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Prospective DC Conversion of a Major 345 kV AC Line

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SUMMARY

As one option to strengthen the interconnection capacity of the American Electric Power Company, serious consideration was given to conversion of a 218 km, single circuit 345 kV AC line to DC. The objective was to see if any DC configuration and DC voltage could, using existing tower geometry and conductor current capability, achieve a target loading of 2,300 MW.

Three DC options were considered: (1) a conventional bipole in which the center phase position would serve as a ground return path, (2) a tripole configuration in which one conductor remains positive, one negative, and the third alternates between polarities, thus making greater use of aggregate ampacity, and (3) a "Split Bipole" option requiring that the center phase position be reconductored to achieve double its present ampacity, thus allowing the outer two phase positions, in parallel, to serve as one pole and the center phase position the other. The challenge is complicated by the desire to tap the circuit near one terminal, converting one side of an existing 345 kV double circuit line to access the tap load point, the other side to return to the primary route of power (See figure 1).

Limitations examined in seeking maximum sustainable DC voltage included: (1) The ability to install new DC insulation sufficient to withstand full voltage in a light pollution environment, (2) The ability of resulting air gaps to withstand anticipated DC overvoltages, and (3) Audible Noise, conductor gradients and ground-level field effects to remain within designated limits. These were assessed using the Transmission Line Workstation (TLW) developed by the Electric Power Research Institute.

It was shown that adequate insulation and clearance could likely be provided for voltages otherwise limited by ground-level electric field effects, the latter quite sensitive to conductor

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height above ground. Since a relatively small fraction of the line approaches the nominal minimum clearance to ground, selective tower height remediation is indicated as a reasonable option in supporting a higher DC voltage. On that basis DC voltage and MW limits were established for three levels of minimum clearance – all above the nominal minimum.

The bipole option was considered but did not reach the objective DC transfer limits. The tripole option too fell just short of the objective limit at the lowest (adjusted) minimum clearance, but exceeded it for higher mitigation levels. The split bipole easily met the objective for even moderate voltages, but was ruled out due to the doubtful ability of the existing structures to withstand the associated additional mechanical loading.

The use of ground wires below the pole conductors was also explored as a mitigation measure. If customary sizes of overhead ground wires are used, a bundle of two would be required. It was also shown that a significant reduction in ground-level field effects can be achieved, even if they are offset laterally from the pole conductor to prevent risk of flashover on ice-dropping or galloping.

It was also established that tapping of the tripole circuit for the required load would be relatively simple and further, that adequate land area was available for the required converter stations at all terminals.

It was concluded, as well, that much more definitive industry guidelines are needed for target ground-level field effects recognizing (1) DC ground level field effects represent primarily an annoyance risk (2) a number of existing DC lines operate above commonly accepted field effect guidelines without a history of complaints, and (3) Strict interpretation of those guidelines may impose a considerable economic penalty.

KEY WORDS

Overhead Transmission Lines, HVDC, HVDC Overhead lines, AC to DC Line conversion, DC ground level field effects.

BACKGROUND

Among the planning options to increase overall transfer capability of the American Electric Power Corp. was the prospect of converting to HVDC, a 218 km 345 kV AC transmission line from Kanawha River substation, southeast of Charleston, West Virginia, to the Cloverdale substation, Northwest of Roanoke, Virginia. The line, illustrated in Figure 1, has a diversion known as the OLAF Extension, to Matt Funk substation west and south of Roanoke. Feasibility of this undertaking was contingent on the MW rating achievable by the converted line and, therefore, on the DC voltage that it could support while still using the existing structures.

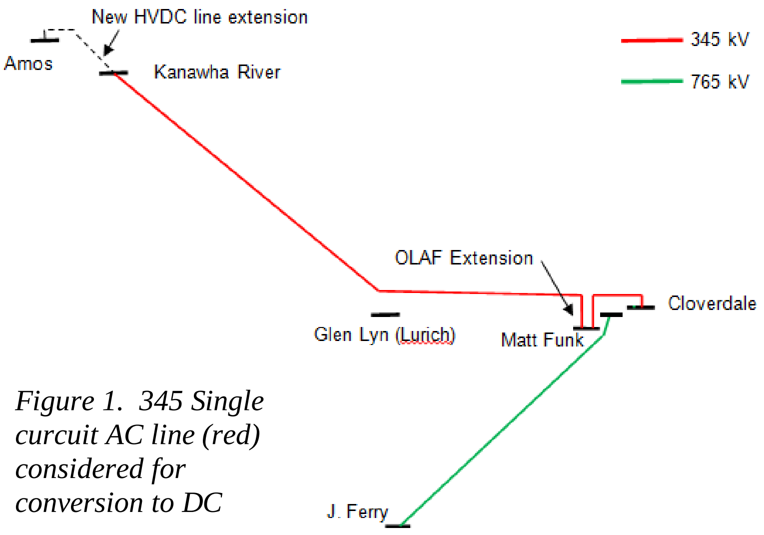


Figure 1. 345 Single curcuit AC line (red) considered for conversion to DC

The desired ratings for the converter stations based on AEP planning studies were 2300 MW at Amos, 2000 MW at Cloverdale and 800 MW at Matt Funk. Table 1 lists typical conductor dimensions of single-circuit towers comprising the

