instantaneously adjust the transfers so that changes in the sending end WTG in response to the meteorological conditions at the windward converters and that exceed a pre-set value are transferred to another area (e.g., PJM) to where the generation responds to a completely different set of conditions, thus minimizing the impact that it would otherwise had if it were injected within SPP while producing minimum impacts in PJM. Moreover given the bi-directional nature of the link this can be used as a source of reserves within SPP that can provide support during periods of low availability due to renewable generation or otherwise.

Finally, long distance HVDC will allow far more resources to be developed in the area than could otherwise be incorporated into SPP.

To further support the integration benefits of long-haul HVDC, the authors performed analysis to determine the variability impacts of injecting 7000 MW of southeastern wind into the SPP compared to exporting 3500 MW to TVA and 3500 MW to PJM. Hourly data from 2006 were used to generate distributions of the hourly step changes for the load and net loads of the TVA, SPP, and PJM. A comparison of load variability was done by finding three times the standard deviation (three-sigma) of hourly load and net load changes. Three times the standard deviation contains 99.7% of a normal distribution; therefore, the difference of the load and net load three-sigma variations is a good approximation for the additional reserve requirement for integration.

Production data came from the Eastern Wind Integration and Transmission Study (EWITS) dataset [7]. Seven sites were selected in Oklahoma with a total rated capacity of 4378.7 MW to represent generation on P&E. Seven sites were selected in Kansas with a total rated capacity of 4374.9 MW to represent the generation on GBX. The hourly values were curtailed to a maximum of 3500 MW to reflect the actual transmission capability of the HVDC lines. Hourly load data for PJM and SPP were obtained from the RTOs' websites. Analogous data for TVA was acquired from TVA directly. In order to model the existing wind in the PJM, SPP, and TVA systems, a mapping of all projects in the respective generation interconnection queues to the nearest EWITS sites was performed.

Figure 2 depicts the duration curves for the three systems with and without the Projects.

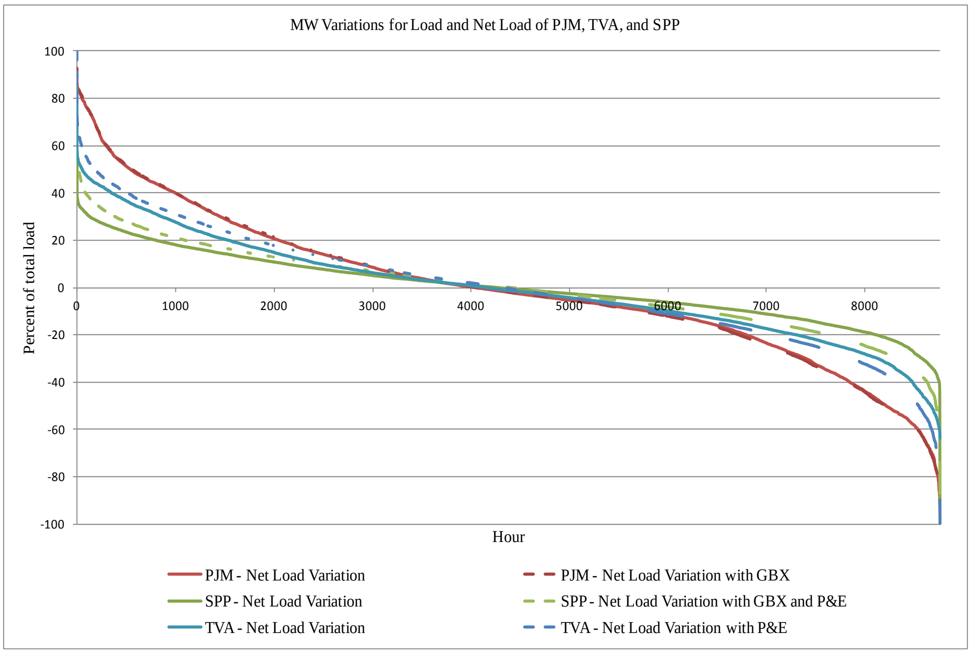

Figure 2: 2006 Duration Curves of Net Load and Clean Line Project Scenarios

Table 1 shows the difference in the three sigma variations between the existing TVA, PJM, and SPP loads.

