Determination of Voltage Stress in Case of Operation of a Hybrid HVAC/HVDC Transmission Line

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***Abstract*— This paper is a study of the proposal to convert one of four 380 kV AC circuits on the one transmission line to a bipolar DC circuit with metallic return, using one of the three phase conductors. The line length will be approximately 348 km. This study examines the voltage stresses and line insulation on the DC circuit.**

***Keywords*: HVDC, VSC transmission, AC to DC circuit conversion, AC coupling to DC, DC transient overvoltagess.**

I. Introduction

THE fundamentals for voltage stress on a conductor installation for an HVDC transmission circuit converted from one of four 380 kV, 50 Hz AC transmission circuits on the one transmission tower structure. The DC line rating is anticipated to be 2940 MW at ±400 kV DC. The converters are expected to be voltage sourced converters (VSC) using the modular multi-level converter (MMC) in bipolar configuration with full bridge sub-modules. Voltage stresses on line DC insulation is the main concern discussed in this paper along with impact of fundamental frequency coupling from the AC circuits to the DC circuit. MMC converters are selected for ease of line protection and increased power transfer capacity is the incentive for converting a circuit to DC technology.

II. Basis for DC Design of Hybrid Transmission.

Design and layout of a hybrid HVAC/HVDC overhead transmission line for this study is based on what was presented by Neumann et al [1]. An example of a four circuit tower used for this study is shown in Fig. 1.

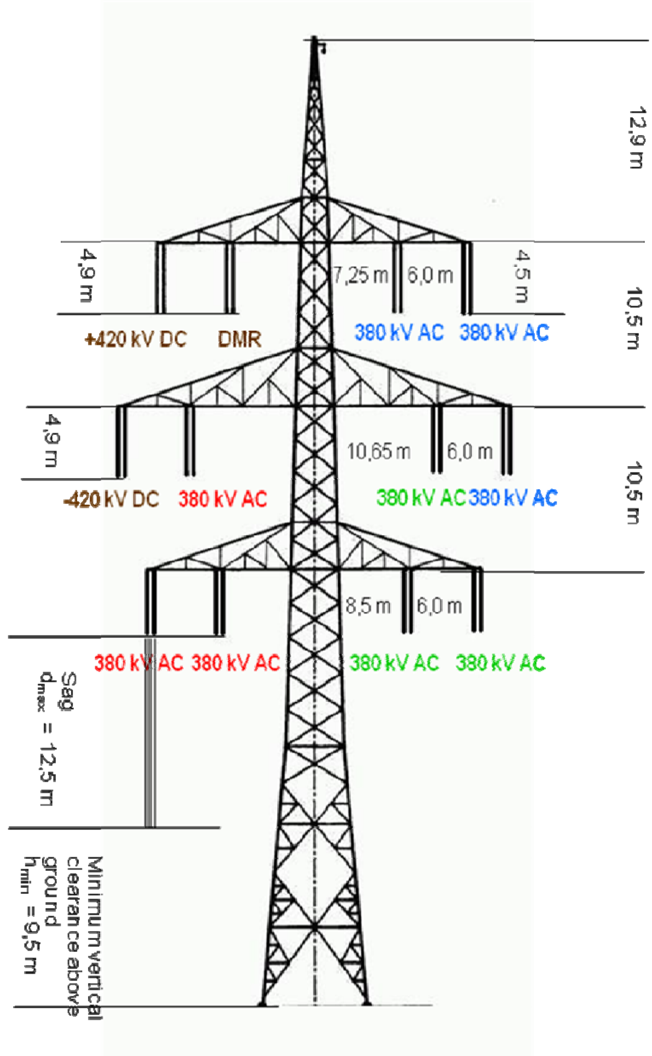

Fig. 1, Transmission structure for hybrid AC-DC transmission study of voltage stresses and fundamental frequency coupling to the DC circuit

Line insulators for the DC circuit were assumed to be replaced with composite insulators with less weight than previously installed porcelain or glass cap and pin insulators. Conductors were unchanged and so the overall weight to the towers was considered unchanged.

