

Evaluation of coupling between dc and ac transmission lines on the same right-of-way: Parametric analysis and mitigation methods

Jingxuan (Joanne) Hu
RBJ Engineering Corp.
Winnipeg, MB, Canada
j.hu@rbjengineering.com

Bruno Bisewski
RBJ Engineering Corp.
Winnipeg, MB, Canada
b.bisewski@rbjengineering.com

Abstract:

This paper describes a study carried out to investigate the level of induced fundamental frequency ac voltage and ac current in the 500 kV dc line due to coupling from 275 kV and 500 kV ac lines that run in parallel to the dc line. A set of systematic parametric analyses were simulated so that guidelines for planning and siting of parallel ac/dc lines could be developed. Mitigative measures that could be applied to limit the impact of fundamental frequency coupling on the dc equipment were also explored.

Keywords: Right-of-way, ac/dc coupling, induced voltage, dc current, separation distance, transposition, blocking filter.

I. INTRODUCTION

When ac and dc lines are in close proximity or on the same right of way, voltage and current can be induced on either ac or dc lines for both steady and transient conditions. The phenomenon is generally referred as ac/dc coupling and it has been investigated and discussed by many engineers/researchers [1][2][3] [4][5][6][7].

Steady state coupling includes both inductive and capacitive coupling between the parallel ac/dc lines: a fundamental frequency component superimposed on the dc current in the dc line, and a dc component induced to the disconnected ac lines.

Ac/dc coupling can also occur during transient conditions such as faults and line energization. The ac current induced in the dc line during transient events such as ac line faults can be several times higher than the steady state value but would be of short duration and would subside quickly after fault clearing. Similarly faults and transient events on the dc system can induce transient dc currents into the parallel ac circuits. This could adversely impact the ac line protections if the dc current is large enough to saturate the CTs.

On a recent project, a number of 275 kV lines and 500 kV ac lines were planned to be constructed in parallel with proposed 500 kV HVdc transmission line. This paper describes an investigation of the steady state fundamental frequency component induced on 500 kV dc from the parallel 275 kV and 500 kV ac lines.

The major issues associated with the fundamental frequency current in the dc circuit are:

- Possible core instability in the converter transformers due to dc offset. The fundamental frequency component would be seen as a dc current and second harmonic current on the line side of the converter transformers. The dc current component would cause an offset in the converter transformer flux and cause core to saturate in one direction over a period of time. This saturation would inject a series of even harmonics into both the ac and dc sides and can affect overall system performance. Thus, it is of most concern to the operation of the dc converters
- Heating within the converter transformers due to leakage flux
- Loss of life of the converter transformers associated with deterioration of interlamination insulation due to the increased magnetostrictive forces
- Increased converter transformer audible noise due to greatly increased magnetostriction of the saturated core.
- Saturation of current transformers (CT) used for dc control and protection. Ac current transformers can also be affected during dc system disturbances.
- Increased harmonic generation by the converters that must be considered in the ac and dc filter design.

The level of the coupling between the ac lines and the dc lines is affected by the following factors:

- Separation distance between dc and ac lines
- Power transfer level on the ac lines
- Unbalance of the ac transmission lines (transposition scheme of the lines)
- Length of coupled line section(s)
- Soil resistivity along the line ROW
- Converter operating conditions such as firing angle
- dc control system response at fundamental frequency

While the above factors affect the ac fundamental voltage induced in the dc line, the fundamental current is a function of:

- the overall dc circuit impedance
- converter transformer impedance
- impedance of the ac system seen from the ac side of the converter including the ac filters

II. CRITERIA FOR ACCEPTABLE LEVELS OF AC CURRENT IN THE DC CIRCUIT

The magnitude of fundamental frequency current in the dc lines under steady state conditions will be used to judge whether the level of coupling from the ac line to the dc line conductors will be likely to cause any observable adverse impact. It is considered that the dc system performance would not be affected if the induced fundamental frequency current on the dc side is less than 0.1% of the rated dc current [1].

III. METHODOLOGY

The study was carried out using the PSCAD/EMTDC time-domain simulation program. The level of steady state ac voltage induced on the dc line and the corresponding ac currents in the dc pole conductors were determined directly using the program with two system models, a simplified model and a detailed model. The simplified model does not include the adjacent ac system at converter station, dc controls and converter transformers and it was used for the sensitivity studies. The detailed model was simulated to verify the results from simplified model and also to investigate the mitigations.

