PJM Planning Study Practices and Market Impacts on the Integration of Renewable Resources with AC-HVDC Systems

J. TONG, M. SOBOTKA, W. QIU, B. CHOI, A. KEECH

PJM Interconnection
2750 Monroe Boulevard, Audubon, PA 19403, USA

SUMMARY

Renewable resources in PJM are growing extensively and are projected to serve approximately 20% of the load in PJM by the year 2020. This growth is due to federal and local incentives that are driving the expansion of these resources. Great care needs to be taken when integrating these resources into the grid as their operational characteristics differ greatly from those of conventional thermal resources. For example, wind and solar renewable resources in PJM are dispersed and often located far away from major load centers in the PJM footprint. These resources have uncertain and at times uncontrollable outputs, have less inertia, which will degrade frequency control, and in general, are incapable of voltage control without the addition of a smart inverter device. Due to their remote location, new electric transmission infrastructure will likely be needed to deliver these resources to the PJM load centers for the maximum economic benefit. For optimal transmission development, it is essential to take a long term approach that incorporates the characteristics of the sources being connected. The transmission system must have the capacity to efficiently and reliably aggregate these diverse renewable resources, transport usable blocks of power from remote areas to the load centers and disperse the power to load serving entities.

The first part of this paper will discuss the PJM planning study practices on the integration of renewable resources with AC-HVDC systems. The results show the comparison between AC and HVDC integration focusing on losses, voltage control and power system dynamics. The second portion of the paper will briefly discuss the potential market implications of the efficient integration of these resources into the market using and AC-HVDC system. Several simulations will be presented based on different cases and assumptions.

This paper includes following parts: PJM system models including the modelling of HVDC, PJM planning study procedures, the study of the renewable resource integration with HVDC, comparison with traditional AC, and potential market implications and conclusions.

KEYWORDS

HVDC Integration, Renewable Energy Resources, Power System Voltage Control, Power System Stability, Energy Markets.

I. INTRODUCTION

Renewable energy is growing quickly in the United States and accounted for 12.9 percent of the domestically produced electricity in 2013, and 11.2 percent of total energy generation. In the PJM territory, renewables are projected to represent approximately 20% of the total resources by the year 2020. Renewable resources such as wind and solar resources have very different aspects when compared to the conventional generations; wind and solar are often more dispersed, remote from major load centers, uncertain in their output, less inertia and lacking voltage control. Additionally, many renewable resources that are located in remote areas lack cost–effective access to transmission and can be deterred by the lack of coordinated planning and permitting processes and the absence of established and clear utility regulations to enable investments in transmission to be reimbursable (i.e., cost recovery). New electric transmission infrastructure is needed to access recently developed renewable resources. For optimal transmission development, it is essential to take a long term approach that reflects the characteristics of the sources being connected. The transmission system must have capacity to aggregate these diverse renewable sources, transport usable blocks of power to remote load centers and disperse the power to load serving entities in an efficient and reliable manner.

As reported in [1], HVDC is a viable option to integrate renewable resources like wind power and has several competitive advantages when compared against HVAC. The benefits of HVDC are increased energy efficiency to help operators meet growing electricity demand while reducing transmission losses and the amount of land required for transmission lines. HVDC can also connect AC grids to renewable resources while improving power quality, stability and reliability on those networks by reducing disturbances. The networks can be managed by control centers while operators keep the grid balanced by injecting the necessary power when there is a dip or peak in demand. One advantage that will be increasingly valuable in the near future is the controllable nature of HVDC lines. Balancing generation and load has become more complicated with the increased penetration of intermittent renewable resources. [2] has reported that E.ON Netz, a high voltage grid operator, has operated HVDC lines to provide increased flexibility to balancing generation and load. This control will allow for increased flexibility of operating the high voltage electrical grid and will also allow for increased penetrations of renewable resources.

The difference in cost of equipment and operation of HVAC and HVDC can be significant. As documented in [3], HVDC lines are able to be built using a smaller right of way, to provide more power per conductor, to occur less power losses, and to operate without reactive compensation. However, the cost of the purchase and maintenance of the converters and AC side filters are expensive. Depending on specific circumstances, the breakeven distance of overhead lines between AC and DC line ranges from 500 km (310 miles) to 800 km (497 miles). Therefore, HVDC would be the most cost effective choice to transport bulk power from remote renewable resources when the distance is approximately 650 km (400 miles) or more.

II. PJM SYSTEM MODELING

a. PJM Planning System

The PJM Planning System used in the study case is the whole US Eastern Interconnection model, including 68,607 buses and 9,470 generators. The dynamic model used for this study includes details of generators' excitation systems, governors, power system stabilizers (if one exists), loads and various other equipment. The minimum modeling for machines is a generator model. PJM currently represents loads as 100% constant current real power and 100% constant impedance reactive power.