For this study, a generic bipolar MMC converter is located at each end of the DC circuit with full bridge sub-modules. The question of a line reactor was examined. How two parallel MMC converters will be connected and controlled is open to further design since a reactor makes a difference to

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the results of the 50 Hz coupling studies. This difference is examined. For DC line faults, the full bridge MMC converter was controlled to do the protective function of reducing line volts to zero or near zero on the faulted pole to earth or to both poles if a pole to pole fault occurs

Presently there is no standardized basis for hybrid AC-DC transmission systems. There has been no high voltage AC transmission lines converted to a DC circuit except for experimental purposes of one line in India.

III. FUNDAMENTAL FREQUENCY COUPLING TO DC CIRCUIT

Regarding HVDC interconnections, there are many successful schemes throughout the world, operating for over 40 years, some of which having overhead transmission lines sharing the same way-leave or right-of-way with AC transmission circuits where fundamental frequency coupling from the AC line to the DC line occurs. The one HVDC scheme where remediation was undertaken was the Hydro Quebec to New England HVDC transmission line where a fundamental frequency blocking filter was applied in the neutral end of each pole in the Sandy Pond converter [2].
Fundamental frequency coupling to a DC circuit with voltage sourced converters (VSC) has only recently been investigated [1], [3] and [4].

The concern is that induced fundamental frequency currents will flow into the DC terminals of each of the VSC converters, causing reverse rectification, so that DC currents will flow through the converter side windings of the interface transformers for VSC converters. This, of course, can lead to saturation in the unit transformers, which is highly undesirable. Means to block the DC current from flowing into the interface transformers may be achieved by one or more of the following methods:

- Use of a fundamental-frequency-blocking filter in each pole in series with the pole converter
- Fully transpose the AC transmission lines that are coupling and superimposing AC fundamental frequency voltage and current on the DC circuit
- Controls to the VSC converters that block DC current from entering or leaving the AC side terminals of the converters [5]
- Fundamental-frequency shunt filter across the DC terminals of the converter poles to bypass fundamental-frequency current away from entering the converter. Such a filter can be placed on the line side of line end reactor; tuned to 50 Hz to divert 50 Hz induced currents from entering the converter.

Elimination of the DC current through the interface transformers may not eliminate the superimposed fundamental-frequency voltage on the DC transmission line. If small, this may not be of much consequence. If large, then the DC voltage will have to be reduced so that the peak of the combined voltages stays at or below an acceptable level for the line insulation. This reduces the DC power level of the VSC transmission.

To avoid saturation of the unit transformer, the DC current passing through its valve side secondary windings must be reduced to about the same magnitude as the normal magnetizing current if the transformer is energized at no load from its secondary winding.

When fundamental-frequency coupling is present for a specific VSC transmission system, the technical specification for the converters must identify it adequately so that the equipment supplier can design and demonstrate an acceptable remedy.

For the hybrid AC-DC transmission line with typical tower as shown in Fig. 1, there are a number of issues that impact the continuous peak voltage on the bipolar DC circuit. These are:

1. Whether the AC circuits are transposed
2. If one AC circuit is out of service, particularly the top AC circuit on the opposite side of the tower the fundamental frequency coupling to the DC circuit is increased.
3. Use of fundamental frequency blocking filters in series with each pole, which blocks fundamental frequency current but the superimposed AC voltage will increase significantly.
4. The fundamental frequency coupled current superimposed on the DC current will increase as power flows increase on the AC circuits.

The stability of the MMC converters was impacted by the fundamental frequency current superimposed on the DC current. Effort is required to ensure the VSC transmission controls are robust. Equipment suppliers will be able to develop a robust design but will need to do so with the coupled AC circuits represented in their design model.

With a hybrid AC-DC transmission line 348 km in length configured like Fig. 1, a steady state fundamental frequency coupling study was undertaken with results presented in Table 1. The equivalent circuit diagram showing where the steady state coupling measurements were recorded from is shown in Fig. 2.

The frequency dependent phase based line model in the PSCAD library was used with all four circuits of 12 three conductor bundles and a mid-line tap 174 km from each end. Because of the frequency on the line model was curve fitted over the frequency range of 0.5 Hz to 10,000 Hz, no adjustment was required for all steady state and transient studies undertaken. The circuits were studied with un-transposed or with ideal transpositions.

Line voltage was most impacted at line centre and line current at converter poles at one end. PSCAD/EMTDC was used to represent the MMC converters and hybrid AC-DC transmission line. When transposed, the AC circuits were ideally transposed.

The MMC converters were based on the technique of Gnanarathna et al [13] with further development for half bridge and full bridge sub-modules.