Both the simple and detailed models provide detailed modelling of the coupling between 500 kV dc overhead lines and 275 kV and 500 kV ac overhead lines as shown in Figure 1.

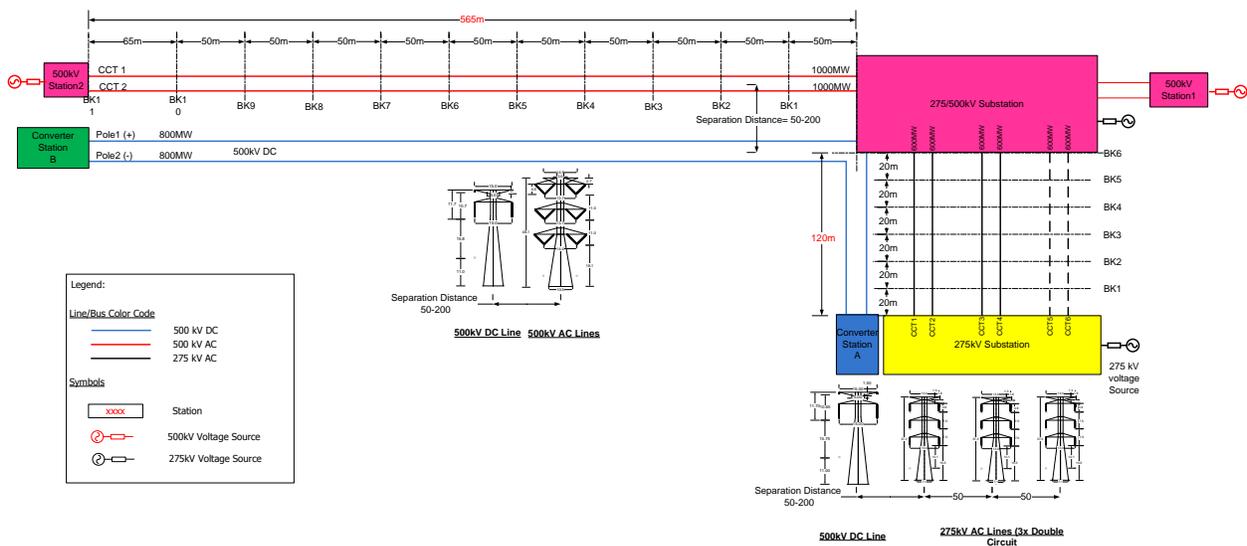


Figure 1 Single Line Diagram Showing the Orientation of DC and AC Lines

The PSCAD model was set up to allow the modelling of a variable length of dc line coupled with the 275 kV and 500 kV ac lines to cover possible changes of the lengths of coupled lines. The 275 kV ac lines together with 500 kV dc lines were divided into six 20 km segments so the coupled line length could be varied from 20 km to 120 km in steps of 20 km. Similarly, the 500 kV ac lines were broken into eleven segments with the first ten sections having the equal length of 50 km and last section of 65 km, which provides a total of 565 km.

A parametric approach was taken to investigate the impact of main variable affecting the ac/dc coupling so that the study results and guidelines provided could be applied to any possible future system configuration.

IV. RESULTS

1) Sensitivity Studies using Simplified Model

a). *Effect of Coupled Line Length, Transfer Power on AC Lines and AC Line Operating Voltage*

A first set of sensitivity studies was carried out to explore the impact of different system configurations such as coupled line length of 275 kV and 500 kV ac lines, coupling from 275 kV lines only, coupling from 500 kV line(s) only, and coupling from both 275 kV and 500 kV lines. The induced fundamental frequency voltage and corresponding current on 500 kV dc lines were calculated for the following conditions:

- The separation distance between dc and ac lines was assumed to be 50 m (most conservative assumption)
- The ground resistivity was assumed to be 5000 ohm*m. (higher resistivity results in higher coupling)
- No line transpositions were modelled on either the 275 kV or 500 kV lines.
- The impact of the dc converter station impedances (converter transformers, smoothing reactors) and ac system are ignored.