Thus, power system models in the study can be mathematically represented as shown below as a set of differential equations to represent generators and the associated control systems.

$$\begin{cases} \dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, \mathbf{y}) & (1) \\ \mathbf{0} = \mathbf{g}(\mathbf{x}, \mathbf{y}) & (2) \end{cases}$$

where $\mathbf{x} \in \Re^n, \mathbf{y} \in \Re^m, \mathbf{f}: \Re^n x \Re^m \to \Re, \mathbf{g}: \Re^n x \Re^m \to \Re$.

For stability analysis three phase faults, single line to ground faults with stuck breaker and single line to ground faults with the communications failure cleared within zone 2 times will be examined. Rotor angle, real power output, EFD, speed and terminal voltage of units under study are monitored. Bus voltages in the same area are also monitored. Following the disturbance, the voltage profile and oscillation envelope should meet the requirements +/-5% of the pre-contingency voltages and 3% damping margin.

b. Conceptual Interregional HVDC Network Model

The HVDC system consists of a 3,000 MW bipolar link operating at 600 kV DC. Each pole of the DC line connects to the PJM system through 12-pulse bridge line commutated converters and two 3-phase transformers.

Shunt compensation is provided at both ends of the line to offset reactive power demands of the converters determined to be about 60% of the total active power injection (1,700 MVA). Additional shunt capacitors as well as dynamic compensation were added to properly regulate the voltage at both ends to desired values based on PJM Operating Procedures [4].

An equivalent representation of the interconnection through a DC link is shown in Figure 1. Note that the converter transformers which facilitate coupling between the AC and DC networks are implicitly modeled as part of the converter.
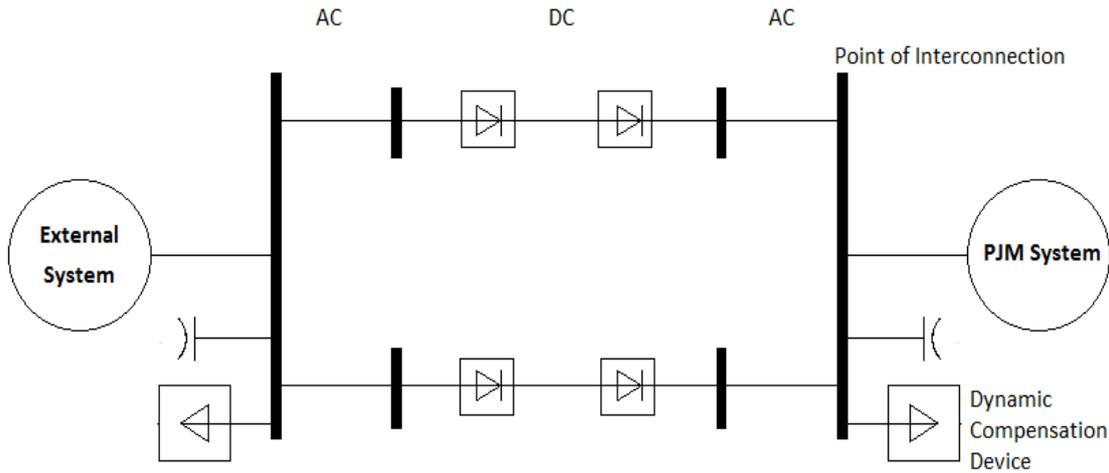
Figure 1. Conceptual representation of the proposed HVDC connection

The dynamic model for the DC line and the Dynamic Compensation device are based on standard PSS/E® models populated with typical values.

III. Study of Renewable Resources with HVDC Integration

1. Static State

For the purpose of comparison in the study, a proposed set of wind generation plants are connected to PJM transmission system through either two parallel, 500 miles long, 600 kV HVDC lines, or, two parallel, 500 mile long, 765KV HVAC lines. The AC line parameters are shown in Table 1.

Table 1. AC line parameters

Phase Bundle	6-795 kCM ACSR
conductor Diameter (in)	1.063
Conductor Weight (lb/ft)	0.896
No. of Phase Bundles	3
Bundle Diameter (in)	30
Line Resistance %)	0.18
Line Inductive Impedance (%)	4.35
Line Charging (%)	2500
Surge Impedance Loading, SIL (MW)	2390
Practical loading Limit (0.68*SIL) (MW)	1625.2
Theoretical Loading Limit (MW)	3080

The voltage analysis indicates that for a 3,000MW power transfer, approximately 3,500 MVAR shunt capacitors are needed for HVDC to maintain the system voltage within the limits; while with AC line, approximately 2,000 MVAR reactors are needed to maintain

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the voltage since the long AC lines have significant amount of charging. For a 1,000MW power transfer, approximately 850 MVAR shunt capacitors are needed for HVDC to maintain the voltage; while with AC line, approximately 5,200 MVAR reactors are needed.