TABLE 1
RESULTS OF STEADY STATE COUPLING STUDY OF HYBRID TRANSMISSISON LINE WITH SUPERIMPOSED AC VOLTS AND CURRENTS

Test: AC and DC lines fully loaded	AC volts +ve pole (kVrms)	AC volts -ve pole (kVrms)	AC current +ve pole (Arms)	AC current -ve pole (Arms)
1. 2500 MW, transpositions	0.01	0.01	0.26	0.26
2. 2500 MW DC, blocking filters, transpositions	35	35	≈1	≈1
3. As 1, no transpositions	1.4	2.3	43.5	72.0
4. As 2, no transpositions	80.3	39.4	≈1	≈1

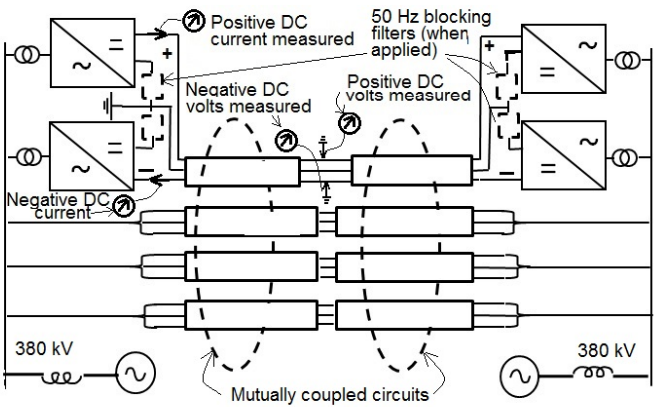

Fig.2: Equivalent circuit diagram of the hybrid transmission line showing where the DC volts and currents were measured as recorded in Table 1

A number of important conclusions can be drawn for the results of Table 1. The superimposed AC voltage on the DC pole conductors due to mutual coupling from the AC circuits when blocking filters are applied will require the DC voltage level to reduce. This will in turn reduce the power transfer capability of the DC circuit.

Transpositions of the AC circuits are the most effective solution to reducing adverse mutual coupling effects but are costly and inconvenient. Without transpositions or fundamental frequency blocking filters, DC line end reactors have some effect on reducing fundamental frequency current into the converter poles without significantly increasing the AC voltage coupled to the DC lines.

The analysis of the results recorded in Table 1 present the need to determine how MMC converters can protect the secondary windings of the VSC unit transformers from reverse rectified DC currents causing their saturation. A control concept has been proposed for line commutated converters (LCC) [5]. For this study detailed but generic full bridge MMC converter models (two in parallel at each end to reach the DC power capacity required) were developed. They were successfully adapted to prevent saturation in the unit transformers for the configuration of the hybrid AC-DC transmission line with no AC circuit transpositions and no series line reactors. So it may well be possible that the MMC converter can be designed to be relatively impervious to the fundamental frequency coupling to the DC circuits as this simulation study suggests.

IV. IMPACT OF HVAC FAULTS ON DC VOLTAGES

An important factor in the design of the conversion of the AC circuit to DC is the switching or transient surges the insulators may be exposed to. Unlike studying switching surges for AC lines, the equivalent switching surge level for insulator design is often guessed rather than studied and values between 1.5 per unit and 2.0 per unit of rated voltage may be applied.

The stability of a VSC transmission system is challenging in that it is non-linear and its optimum damping operation requires varying values for gains and time constants of some of the proportional – integral functions in the vector control as a function of load or state of operation. As a consequence, the response to an AC system fault near one of the terminating busbars can impact the overvoltage on the DC transmission through control performance. Although a significant effort was undertaken in optimizing the VSC transmission controls, they were challenging to adequately damp and minimize transient voltage surges due to nearby AC system faults. Multi-variable simplex optimizing was applied for the VSC controls to obtain acceptable performance for the VSC transmission.

The VSC equipment supplier will have to design around these problems to minimize DC line overvoltages due to AC system disturbances. The cases were run near full load on the AC circuits and the VSC transmission. The AC transmission lines on the same tower were not transposed.

The most severe DC line transient overvoltage occurred when an AC single phase to earth was applied on the 380 kV AC interconnection busbar at the receiving end (operating voltage was 400 kV). The maximum DC pole to earth line transient voltage occurred towards the centre of the hybrid transmission line and exceeded 2 per unit. This example had no surge arresters on the DC line and no line end reactors on each pole.