Kanawha River -Cloverdale circuit as well as the double circuit extension to Matt Funk. In both cases, phase conductors were 2xACSR Cardinal of radius 3.04 cm. Shield wires are 1 cm in diameter. While the nominal minimum clearance to ground for both circuits was 11 m, that clearance was highly variable due to the mountainous terrain traversed by the line. For example, at maximum loading approximately 3% of the Kanawha River - Cloverdale line has clearances less than 9 meters. Thus clearance remediation was a viable means to increase maximum sustainable DC voltage where ground-level field effects limited that voltage.

Table 1 Conductor Suspension Points (m)

	Kanawha - Cloverdale			Olaf Extension		
Conductor	X	Y	Sag	X	Y	Sag
A	-9.4	25.9	13.7	-6.2	39.2	13.7
B	0.0	25.9	13.7	-8.8	31.2	13.7
C	9.4	25.9	13.7	-6.5	24.7	13.7
D				6.2	39.2	13.7
E				8.8	31.2	13.7
F				6.5	24.7	13.7
GW 1	-8.0	35.1	9.1	-4.3	45.7	9.1
GW2	8.0	35.1	9.1	4.3	45.7	9.1

Since the project being considered consists both of adapting a single circuit horizontal circuit to DC and a vertical double circuit to the same DC voltage, that voltage will be determined by the more limiting of the two. Because the Olaf tap is only 13.3 km in length, economics suggest that one circuit on the double circuit line carry tapped DC power to the Matt Funk Station and the other be part of the ongoing supply to Cloverdale. On that basis the single circuit line was clearly more limiting to maximum DC voltage than the double circuit line.

DC OPTIONS CONSIDERED

In Figure 2, which illustrates the three options considered for AC to DC conversion, (a) consists of a simple bipole with the center AC phase position used as an earth return, (b) consists of a tripole in which the center pole alternates polarity to achieve greater current utilization of the conductors [1], and (c) represents a “split” bipole which presumes the ampacity of the center conductor position be doubled by a whole or partial restringing, assuming the existing towers are capable of the additional wind and weight loading on the center conductor position. Option (c) would double the MW capability of option (a) but for different limits to DC voltage due to reduced pole-to-pole spacing.

The three configurations shown in Figure 2 will differ in MW capability as well as in $/kW for conversion cost. The cost per incremental kW gain over existing flow levels will drop sharply as the DC MW rating is increased since the benefit of conversion is limited to *gain* in flow but the cost will be based on *total* flow.

Operational issues may also be important in the choice of DC options as well. If the converted line, by virtue of its new role in system transfers, becomes critical to (n-1)-based system loading, either by virtue of its loss or the load it can assume on loss of another circuit, the redundancy of the option chosen may be an important issue. Option (a) in Figure 2 has 50% redundancy, option (b) 73%, and option (c) none.

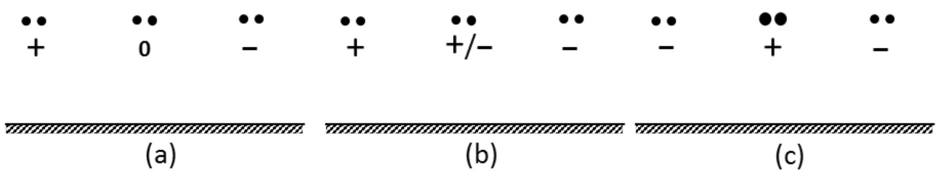


Figure 2 – AC to DC Conversion Options

INSULATION & CLEARANCE LIMITATIONS

DC insulators must be long enough to withstand continuous DC voltage after accumulation of pollution on the insulator surface. Their surface contour is specially designed to withstand the unique mechanism of DC flashover and their adequacy determined by the total "creepage" distance of the string, i.e. the total distance of the surface path from pole-to-ground divided by the pole-to-ground voltage (mm/kV). While there are no international standards for creepage distance for continuous operation, IEC guidelines suggest that the rights-of-way considered in this study would fall in the "light contamination" category for which a creepage criterion of 30 mm/kV would be adequate [2]. A one-for-one replacement of the present 15 disc insulators with DC disc units of the same length would increase creepage from 292 mm per disc, as characterize the AC discs now in place, to 455 mm per disc on the same length insulators designed for DC applications. On that basis, replacing the 15 insulators per phase position with DC units would accommodate 455 x 15/30 = 227 kV. However, a changeover to modern DC polymer insulators would increase the effectiveness of whatever creepage distance is provided. For example, an intensive investigation looking forward to conversion of a 400 kV AC line in Germany to 400 kV DC, assumed a ratio of polymer-to-porcelain creepage effectiveness of 5m/3.65m = 1.37 [3]. That ratio, applicable to a medium contamination zone, would, if adjusted for light contamination, suggest support of a voltage in the order of 350 kV.

