Comments on the Regional Transmission Expansion Plan as presented to the TEAC Meeting on August 30, 2006

Mid-Altlantic/Eastern PJM
500 kV versus 765 kV Alternatives
Submitted by PPL Electric Utilities
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Introduction

What is the long range least cost solution to resolve the forecasted overloads on the PJM transmission system? That is the question that must be answered as PJM reviews the many proposals presented at the recent TEAC meetings. As shown by the preliminary studies, several alternatives appear technically acceptable and can provide the needed relief to the identified system constraints. However, such proposals must be evaluated for not only technical merit, but long term benefits and cost-effectiveness of the projects. On that basis, when evaluating any potential solutions, an evaluation would be incomplete without due consideration of the project cost.

As the independent transmission planner, it is the responsibility of PJM to recommend a long term plan to ensure the adequacy of the transmission system with prudent investments. When a lower cost alternative is available to solve a system problem and offers comparable benefits, the lower cost alternative should be selected. There may be situations where it is appropriate to select a higher cost alternative if significant system benefits can be achieved for an incremental cost increase, but only when the increased cost is reasonable compared to the long range least cost alternative.

Executive Summary:

Reinforcing the existing 500 kV system with new double circuit 500 kV construction for the eastern portion of the PJM transmission system provides more benefits than the 765 kV options, and at a lower cost.

In summary, when compared to 765 kV options, 500 kV double circuit construction provides:

- Enhanced reliability performance
- Enhanced integration into the existing system
- Reduced environment impacts
- Enhanced flexibility for daily operation and maintenance with two circuits instead of one circuit on each transmission structure
- Long Range Least cost investment

The following sections provide further discussion of the specific issues that may be considered when evaluating various options for system expansion. A final determination of the best alternative would take into consideration all of these issues.

Reliability

Reliable performance must be assured for any planned system upgrade to the transmission system. There is more than ample operating experience at 500 kV within PJM to demonstrate excellent historical performance. Within PJM, 500 kV lines have been in operation since 1967 with approximately 5000 miles of 500 kV circuits currently in service. The performance of the 500 kV system is under 1 operation per 100 miles of line, which is the design parameter for such circuits. A review of operation reports dating from 1967 to the present indicates that approximately 90 percent of faults involve only a single phase. A few multiphase faults have occurred on the 500 kV system, but causes generally are related to structure failures, plane contact, gas explosions, etc. Such events occur with a low frequency on both 765 and 500 kV transmission lines, but they do occur and must be planned for accordingly. Approximately 2000 miles of 765 kV lines are in service in western PJM. Although 765 kV statistics may indicate fewer outages, the difference between the number of fault events for 500 kV and 765 kV on a per 100 mile basis is negligible. Fault events are a function of total exposure as well as voltage level. Systems with greater line exposure would naturally have more fault events in total. In Canada, where the number of circuit miles of 765 and 735 kV is on the order of 7000 miles, the line performance is comparable. Consequently, it is misleading to consider only the number of outages. An outage rate on a per mile basis is a more appropriate measure of performance. As noted earlier, the 500 kV outage rate is approximately 1 outage per 100 miles, including events associated with substation equipment.

Further, a comparison of the substation equipment performance of the two voltage classes indicates higher failure rates for 600-799kV class equipment than 500 kV class equipment. Based on a report prepared by the Canadian Electric Association (CEA Report 485T1049), the failure rates for equipment greater than 700 kV is more than double that of 500 kV class equipment. Consideration must also be given to the availability of job skills, equipment and material to conduct planned maintenance as well as emergency repairs. 500 kV equipment is commonly used throughout out PJM territory and companies already have material inventories and work methods in place. Should a major event occur on the system, there is a wide pool of potential sources available to allow for restoration of 500 kV transmission. Currently in the U.S., 765 kV equipment is only in service in AEP territory.

Considering exposure to line outages, station equipment reliability, equipment restoration times, and ability to operate/maintain, there is no question that the same, if not more reliable performance can be expected for 500 kV when compared to 765 kV.

Operation flexibility

The use of 500 kV double circuit offers flexibility in operation that may not be achieved with 765 kV single circuit. With a double circuit configuration, it is possible to de-energize only one of the circuits, thus allowing for a partial reduction in loading for maintenance outages. Such flexibility may allow PJM Transmission Operations more opportunities to schedule outages with minimal impact on the day-to-day operations. When terminal equipment or dead line maintenance is required on 765 kV, the single circuit will be opened and total flow interrupted.