This severest case from an AC side fault was repeated with line end arresters whose DC MCOV was a minimum 424 kV. The simulated results of DC line pole voltages measured at four locations along the line are presented in Fig. 3. The fault was applied at 3.01 seconds cleared after 0.06 seconds at 3.07 seconds. The equivalent circuit for this fault simulation is shown in Fig, 4.

The maximum mid-line peak transient voltage was observed to be 1.76 pu on the positive pole. This compares with the 2.16 pu DC line voltage for the case run without line end surge arresters. Practically, the line surge arrester could have a higher DC MCOV such as 476 kV. This would of course lead to higher maximum transient voltages on the DC line unless the controls for the full bridge MMC converters can be designed to assist in reducing the maximum transient DC line voltage for this severe AC system fault. This is critical and possible if the minimum conductor to cross arm distance is to be equal to or less than 1.7 pu transient voltage.

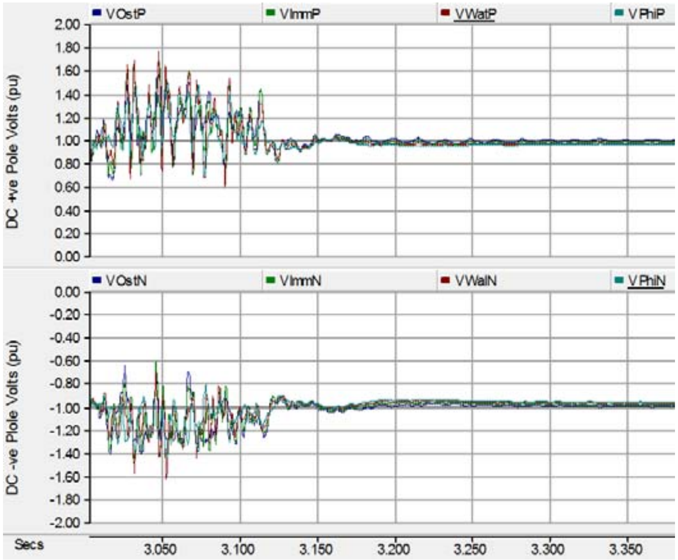

Fig. 3: A single phase to earth fault on the AC receiveing interconnecting 380 kV busbar cleared in 0.06 seconds and with DC line end surge arresters (operating voltage 400 kV)

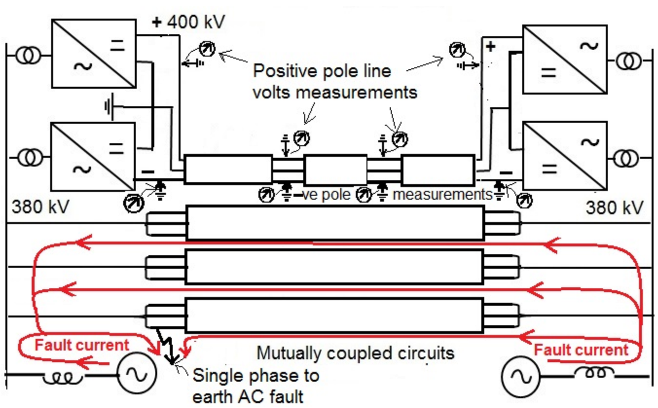

Fig. 4: The equivalent circuit diagram of the hybrid transmission line showing where the single phase to earth AC fault was applied, where the fault current flows and where the positive and negative pole voltages were measured for the results in Fig. 3

V. IMPACT OF DC LINE FAULTS

Various earth faults studied on a multi-circuit hybrid line indicate that DC line faults with bipolar configuration on the hybrid AC –DC transmission line are within 2.0 pu [1]. The full bridge configured MMC converters were applied to the DC circuit on this hybrid transmission line.

The full bridge configured MMC converter has the ability to limit the DC fault current for a pole to ground fault such as from lightning by forcing the DC side voltage at each converter on the faulted pole to zero or near zero volts. After the arc extinguishes and the time is allowed for the arc path to deionize, DC pole volts can be restored. This simulation of the full bridge converters and transmission system replicates the transient voltages that result.