At both transfer levels (3,000MW and 1,000MW), the loss of HVAC lines is a little lower than the HVDC lines.

Table 2. Power Loss

Power Loss	600KV HVDC	765KV HVAC
3,000MW power delivery	4.7%	3.1%
1,000MW power delivery	1.5%	1.1%

N-1 and N-1-1 voltage studies (Voltage Magnitude and Voltage drop) were performed for the contingencies within 5 electrical layers. The results show no significant difference between HVDC and HVAC lines.

2. Stability

A stability study was then conducted to evaluate the dynamic performance of the HVAC and the HVDC options to transfer 3,000MW of wind generation to PJM system. To make the topology of the HVAC option similar to the HVDC option, a phase angle regulator (PAR) is used as a link to the external system. It is noted that PAR is used to control the power flow of the link in steady state condition similar to the HVDC model.
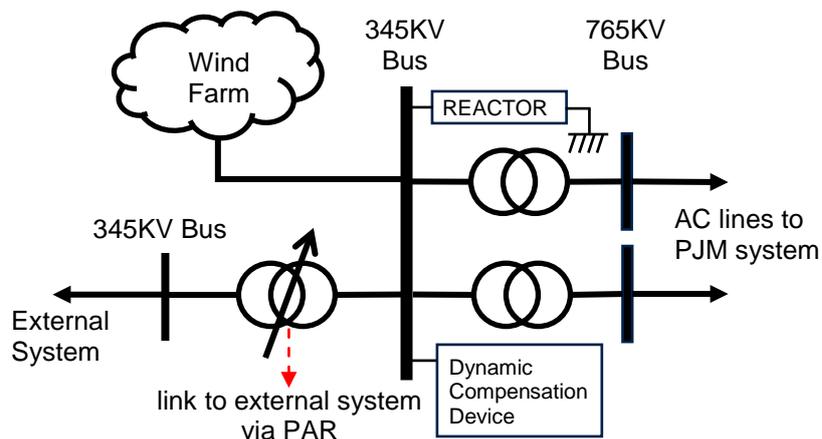

Figure 2. HVAC option with AC link to an external system via phase angle regulator (PAR)

To evaluate dynamic performance of the two options, several contingencies and system conditions are chosen. Baseline stability and N-1-1 stability studies are conducted using the selected contingencies. NERC category B and C contingencies are applied to baseline condition and NERC category B contingencies are applied to N-1 outage condition.

For baseline condition, transient stability simulation was conducted for NERC category B and C contingencies and maximum angle swings of generators were monitored. Table 3 shows maximum angle swings for top 5 critical contingencies.

Table 3. Maximum angle swings for several contingencies

Contingency No.	Contingency Type	Maximum angle swing (degree)	
		HVDC option	AC option
Ctg. 1	SLG* fault w/ delayed clearing	93	92
Ctg. 2	SLG fault w/ delayed clearing	83	80
Ctg. 3	3-phase fault w/ normal clearing	41	37
Ctg. 4	3-phase fault w/ normal clearing	37	35
Ctg. 5	SLG fault w/ delayed clearing	27	28

*SLG: single-line-to-ground

For the most of the tested contingencies, the HVDC option shows a slightly larger angle swing which indicates that the HVDC option shows a comparable performance to the HVAC option from a transient (angle) stability perspective. Sustained angle oscillation was not observed from the tested contingencies.

N-1 outage condition

In addition to the baseline stability, N-1-1 stability was also conducted for selected N-1 (maintenance) outage condition. Under N-1 outage condition, a 3-phase fault w/ normal contingency was applied. Table 4 shows maximum angle swings for two 3-phase faults w/ normal contingencies for an N-1 outage condition. It is observed that the tested Category B contingencies are quite stable under the N-1 outage condition and the HVDC option still shows a comparable performance.