In addition, DC voltage can also be increased for a given mm/kV pollution criterion by taking advantage of the fact that a lower overvoltage ratio can be expected after conversion to DC. This would allow a slight lowering of the conductor for the same degree of code compliance where, in the latter, minimum clearance is governed by the product of DC voltage and overvoltage level. That reduction could, in the present case, allow lowering the conductor by about 50 cm allowing another 20% increase in insulator length. Effective total creepage distance could be increased even more substantially by replacing existing "I" strings with inverted "V" strings. The insulation gains thus achieved would be offset in small measure (~ 5%) by increased pollution flashover exposure resulting from two paths to ground instead of one. [4]. Thus providing adequate support insulation would very likely not be a limitation considering constraints imposed for ground-level field effects.

Clearance to tower walls would likely be even less limiting after conversion to DC. Again, using an AC switching surge criterion of 3.0 and an example DC pole voltage of 400 kV, the DC overvoltage for equal exposure would have to be a value not likely reached with any of the DC configurations considered, i.e.

$$SS_{dc} = 3.0 \times 282/400 = 2.1 \qquad (1)$$

Because DC converters may be configured to limit fault current to values comparable to load current, arcing horns could be removed at the time of insulator replacement.

GRADIENT AND ENVIRONMENTAL LIMITS

Based on local regulations, audible noise limits at the edge of the 46 m right-of-way was to be maintained at or below 41 dB - in the DC case limited by dry, rather than wet conditions. However, audible noise was not a limiting issue for the configurations and voltages considered in this study.

DC voltage was also limited to a level which produced a conductor surface gradient of 26 kV/cm or less. While some HVDC lines operate with higher gradients, unexplained (anomalous) flashovers on the negative pole of Nelson River's +/- 450 kV line where calculated gradient has been variably reported between 25 and 27 kV/cm suggest a 26 kV/cm limit…at least for that polarity [5]. Results which respected that negative gradient but allowed a positive pole gradient as high as 27 kV/cm were considered in some cases.

Perceived annoyance from ground level fields effects under DC lines results from an electric field that is too high at ground level and/or too high a flow of ions from energized pole conductors to ground under the line. Unlike AC where ions generated at one polarity are drawn back to the conductor on the succeeding half-cycle, ions from DC conductors flow away from the conductors…either to other conductors, to ground, or to be neutralized by ions of the opposite polarity. Ions that gather between conductor and ground distort the normal electrostatic gradient pattern, raising the gradient at ground level and the corresponding perception of it. Ions flowing to ground, traverse an extremely high resistance path, thus making a human standing on the right-of-way a preferred current path and causing ion accumulation on the surface of the skin…neither a source of danger, but if sufficiently intense, a source of annoyance.

Ground-level field effect limits, as important as they are in establishing maximum DC voltage, are loosely defined. While experts generally agree on independent limits for ground level electric field (25 kV/m) and ion current density (100 nanoamperes/m^2), those values being dependent on ion dispersion at a particular instant, vary over a wide range, even on the same day and in the same weather. They also vary with line loading and the prospect of annoyance should really consider a number of other probabilities, e.g. the likelihood that a person will be on the right-of-way at a point of minimum clearance when extremes of the annoyance potential are reached.

A number of algorithms are used to calculate ground level fields and current densities, one of the most comprehensive being a part of the Transmission Line Work Station (TLW) available from the Electric Power Research Institute, and used in the study cited herein [6]. The latter calculates values expected to be exceeded only 5% of the time. Other commonly used software is based on 10% exceedance values. All such programs predict levels in excess of the criteria for lines currently operating without complaints. The only DC line with a clear record of complaints is the Cahora Basa 500 kV line in South Africa, where positive and negative poles are separated by 1 km and calculated values of electric field and current density at the voltage levels where complaints occur are several times the criteria cited above [7]. Efforts have also been made to test individuals for sensitivity to controlled field levels [8]. However being relatively subjective, sensitivity scales were not used in this study as a means to determine DC voltage limits.