Establishing clearances from conductor to tower and cross-arms are determined by switching surge type faults. On DC lines these are mainly caused by overvoltages due to an earth fault [6]. The impact of DC line faults for determining the minimum air clearances to cross arms were established for hybrid AC-DC lines.

The DC line to earth fault that created the highest transient over voltage was applied on a pole near the sending end. The full bridge MMC converter model was used and its DC side voltage on the faulted pole was reduced to zero volts at each end when the line fault was detected. This control action caused the fault arc to extinguish and a delay of a further 250 milliseconds at zero pole volts was maintained to allow the arc path to deionize. Then the DC voltage on that faulted pole is ramped back to its set level and the power order for that pole.

One control feature that was not applied was that with the un-faulted pole which had the highest transient overvoltage as seen in Fig. 5, its DC pole voltage could be temporarily lowered as well, perhaps by 20%. It remains to be seen whether this can be fast enough to prevent the peak transient over voltage on the un-faulted pole. Fig. 5 shows positive and negative pole voltages for measured at four locations along the hybrid AC-DC transmission line. Recovery of the faulted pole is not shown.

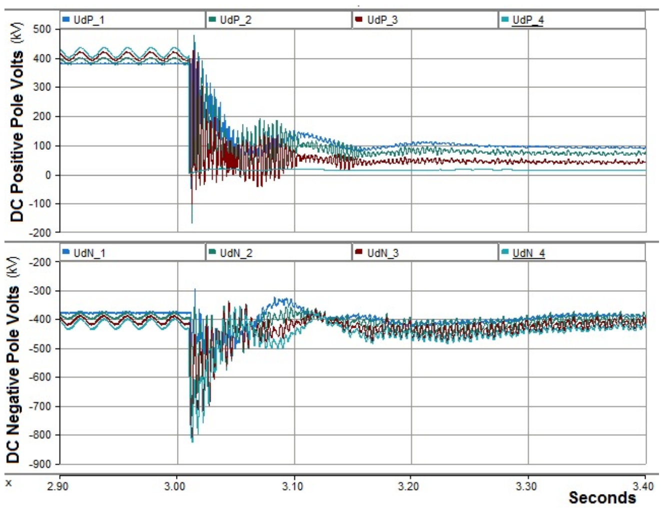

Fig. 5: Transient overvoltages on the DC circuit when a pole to earth fault occurs on one pole. Voltages measured at four locations along the hybrid line

The fundamental frequency component of common mode on both poles can be observed before the fault occurs at 3.1 seconds. The peak transient voltage on the un-faulted pole reached 1.95 per unit.

The equivalent circuit diagram for the DC line to earth fault of Fig. 5 is presented in Fig. 6. Also shown in Fig. 6 are the initial fault current paths before controls and protections act to reduce or eliminate them.

as to aid the initiation of the breakdown streamers across the insulator

6. The probability that the stroke current will exceed a certain amplitude and have a front less than a prescribed value (no two strokes are alike)

There are other probabilities such as the nature of the soil around the tower footings as a function of lightning current amplitude. The solution of the problems is simplified without highly sophisticated mathematics [7].

Lightning is usually of negative polarity so the frequency of back flashover frequency to the uppermost positive pole as in Fig. 1 would be expected to increase with conversion to DC. The frequency of lightning striking the tower and conductors is estimated by the procedure presented in [7]. Using this method knowing the tower height, and lightning strokes per year per square km, approximate results for the impact of lightning on the subject hybrid AC-DC transmission line were determined. The modelling factors that enabled the probabilistic included:

1. The lightning current impulse was approximated by the well-known two exponential functions
2. The probabilistic relationship between lightning crest value and front time was determined as per [8]
3. The probability relationship between lightning crest current, frontal rate of rise and time-to-crest of a lightning ramp function [8]
4. The surge impedance of the tower that was applied is in accordance with [9] with the wave propagation velocity down the tower at 85% the speed of light.
5. The travelling wave model of the tower of Fig. 1 as per [10]
6. The transient tower footing resistance applied from [10]
7. The model for insulator voltage withstand capability [10]

From these computations and simulations for lightning impact on this hybrid AC-DC transmission line under study, the following results were determined and summarized in Table 2.