Table 4. Maximum angle swings for two NERC category B type contingencies for an N-1 outage condition

Contingency No.	Contingency Type	Maximum angle swing (degree)	
		HVDC option	AC option
Ctg. 6	3-phase fault w/ normal clearing	42	17
Ctg. 4	3-phase fault w/ normal clearing	36	35

Transient voltage recovery performance is another important aspect in stability analysis. Figure 3 shows transient voltage recovery behaviors of the two options at 345kV bus on

the PJM side. To compare the voltage recovery performance, a single-line-to-ground (SLG) fault with delayed clearing contingency due to stuck breaker was tested.
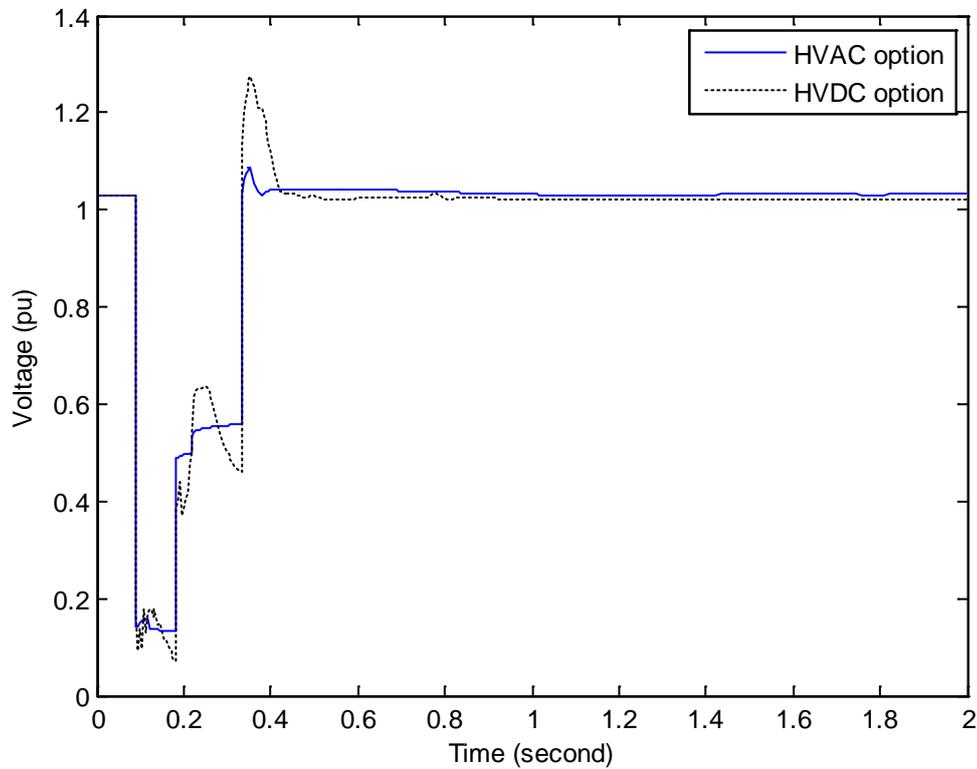

Figure 3. Voltage comparison of 345kV bus on PJM side for a delayed clearing contingency

At the instance of the fault the voltage drops below 0.2 pu. At the normal clearing the remote end breaker is open which boosts the voltage up to 0.5 pu. However even after the normal clearing the SLG fault is not cleared completely due to a local stuck breaker. The SLG fault is completely cleared at a delayed clearing time and the voltage is finally recovered to a pre-contingency level.

It is interesting to note that the HVDC option shows a marginally higher voltage spike than the HVAC option at the instance of the fault clearing. The peak voltage is around 1.3 pu. This can be due to the HVDC option including shunt capacitors and that the dynamic compensation devices are not fast enough to control the fast voltage rise at the instance of the fault clearing.