Coupling from 275 kV AC Lines Only

The induced 50 Hz currents on the 500 kV dc line conductors from the 275 kV ac lines only are shown in Figure 2. There are two variables in this figure, length of the coupled lines and the number of 275 kV ac lines. The induced currents on the both Pole 1 and Pole 2 conductors at Converter Stations A and B are shown.

The results can be summarized as follows:

- The induced 50 Hz current (I_{50}) is a linear function of the coupled line length. The longer the coupled line length, the higher the induced current.
- The induced current is higher on Pole 1 than Pole 2 as Pole 1 is closer to 275 kV ac lines
- The highest induced current is 4.64 A with one 275 kV twin circuit energized, and 5.78 A with two double circuit 275 kV circuits energized. The second double circuit, which was 50 m further away, would cause only a 25% increase to the 50 Hz induced current in the dc conductors.
- The induced voltages in the dc poles corresponding to the highest induced currents are 1.28 kV and 1.69 kV, respectively.

Coupling from 500 kV ac Lines Only

The coupling effect due to 500 kV ac lines only are plotted in Figure 3 as a function of coupled line length and number of 500 kV lines. The main observations are:

- The induced 50 Hz current (I_{50}) varies proportionally to the coupled line length. The longer the coupled line length, the higher the induced current.
- Higher 50 Hz currents would be induced into the Pole 1 conductor, which was closer to ac lines.
- If only one 500 kV circuit was energized, the highest induced current would be 17.53 A. With the second circuit energized, about 70% more current would be induced into the dc lines, which results in a total of 29.77 A.
- The induced voltages in the dc pole conductors corresponding to the highest induced currents are 6.55 kV and 11.34 kV, respectively.

Coupling from both 275 kV and 500 kV ac Lines

- If both 275 kV (120 km) and 500 kV (565 km) ac lines are energized, the coupling from 500 kV line(s) dominates the total coupling effect as the coupled line length is longer, the power transfer is larger and degree of unbalance is larger due to the greater conductor spacings. When all the 275 kV and 500 kV lines are energized with maximum power transfer, the induced current in the dc line poles could be as high as 36.53 A which corresponds to an induced voltage of about 13 kV.

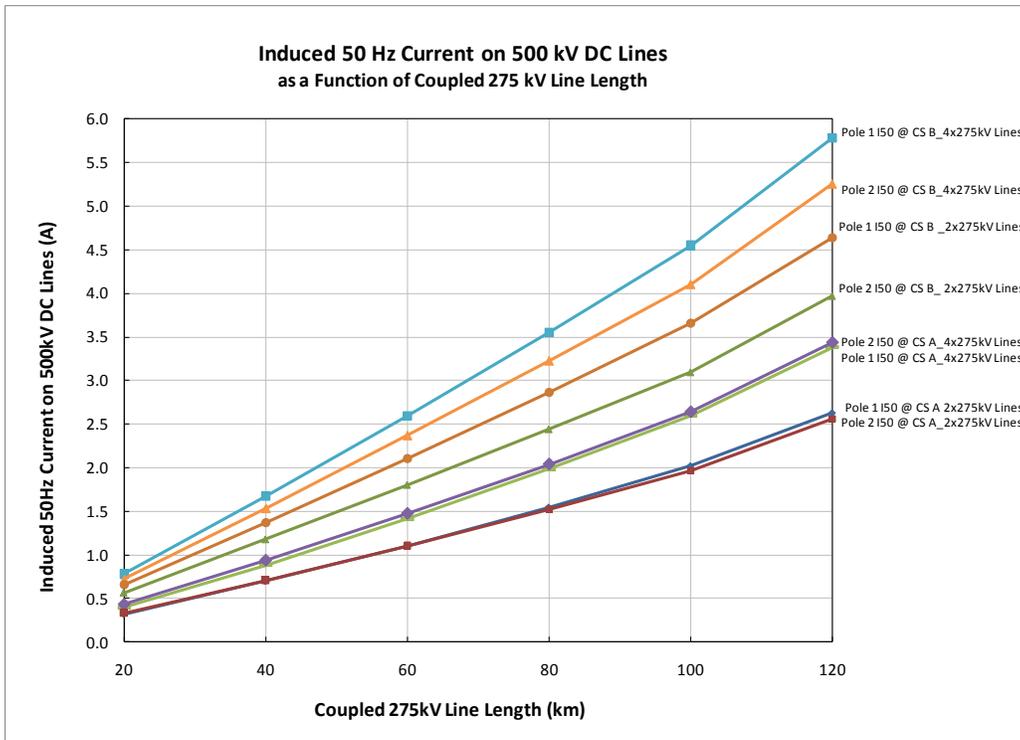


Figure 2 Effect of Coupled 275 kV Line Length and Number of Lines on Induced 50 Hz Current