Transmission Line Capability

For a first-cut assessment of transmission line loading, surge impedance loading (SIL) is often used to compare alternatives on a generic basis. To make an assessment of line carrying capability for a specific proposal, more information than SIL is needed, including conductor size/quantity, circuit configuration, structure design, line distance and other system limits. In actual practice, the addition of 500 kV shunt capacitor compensation has been shown to be a proven and effective means to achieve transfer capability above the SIL. For a long line of 250 miles or more, shunt compensation would be required for both 765 kV and 500 kV. At high MW load transfer levels a 765/500 kV transformer will consume MVArs and require shunt compensation. In reality, most transmission lines between PJM substations will be less than 250 miles.

Building on Existing infrastructure

The backbone of the Eastern PJM system is 500 kV construction. Integrating a new 500 kV line into the existing system is easily achievable. The majority of the 500 kV stations have been designed to accommodate additional circuits when initially designed. There are no 765 kV transmission circuits in the eastern PJM zone. In order to take full advantage of the transfer capability of a 765 kV transmission line overlaid on an existing 500 kV system, multiple interconnections are required – each with a set of transformers – not just a single transformer at the terminal end of the 765 kV line. For each connection to the existing network, 765/500 kV transformation will be required. As stated above, the 765 kV equipment has a lower reliability in terms of typical failure rates. Additionally, the physical space required for a 765 kV substation is roughly 1.5-2 times the size of a comparable 500 kV switchyard. When interconnecting a new 500 kV line to an existing 500 kV switchyard, minimal expansion would be needed to connect a new line. Interconnecting 765 kV to the existing 500 kV system is more onerous and much more expensive. Conversely, limiting the number of interconnections to the existing system would reduce the likelihood of realizing potential benefits of a 765 kV line.

Environmental Impacts

During their operation, all electric transmission lines obey the laws of physics. Certain effects thus occur naturally. Three of the more common ones are audible noise, electric fields, and magnetic fields. As summarized below, the proposed 500kV double circuit design has fewer operational effects than a functionally similar single circuit 765kV line.

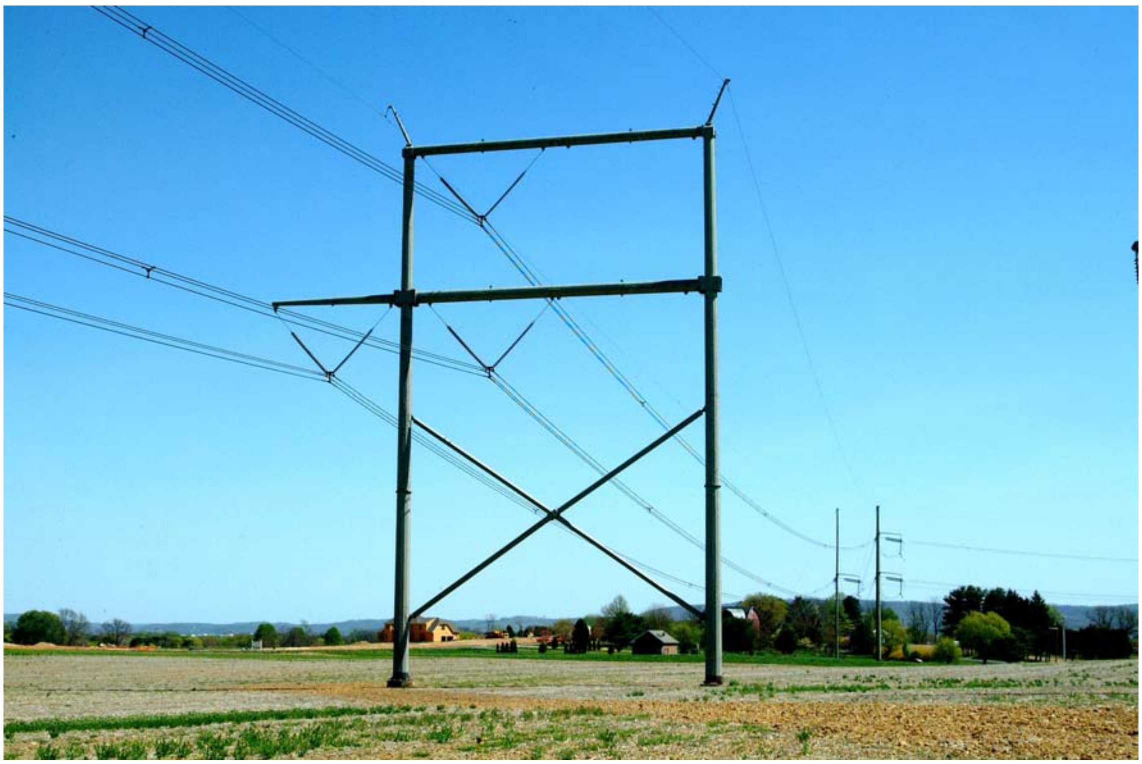
Audible Noise:
Audible noise from transmission lines occurs primarily in wet weather. Water drops collecting on the conductor surface produce a large number of corona discharges. Each of these discharges creates a burst of noise. The highest exposure to line noise occurs during heavy fog, snow, or just after a heavy rain when the ambient noise level is lower. Noise measurements and calculations are expressed in units called decibels (dB). On this basis, the 765kV line design is estimated to produce about 56 dB at the edge of a 200 foot wide right-of-way while the 500kV line design produces about 52 dB at the edge of the same width of right-of-way. To put this in perspective, noise in the range of 50 to 55 dB is about the noise level of a typical office.