Table 1: Three-Sigma Variation of Net Load and Clean Line Injection Scenarios

	Three-Sigma Variation		
	Net Load	Net Load w/Clean Line Projects	Delta
SPP	3,187	4,006	819
TVA	2,395	2,764	369
PJM	10,280	10,410	130

If all 7000 MW are injected into SPP, the three-sigma variation for SPP increases by 819 MW. If the wind is split and exported to TVA and PJM, those systems' three-sigma variations increase by 369 MW and 130 MW, respectively. The export scenario sees a reduction in the total change of three-sigma variation (499 vs. 819 in the SPP scenario) because a smaller proportion of wind, in respect to the base load, is integrated into a larger system.

PATH TO IMPLEMENTATION

Technology – HVDC the Smart Grid Solution

As described, the projects clearly lend themselves to the application of HVDC just from the perspective of moving significant amounts of power long distances. The inherent benefits of being able to quickly and precisely control power flow and track the associated wind injection make HVDC the obvious choice. Many references extol virtues of a well integrated system that makes use of both HVDC and extra high voltage (EHV) lines for the purposes as described by this paper, for instance [8] clearly outlines the complementary nature of HVDC and EHV AC in implementing access to remote renewable resources.

The biggest challenge in design and implementation of the technology, however, is in regards to weak system interactions. The areas of remote resources typically also lack a robust transmission network that would allow for adequate short-circuit levels for implementation of large line-commutated converter (LCC) HVDC projects. Thus, the applications require special attention and ancillary equipment to provide dynamic reactive response and potential additional system inertia. During final design, the number of synchronous condensers and other dynamic reactive equipment will be fine tuned. Additionally, employing capacitively commutated converters (CCC) may also be a reasonable alternative to reducing the requirement of synchronous condensers. Given the current voltages and ratings of the projects as well as the relative strength of the system, voltage-sourced converter (VSC) technology (which would alleviate the need for any dynamic reactive equipment) is not available at this point in time.

Interconnection Studies

The interconnection studies required to allow the connection of P&E and GBX to the host systems of SPP, TVA, MISO and PJM represent interesting challenges, not only given the number of separate System Impact Studies (SIS) that need to be carried out (one per system), but also due to the special nature of the studies.

In particular, the interconnection with SPP is quite unique as given the controllability of HVDC, the interchange under system impact conditions is perfectly controlled and for the SIS it was assumed to be near zero.

In order to identify the most appropriate way to study this "wires to wires" interconnection and give assurances that all relevant impacts had been identified, the work was done closely with SPP and under its leadership a group of companies within the SPP footprint that were identified as potentially affected by the project, were brought together in a Working Group. With the help of this Working Group a number of relevant cases and conditions were selected for evaluation as presented below.

2017 and 2022 summer peak and winter peak as well as 2017 light load for three different dispatches were selected for the study. Given the near zero interchange, for N-1 condition only the loss of one pole was relevant. Similarly the only category C event (double contingency) that was relevant was the loss of a double pole (N-2). However, studying these two conditions was not deemed appropriate by the Working Group and a set of N-1-1 and N-1-2 additional contingencies was developed that consider an outage in the system when there is also a pole outage and half of the project's generation flows in the underlying AC system. The results indicated that under most scenarios a single pole outage (N-1) results in no overloads in the system and even under double pole outage there were only a few facilities that would overload in the immediate vicinity of the project rectifier.

For the identified overloads, a mitigation strategy was developed considering that the likely path for the overload to occur would be that there is a prior outage in the system and this is followed by the pole outage. Considering this, an assessment was made of how much the generation would have to be ramped down to prevent the overload and in all cases this was determined to be a successful strategy. Therefore, the project can be integrated into SPP with minimum impacts by monitoring the system conditions. If certain contingencies become active, upon the trip of a pole a percentage of the project generation could be curtailed, if necessary.

Extensive stability analysis was conducted which indicated in the remote areas where the rectifier would be located, the WTG appeared to have voltage stability issues. This was traced to low short circuit availability in the area (the ratio of the short circuit level to the installed WTG capacity was less than 2.0) and was addressed with the use of Synchronous Condensers to make this ratio above 2.5. By using this strategy combined with fast switching of the capacitor banks at the HVDC terminals all cases were seen to be stable.