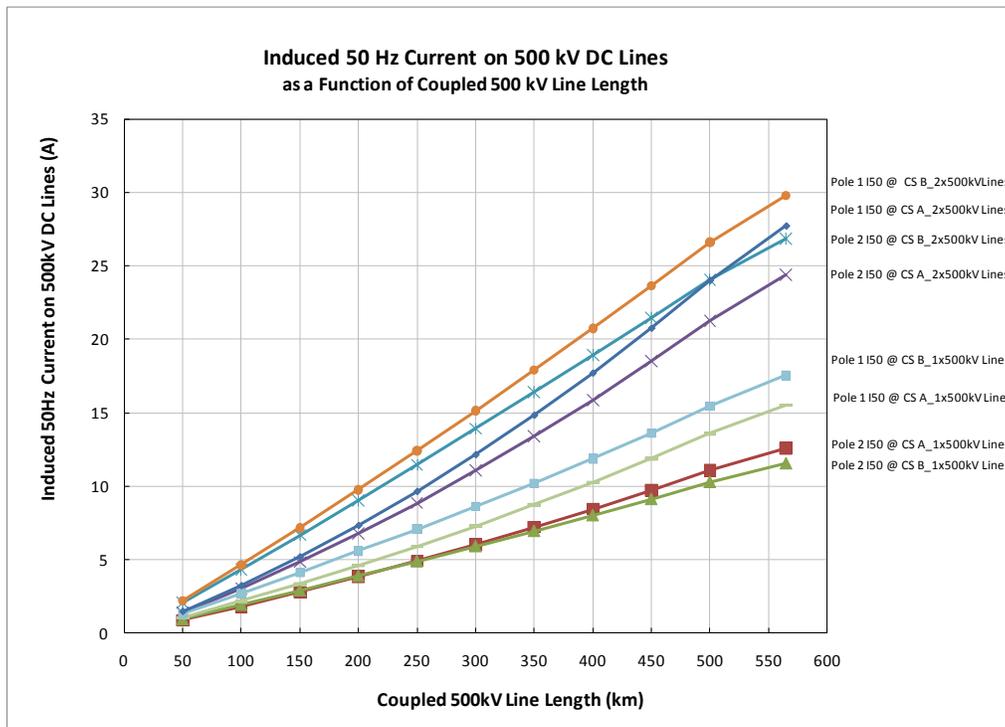
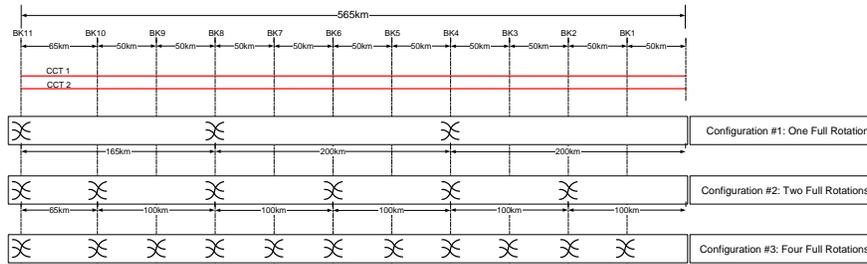


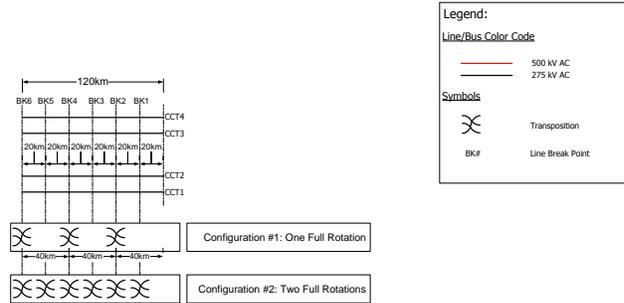
Figure 3 Effect of Coupled 500 kV Line Length and Number of Lines on Induced 50 Hz Current

b). *Effect of Line Transpositions*

The effect of line transpositions on reducing the induced fundamental frequency current on dc lines was investigated for the worst-case scenario as identified in Section a). Figure 4 demonstrates two transposition configurations studied for 275 kV ac lines and three transposition configurations for the 500 kV ac lines.