Figure 4 shows transient behaviors of power transfer to PJM system for the same contingency. It is observed that the HVAC option gives faster recovery of power transfer after fault clearing. However, it also shows a power dip and that the new steady state power transfer level is not fully recovered to a pre-contingency level. From the viewpoint of power recovery level, the HVDC option shows better performance with slightly slower recovery speed.
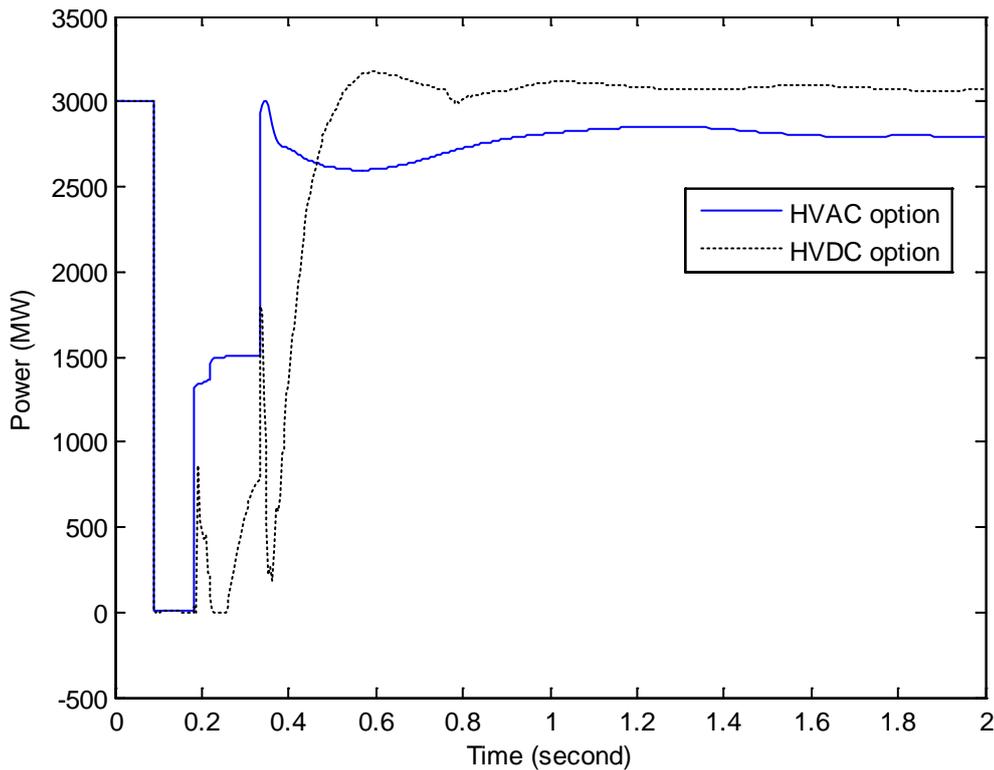
Figure 4. Comparison of real power transfer to PJM system for a delayed clearing contingency

IV. PJM Market Implications

PJM executed several market simulations in an effort to measuring the impact of the integration of HVDC systems into the RTO. The simulations were conducted for annual periods using an hourly unit and commitment software tool. The assumption for the simulations was that renewable resources would be integrated into PJM from remote areas outside of the RTO footprint using a HVDC system and that an AC system would not practically be able to be built for the same capacity and distance as the HVDC system. In other words, the AC system would not be an option to build in order to meet the same objective of integrating large amounts of renewable resources over long distances into PJM. Therefore, the benefits measured from the HVDC system for the simulations conducted represent the benefits as compared to an AC system. In addition, the analysis was conducted assuming that all the necessary transmission upgrades required to connect the HVDC system reliably to the PJM RTO grid were included in the base simulation. The key metrics from the analysis were the production costs, demand costs, and the emissions tons. Several simulations were conducted using both speculative and queued HVDC interconnections for the 2019 study year. The analysis used an interconnection of 1,000 MWs, 2,800 MWs, and 3,500 MWs of HVDC capability to develop an average change in metrics for a 3,000 MWs HVDC line interconnection. Results of this analysis are shown in the table 5 below.

Table 5. Results of Metrics Analysis

3000 MW HVDC Interconnection		
2019 Average Savings ($ millions)	Production Costs	$405

	Load Payments	$181
2019 Average Reduction (tons)	CO2	6,178,284
	SOx	11,386
	NOx	4,388

The average expected production costs savings for a 3,000 MW HVDC line connected from a location externally to PJM and terminates at a location inside of PJM is about $405 million. In addition, assuming the transmission system is enhanced to handle the additional 3,000 MW, the payments made by load over the same period would be reduced by about $181 million not including the cost of the HVDC liune itself. Another aspect that needs to be considered is the reduction in emissions for CO2, SOx, and NOx. The above table shows these reductions which are a direct result of the HVDC line interconnecting 3,000 MW of renewable resources that replace conventional higher emission generation. Reduction in emissions will provide for a cleaner environment as well as aiding in meeting state EPA regulations.

V. Conclusions

1. The comparison results from this study show that the HVDC system is very comparable with the HVAC system in terms of the system security and reliability in the static state and dynamics (transient stability and system oscillations). The HVDC can regulate the transfer MW flow (3,000 MW) through HVDC lines into PJM system; the HVAC needs an additional phase angle regulator (PAR) to control the power flow to achieve this 3,000 MW transfer.

2. The market impacts can be quite large but one must consider the operational, reliability, and market components when deciding to use HVDC or conventional AC systems on the grid. From a market's perspective, the driving force for continued integration of HVDC systems is ultimately the economics and weighing the integration costs, including transmission upgrades, versus the cost savings. HVDC systems are still a relatively new technology and with continued enhancements it may become a suitable and effective replacement to more traditional AC systems.

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