Finally, to check the impact on the frequency, a simulation of the trip of the entire project generation was ran and looked at the frequency in the system. It was observed (see Figure 3) that given the large inertia of the eastern interconnection the maximum frequency deviation was 0.17 Hz and it returns to 0.022 Hz deviation in about 10 seconds.

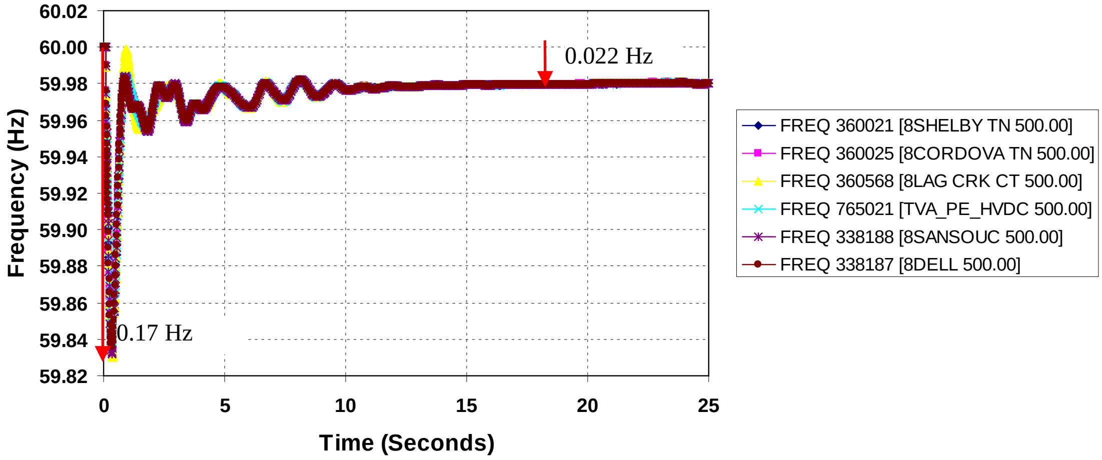

Figure 3: Frequency deviations of the eastern interconnection

From this it was concluded that the studies of this type of projects require close collaboration with the ISOs, RTOs, and all affected parties. In the case of the P&E and GBX the system impacts were found to be relatively small and manageable.

CONCLUSIONS AND REMARKS

It is clear from the literature and the analysis at hand that long-haul HVDC is the appropriate application for integrating large amounts of wind into the U.S. energy portfolio. It is also clear from extensive system studies that this can be such that the reliability and security of the bulk electric system is both maintained and enhanced with additional flexibility.

BIBLIOGRAPHY

[1] Clean Line Energy Partners. Estimate for Southeastern United States represents potential demand based on TVA's 3,500 MW 2020 renewables target and assuming 10% renewables penetration in Duke, Southern, and Progress Power and includes current wind PPA's in TVA and Alabama Power. Figure for PJM includes current wind power supply and wind power under construction (from AWEA's 4Q2011 fact sheets). In terms of wind power capacity (assuming a 40% capacity factor), Demand equals ~23-41GW for PJM states and ~13GW for Southeastern U.S.

[2] Wiser, Ryan, Bolinger, Mark, DOE 2010 Wind Technologies Market Report, June 2011.

[3] EnerNex Corp. 2007. *Avista Wind Integration Study*. Knoxville, Tennessee: EnerNex Corporation.

[4] Acker, T. 2007. *Arizona Public Service Wind Integration Cost Impact Study*. Prepared for Arizona Public Service Company. Flagstaff, Arizona: Northern Arizona University.

[5] EnerNex Corp. 2008. *Wind Integration Study for Public Service of Colorado, Addendum, Detailed Analysis of 20% Wind Penetration*. Prepared for Xcel Energy. Denver, Colorado: Xcel Energy.

[6] EnerNex Corp. 2011, Eastern Wind Integration and Transmission Study, prepared for NREL.

[7] "Obtaining the Eastern Wind Dataset." *NREL: Wind Integration Datasets*. N.p., n.d. Web. 15 Aug. 2012. <http://www.nrel.gov/wind/integrationdatasets/eastern/data.html>.

[8] J.A. Fleeman, R. Gutman, M. Heyeck, M.Bahrman, B. Normark, *EHV AC and HVDC Transmission Working Together to Integrate Renewable Power*, CIGRE/IEEE PES, Calgary 2009.