(a) 500 kV AC Lines Transposition Configuration



(b) 275 kV AC Lines Transposition Configuration

Figure 4 Transposition Configurations Studied for 500 kV and 275 kV AC Lines

This sensitivity study was carried out with the following assumptions:

- The separation distance between dc and the nearest ac lines was assumed to be 50 m
- The ground resistivity was assumed to be 5000 ohm*m.
- If a location was chosen to transpose the lines, all the energized lines on the same right of way (except the dc line) were transposed at the same location.

Figure 5 and Figure 6 demonstrate the calculated induced fundamental frequency currents and corresponding induced voltages as a function of different transposition configurations on both 275 kV and 500 kV lines. Twelve configurations were studied including the repeat of the worst-case scenario without any transpositions on either of the 275 kV or 500 kV ac lines. The major observations can be summarized as follows:

- Transpositions of ac lines are effective at reducing the induced currents and voltages on the dc line conductors. One or two full rotations of the energized 275 kV lines could reduce induced current on the dc lines by about 4 A. One full rotation of 500 kV ac lines could cause a significant reduction of 26 A induced current. Additional transpositions on the 500 kV ac line (two or more full rotations) would only slightly decrease (1 or 2 A) the induced current in the dc line.
- The combination of transpositions on both 275 kV and 500 kV lines would provide most favourable results in terms of reducing the induced current and voltage. If the 275 kV ac lines are transposed with one full rotation and the 500 kV ac lines are transposed with two full rotations, the induced current would be decreased to about 4.25 A. Adding another two full rotations to both 275 kV and 500 kV ac lines would further reduce the induced 50 Hz current to about 3 A.
- Transpositions of both the 275 kV and 500 kV ac lines would effectively reduce the induced 50 Hz voltage on dc lines. The induced voltage was decreased from 13 kV to less than 2 kV when at least one full rotation was applied to both of 275 kV and 500 kV lines

Induced 50Hz Current on 500kV DC Lines
as a Function of Different Line Transposition Configurations on Coupled 275kV and 500kV Lines
50m Separation Distance