Electric Fields:
Electric fields are force fields produced by the voltage on a wire. They decrease with distance from the source and can be either blocked or shielded by common objects such as trees and houses. The usual unit of measurement is kV/meter. Alone among the states through which the 765kV line would pass, only one state, New Jersey, has a limit for the electric field strength at the edge of the right-of-way. This limit is 3kV/meter. With the bottom phase conductors at 55 feet above ground, the 765kV design produces electric fields of 4.25kV/meter, while the 500kV double circuit line produces fields of 2kV/meter or less. For the fields of the 765kV line to be reduced below 3kV/meter, either (a) the conductor height would have to be increased by 35 to 40 feet, requiring 35 to 40 foot taller support towers, or (b) the right-of-way width would have to be increased to 240 feet, requiring 5 more acres of land per mile of line, or (c) other combinations of height, right-of-way width and line redesign.

Magnetic Fields:
Magnetic fields are force fields which result from the flow of the electric current in the conductor(s) of a transmission line. These fields are highest at the source and fall off very rapidly with distance from the source. Unlike electric fields, they are not blocked by common objects such as trees and houses. In the U.S., magnetic fields are typically measured in units called milliGauss. With each line loaded to the 2600MVA load level and the bottom phase conductors located 55 feet above ground, the 500kV double circuit line design produces less than half the magnetic field level of the 765kV single circuit line at the edge of a 200 foot wide right-of-way (95 milliGauss versus 230 milliGauss.).

Visual Impact

PPL has several locations with limited 500 kV double circuit construction. For these cases, PPL employs a tubular steel H frame type structure. The following figure shows an existing 500 kV double circuit structure with one circuit initially installed. The required right-of-way for this design is 200 feet, the same as for the 500 kV single circuit. Aesthetically, the double circuit 500 kV design would be comparable to single circuit 500 kV. The structure design for 765 kV is typically a guyed vee tower design. Based on information available, it is estimated that the overall height for both designs would be about the same (see discussion in later section). The visual impact for the two designs would be comparable.



500 kV Double Circuit Construction, one circuit initially installed

The routing of a transmission line has much to do with its visual intrusion to the surrounding area. To the extent possible, mountain tops, ridge lines and similar high points are avoided. Road crossing are located to avoid long views up a transmission line right-of-way and low-growing vegetation is left in place to further shield the line from view. Additional considerations are given to transmission line backdrops when viewed from more sensitive areas. PPL's standard structure design utilizes weathering steel. These structures, due to their russet-brown appearance, blend well into the Pennsylvania landscape. Utilizing a smaller footprint then lattice steel towers, these structures are generally more acceptable to the agricultural community.

Siting/Right-of-Way requirements

The right-of-way requirements for a double circuit H frame structure design as utilized by PPL require a width of 200 feet. The existing 500 kV single circuit design and the 765 kV single circuit design proposed by AEP would require the same width.

In Pennsylvania, the Public Utility Commission (PaPUC) has the authority to approve or deny construction of a high voltage transmission line. This decision is made after the completion of a detailed siting study including analysis of multiple line routes. Additionally, the process encourages full public disclosure and discussion with affected parties (not only property owners) during the siting process. In order for the PaPUC to approve such a project, a Pennsylvania utility must demonstrate that:

- There is a need for the project;
- The construction, operation and maintenance of the line will not pose an unreasonable risk to the public;
- The line routing minimizes impacts to the social and natural environment.

A new line above 100 kV would be required to satisfy all of these criteria.