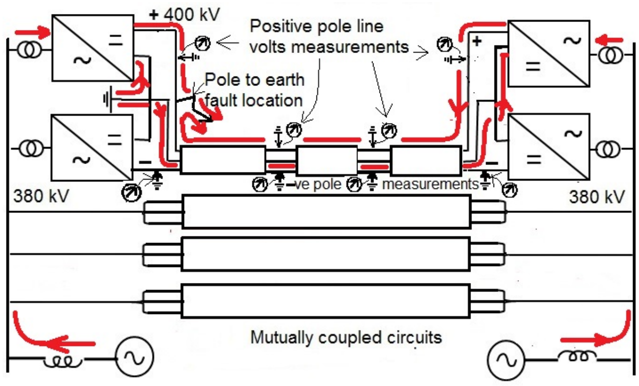

Fig. 6: The equivalent circuit diagram of the hybrid transmission line showing where the positive pole to earth DC fault was applied, where the fault current flows and where the positive and negative pole voltages were measured for the results in Fig. 5

VI. LIGHTNING FAULTS

The lightning design of a DC circuit involves similar criteria to those for an AC line. The magnitude of a current impulse representing a lightning discharge is a probability function. Low discharge levels between 5 to 20 kA may result in a higher tendency for the lightning strike to pass by any shield wires and directly hit a phase conductor. The larger lightning impulse currents may tend to strike the tower top and lead to a back flashover. This requires that the tower be modeled as a vertical distributed transmission line. The surge impedance of the tower and the propagation velocity down the tower are estimated and applied in a traveling wave line model.

A lightning stroke of 40 kA maximum direct to a phase conductor on a transmission line entering a substation is considered a severe condition. Transmission shielding failures tend to occur for low current levels in the lightning strike, in the range 10 kA to 20 kA.

A lightning stroke to a tower top at the station entrance that causes a back flashover is also a severe condition. In this case, a very severe condition is 150 kA. To accommodate multiple strikes, five strikes of around 80 kA each may be a worst case condition for surge arresters in order to absorb all the energy from the multiple strokes.

Lightning strike prediction as a statistical evaluation is based on random fluctuations. So if historical performance is not available or not to be used, then estimation is made based on some of the following probabilities:

1. The probability of a thunderstorm occurring over the line
2. The probability that a stroke will occur to the line from the thunderstorm
3. The probability that the stroke will contact a particular spot on the line
4. The probability that the tower in the vicinity of the stroke will have a certain footing resistance
5. The probability that the magnitude and polarity of voltage at the instant of the stroke contact will be such

TABLE 2
SUMMARY OF RESULTS OF LIGHTNING STUDY

Test	Result
Strokes per year per square km	3.6
Strokes to line/100km/year	110
Strokes hitting near or at towers/100km/year	59
% of strokes at or near tower causing back flashovers	7%
% of strokes to total line causing back flashovers	4%
Most severe maximum crest current of lightning (kA)	130
Time to crest for maximum crest current (μsec)	2.1
Maximum arc current to positive 400 kV conductor (kA)	28
Peak voltage on positive conductor with back flashover (kV)	-6273
Peak voltage on positive conductor at next tower (kV)	-5850
Peak voltage on tower top for most severe back flashover (kV)	-7818
Peak voltage on cross arm above positive conductor (kV)	-6750
Shield failure to positive conductor – flashover, conductor peak volts (kV)	-3236
Shield failure to positive conductor – maximum current crest (kA)	-14.2
Shield failure to positive conductor – time to crest for maximum current crest (μsec)	1.4

VII. INSULATION AND FIELD EFFECTS OF THE HYBRID DC CIRCUIT

Without knowing specific insulator test information, several points are clear regarding time dependency of overvoltages.

1. The withstand voltage of a DC insulator, in per unit of operating voltage will be highest for short duration overvoltages, e.g. lightning impulses, lower for longer term overvoltages, e.g. a standard 250x2,500 µseconds switching impulses, and ultimately equal to 1.0 for long term increases in voltage
2. The reduction in surge withstand will be reduced for conductors having a prior DC voltage of the same polarity as the impulse; a reduction that depends on insulator design. Withstand for the sum of pre-existing DC voltage and impulse voltage may drop rapidly as the pre-existing DC voltage increases [11]. Thus switching impulse tests are generally made with a switching impulse superposed on existing (positive) operating voltage
3. Long term upward excursions in operating voltage should be included in assessing the need for insulator creepage distance

Long-rod polymer insulators are under consideration for the 420 kV DC circuit on the hybrid AC-DC transmission towers, show silicone rubber long-rod units ranging in overall length from 3400 mm to 4100 mm with corresponding creepage distance from 14,710 mm to 14,810 mm. Using those insulators at 400 kV would result in specific creepage values ranging from 27.0 V/mm to 27.2 V/mm. Test programs have shown that the pollution withstand capability of long-rod insulators comprised of hydrophobicity transfer materials (HTM) is superior to disc insulators of the same creepage distance [12]. Thus the insulators proposed for the 380 kV AC to 420 kV DC conversion project are clearly suited for application on a medium contamination classification right-of-way.