Calculations, using the software cited above, showed that the maximum DC voltage sustainable by the AEP 345 kV AC line, once converted to DC in almost all the options cited above and voltage levels considered, was set by ground level field effects at the minimum clearance assumption. A summary of permissible voltages for both the bipole and tripole cases is shown in Table 2. Since minimum height remediation was a realistic option,

Effective	**Bipole**		**Tripole**	
Clearance	**kV**	**MW***	**kV**	**MW***
9.1 m	280	1,624	285	2,265
10.7 m	320	1,856	326	2,590
12.2 m	360	2,088	334	2,645

** @ 2,900 amperes*

Table 2. Summary of MW Capability of DC conversion options

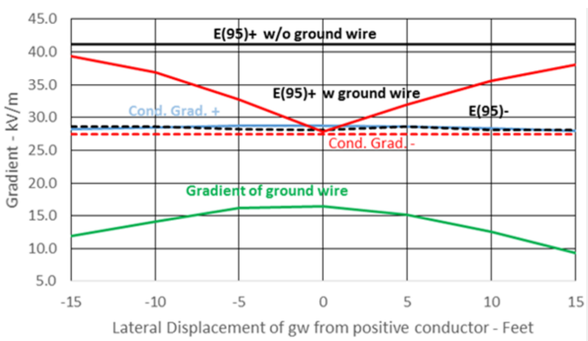
three values of effective minimum were assumed; 9.1 m (30 ft), 10.7 m (35 ft), and 12.2 m (40 ft).

In establishing the voltages in Table 2, values of both ion current density and electric fields were kept to within maximums that, according to the algorithms used, would be exceeded no more than 5% of the time.

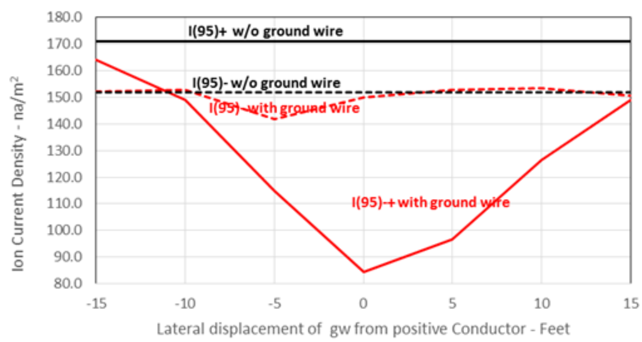
POTENTIAL BENEFIT OF UNDERBUILT GROUND WIRES

The prospect of installing one or more ground wires below the pole conductors was examined where maximum DC voltage is limited by ground-level field effects. The minimum clearance of such wires would have to correspond to the fixed clearance portion of applicable codes, and the clearance between the ground wires and pole conductors with codes for conductor separation. For the US National Electrical Safety Code, that requirement would not have a major effect on clearance of the primary DC conductors. However, in areas subject to galloping or icing, the underbuilt shield wires would have to be laterally offset from the primary pole conductors. Furthermore, underbuilt ground wires, unless bundled, will develop much higher gradients than the 14 kV/cm recommended for wires serving that purpose.

Calculations were made for a bundle of two 1 cm ground wires under just the positive pole, adjusted to a clearance corresponding to fixed code clearance and located at various points laterally from the projection of that pole to ground. The results are shown in Figures 3(a) and (b) for ground level surface gradient and ion current density respectively. While not factored into the maximum DC voltages shown in table 2, these figures show potential for significant ground level field reduction and could be of interest as a means of mitigation under the relatively small segment of right-of-way where clearances are limiting to DC voltage.



a.



b.

Figure 3. Effect of a bundled ground wire below one pole conductor - a. electric fields and gradients, b. ion current density

STATION FOOTPRINT

The study included estimates of land area required for voltage source converter (VSC) terminals. Supporting the above DC options showed the bipole option requiring approximately 25 hectares, the split bipole option requiring approximately 30 hectares, and the tripole option requiring approximately 37 hectares. Adequate land area was deemed available at all terminal locations.

CONCLUSIONS

1. A very substantial increase in loading of the 345 kV single-circuit AC line can be achieved by its conversion to DC. For a conventional bipole, using the center phase position as a ground return path, up to 2,088 MW can be transmitted for a relatively high level of clearance remediation, that value being about 9% below the sought after transfer level.

2. A tripole configuration, at a terminal cost premium per MW, allows a substantially higher rating i.e. 2,265 MW with a lower bound clearance assumption and 2,654 with the maximum clearance assumption corresponding to conclusion 1 above.

3. A split bipole, in which the center AC phase position is reconductored for double ampacity, would yield a still higher MW rating using a simpler terminal system, but is not mechanically practical in this case.

4. Application of underbuilt ground wires appears to be a promising means of remediation and might allow an increase in DC operating voltage sufficient to carry the simple bipole option to the desired transfer level.

5. Considering the extremely high economic value per incremental MW of capability achievable with each upward step in allowable DC voltage and the fact that voltage limits are determined by ground field effects which cannot be firmly linked to actual annoyance potential, suggests that the industry needs to improve its methods for field effect limit assessment.

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