Line Design

Land Use:
The 500 kV two pole design requires two foundations. The design that is proposed by AEP for 765 kV is for self supporting steel lattice structures or guyed Vee lattice structures. Each of these tangent type structures require a large footprint (4 or more foundations) that spread over a large area. The 500 kV double circuit tangent steel pole structures require a substantially less footprint (2 foundations) that is favored by the agricultural community and the general public.

Conductor wind and weight loading:
The current design employed by PPL for the double circuit 500 kV line utilizes 1590 kcmil ACSR (LAPWING) conductors in a triple bundle arrangement. This design does result in increased weight loading of the conductor and tends to increase arm sizes (diameters). The increase in wind loading will probably not increase structure moments significantly since the loading will on average be applied lower on the structure for the 500 kV double circuit design. The specific requirements for the conductor selection are addressed in the design of the line, including structure spacing, structure design, foundations, sag, etc.

Structure Height:
In comparing sags of the conductors at 1300 feet and 1500 feet ruling spans, sag of the 765 kV conductors are 20 to 25 feet greater than the sags of the 500 kV conductors. However, since the PPL design for 500 kV double circuit has 2 levels of conductors with 25 foot vertical separation, the overall heights of the 500 kV structures and 765 kV structures will be the same given the same minimum ground clearance of 55 feet. At a

1300 feet ruling span for 765 kV the average structure height is 53 ft. (ground clearance) + 67ft. (sag) + 30 ft (conductor to Overhead ground wire) = 150ft. Similarly for the 500 kV line the corresponding numbers are 53ft. (ground clearance) + 48ft. (sag) + 25ft. (vertical phase separation) + 25' (conductor to Overhead ground wire) = 151ft . The overall structure height will be about the same for 765 kV single circuit as for 500 kV double circuit.

When considering not only conductor weight and wind loading, but also structure foot print, conductor sag, structure height, and total cost (additional cost for transformers for 765 kV construction), the 500 kV double circuit alternative provide more advantages.

Transfer capability

For a fully developed 500 kV system, 765 kV point-to-point lines on top of the eastern PJM 500 kV system is not the logical next step. As shown in the figure below, a very long 500 kV double circuit line (250 miles) has similar transfer capability to a single circuit 765 kV line. A 250 mile 500 kV double circuit line transfer impedance is essentially the same as that for a single circuit 765 kV line plus 765/500 kV step down bank impedance. See **Figure 1** in Appendix A for comparison of transfer capability.

Assuming adequate shunt compensation, even at the max steady state power limit at 90 degrees, both options can only transfer about 3400MW at a 90 degree angle over 250 miles. As shown in the example, a 765 kV point-to-point alternative does not provide a significant increase in transfer capability compared to a 500 kV double circuit alternative. The difference is on the order of 3%.

In practical terms, the angle must be significantly less than 90 degrees, and the transfer capability for such a long line will be in the 2000-3000MW range. As shown in the example, a 40 degree angle would result in an approximate 2500MW transfer for either the 765 kV line or the 500 kV double circuit line, unless series compensation is provided. If 50% series compensation is used on a D/C 500 kV or S/C 765 kV, the transfer impedance would be cut in half, and transfer capability would double for both alternatives.

Cost

When multiple solutions are technically acceptable to solve a problem, the matter of cost must be considered. If all technical issues are equal for competing alternatives, ultimately it is PJM's obligation and responsibility to the electrical consumer to select the long range least cost alternative as the appropriate choice because it provides the necessary level of reliability and performance. However, if the relative cost of one alternative is significantly higher than another, it is more difficult to justify the more expensive project on a benefit/cost basis. Prudent investment is characterized as the orderly economic development of a transmission system to address system reliability and performance needs in the near term, with sufficient flexibility to meet the longer term future needs. When considering alternatives for expanding the bulk transmission system to resolve identified thermal overloads, the use of double circuit 500 kV is the right option that addresses the near term system need, and provides the right balance between the level of investment and the value in system improvement for the future.

PPL has previously made a cost comparison of a typical 250 mile line, using 500 kV double circuit and 765 kV single circuit construction techniques. Below is a cost comparison that was developed to compare 765 kV single circuit line to a 500 kV double circuit line. See **Figure 2** in Appendix A for cost comparison.

Overall, for a 250 mile line, the cost for 500 kV double circuit is estimated to be about 13% lower or about $107 million less than 765 kV single circuit. This takes into account the different structure designs, different structure span, conductor differences and shunt capacitance requirements. Some comparisons indicate that the per mile cost for 765 kV construction is slightly lower than double circuit 500 kV construction, due to the inherent differences in design. However, these comparisons fail to include the significant added cost that just one 765/500 kV substation would add to the overall project. These costs cannot be ignored when any 765 kV option is considered in a system where no existing infrastructure exists at that voltage level. The importance of this difference becomes more significant when considering additional interconnections to the existing 500 kV network. For each location, an additional investment of $100-$160 million is required, that is ultimately paid for by the electric consumer. This poses a significant hurdle when attempting to interconnect 765 kV into an existing 500 kV network.