The authors are unaware of any experiments on the degradation of pollution withstand when polluted insulators are subject to a constant DC voltage on which is superimposed a 50 Hz AC component. Polluted break down on DC insulators differs from AC insulators in that the partial arc segments tend to be more continuous than with AC. On that basis it is conservative to assume that the specific creepage distance needed for a DC voltage on which is superimposed an AC wave, should be the crest of the combined waveforms. The resulting reduction in specific creepage of the insulators selected (27.2 V/mm) hopefully can be minimized on this hybrid AC-DCc transmission circuit by judicious application of full bridge MMC converters. Any remaining AC component e.g. several percent of the DC level, would not be likely to degrade performance of the proposed insulators significantly.

With conductor-to-tower clearances remaining approximately the same when the AC circuit is converted to DC, we assume that:

(a) The required gap is proportional to the product of crest operating voltage and a surge factor and

(b) That a surge factor for which the AC was designed was 2.3 as cited in [1], then for 400 kV DC operation, the surge factor corresponding to maximum AC operating voltage experience of 420 kV would derive from the equation:

$$420x\sqrt{2/3}\,x2.3 = 400\ x\ SS_{dc}$$

SS_{dc} = 2.0 where SS_{dc} is the maximum DC overvoltage factor up to which one could expect at least as good DC overvoltage protection from air gaps as was seen with AC.

If it is possible to not have a significant AC voltage component in the DC voltage, and assuming a medium pollution environment, and a DC switching surge level that can be kept below 2.0 pu, the hybrid AC-DC transmission line appears limited in DC voltage primarily by pollution considerations.

Field and corona effects from the DC circuit of a similar hybrid AC-DC transmission were evaluated in [1]. From this study, the DC conductor gradient was determined to be 24.7 kV/cm for 400 kV operation. In a separate study for this project EPRI's TL Workstation was used to confirm that values of conductor gradient, audible noise, and ground-level field effects were within normally accepted bounds. The results, using a bundle of four AL/ST 240/40 conductors with 400 mm bundle spacing showed a negative pole gradient of 26.2 kV/cm and a positive pole gradient of 25.2 kV/cm. The latter is below the generally accepted maximum of 26 kV/cm for the positive pole based on experienced with the Nelson River 450 kV line where anomalous flashovers are tentatively associated with negative pole gradients above that level.

Ground level electric DC field effects were found to be quite low in [1] and also from the TL Workstation results. This is due to the shielding provided by the AC circuit located beneath the DC circuit (see Fig. 1).

For the above configuration of AC and DC circuits, the TLW workstation showed an audible noise level in dry weather 30 meters from the centre of the right of way equal to 32 dBA. Many US utilities set 40 dBA as their benchmark. Audible noise from DC is greatest during dry weather whereas for AC it is greatest when the conductors are wet. The latter level for the hybrid AC-DC line was 45 dBA in wet weather.

VIII. CONCLUSIONS

The results of the investigations performed have indicated the switching overvoltages stress as the most onerous for the electrical design of the transmission line, requiring special protection measures or design adaptation. Further work is required to confirm that a suitably controlled and designed MMC converter will reduce the impact of fundamental frequency coupling from adjacent AC circuits, and to participate in limiting transient overvoltages due to DC line faults.

It was estimated that for the isokeraunic level of 30, there would be 110 lightning strokes per 100 km/year to the line of which 4% would cause a back flashover. For the line length of 348 km, the expected lightning failures over the full length of the line may be 15 per year.

This study determined the design and operational issues that attention must be paid to in converting one circuit to DC of a four circuit line where all four circuits were originally AC. Careful design will continue to realize this project and advanced simulation models of the converter, their controls and the transmission lines are essential for finalizing the design of a hybrid AC-DC transmission line.

IX. Acknowledgment

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