Summary

In summary, the above technical review reinforces the concept that double circuit 500 kV construction is functionally equivalent to 765 kV construction and offers additional advantages with respect to operating flexibility, environmental impacts, integration into an existing 500 kV system and overall cost. These advantages must be considered to ensure the electrical consumer receives a robust and reliable transmission system at the lowest possible cost. Based on such considerations, double circuit 500 kV reinforcements in eastern PJM are clearly superior to single circuit 765 kV reinforcements.

APPENDIX A

Figure 1 – Comparison of Transfer Capability, 765 kV Single Circuit versus 500 kV Double Circuit

Figure 2 – Cost Comparison, 765 kV Single Circuit versus 500 kV Double Circuit

765 kV single circuit EHV path versus 500kv double circuit EHV path

		R	X	Line B C (pu)	Line MVar pu	Losses at given MW flow		Net MW & MVAR Losses	
765 kV S/C line	Miles					**R losses in MW**	**X losses in MVAR**	**Net MW losses**	**Net MVAR losses**
765kV S/C line, 6-795 kcmil ACSR, pu per mile		0.0000035	0.0000863	0.049923		0.25	6.07	0.25	6.02
System Backup Transfer Impedance		0.00000	0.00000						
765kV, S/C Line Z	250	0.000875	0.02158	12.48	1248.08	61.56	1517.94	61.56	269.87
Transformer 765/500kV bank (2-2250MVA, 0.00007+j0.00728 each)		0.000035	0.00364	0		2.46	256.10	3.66	256.10
765 kV option, with series Transformer, total transfer Z ~=		0.000910	**0.02522**			1.20	NL xfrmr loss		
Max MW Power transfer capability at 90degrees = 100MVA base * (1/x)			**3966**						
765kV actual power flow assuming angle =	39.1		**2501**			65.22	1774.04	65.22	525.97
500 kV D/C line	Miles								
500 kV, D/C construction 3-1590 ACSR, per mi, parallel 6 wire, in pu		0.0000045	0.000104	0.040642		0.32	7.39	0.32	7.35
System Backup Transfer Impedance		0.00000	0.00000						
500 kV - Line Z	250	0.001125	0.02600	10.161	1016.05	79.97	1848.30	79.97	832.25
500 kV option, no transformers needed, total transfer Z~=		0.001125	**0.02600**						
Max MW Power transfer capability at 90degrees = 100MVA base * (1/x)			**3846**						
500kV actual power flow assuming angle =	**40.6**		**2503**			79.97	1848.30	79.97	832.25
% MW transfer improvement, 765kV Line versus 500kV Double Circuit at 90 deg.			**3%**						
MW & MVAR Losses for 765 kV alternative								**65.22**	**525.97**
MW & MVAR Losses for 500 kV D/C alternative								**79.97**	**832.25**
MW & MVAR loss improvement of 765kV S/C Line versus 500kV Double Circuit @ given MW flow =	**2500**	**MW**						**14.75**	**306.28**

FIGURE 1 – Comparison of Transfer Capability, 765 kV Single Circuit versus 500 kV Double Circuit

765 kV single circuit EHV path COST versus 500kv double circuit EHV path COST

765 kV S/C Line	miles	per mile/unit	Cost
Shunt Capacitor Compensation Cost (included in sub cost)			
765kV, S/C, 6-795 kcmil ACSR, Line Cost	250	2,578,000	644,500,000
765/500kV Substation Cost (incl 2-2250MVA transformers)		169,000,000	169,000,000
765 kV option, total Cost~=			813,500,000
500 kV D/C line			
500 kV, D/C construction 3-1590 ACSR, operated as two circuits	250	2,640,000	660,000,000
Shunt (500kV) Capacitor Compensation Cost for Net MVAR losses		20,000,000	20,000,000
500 kV Substation Cost (2 bays, bkr and half, 6-500 kV CBs total)		25,750,000	25,750,000
500 kV option, total Cost~=			705,750,000
Capital Cost, 765kV Single Circuit versus 500kV Double Circuit			**-13%**
		Difference $	**(107,750,000)**

FIGURE 2 - Cost comparison of 765 kV Single Circuit versus 500 kV Double Circuit