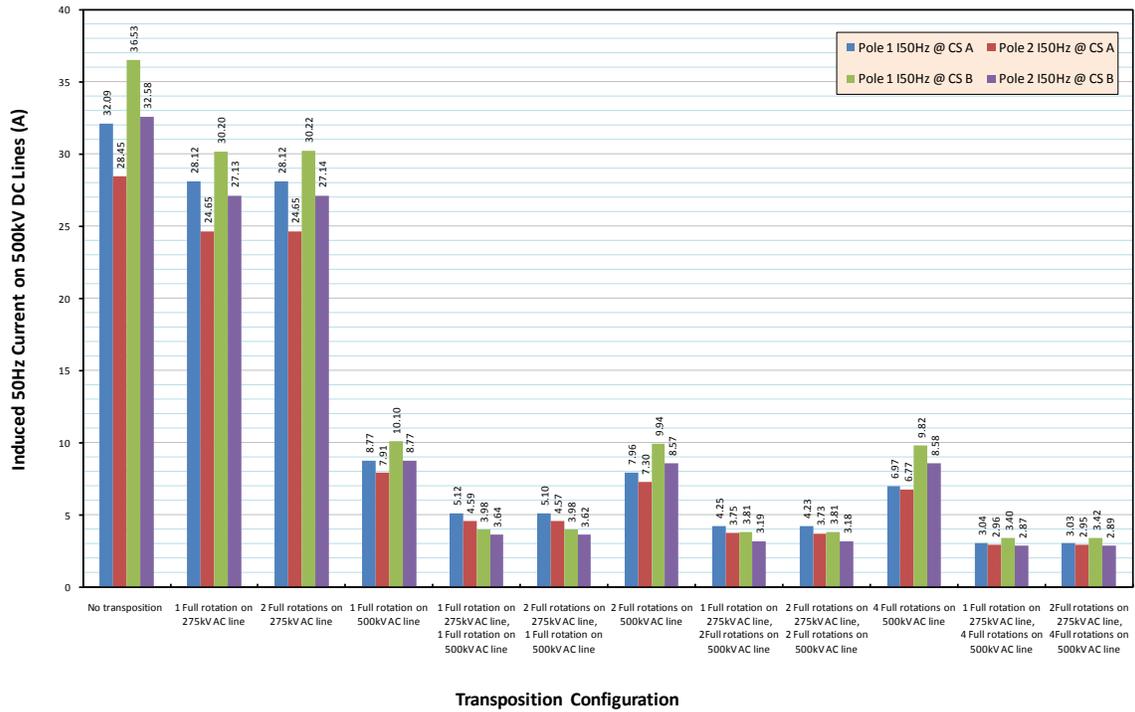


Figure 5- Effect of Transposition Configurations on Induced 50 Hz Current on 500 kV DC Line

Induced 50Hz Voltage on 500kV DC Lines
as a Function of Different Transposition Configurations on Coupled 275kV and 500kV Lines
50m Separation Distance

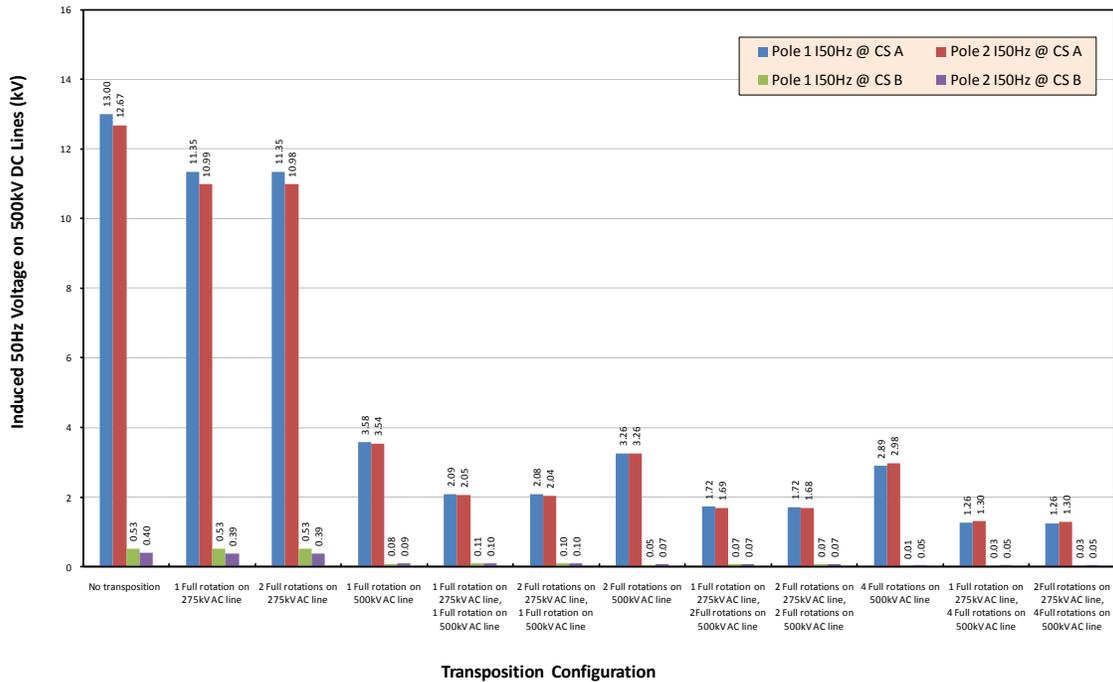


Figure 6- Effect of Transposition Configurations on Induced 50 Hz Voltage on 500 kV DC Line

c). *Effect of Varying the Separation Distance between AC and DC Lines*

The effect of the varying the separation distance between ac and dc lines on the induced fundamental frequency current and voltages in the dc line is shown in Figure 7 and Figure 8. The induced currents and voltages on both Pole 1 and Pole 2 were calculated at 50 m, 100 m, 150 m and 200 m separation distance for different transposition configurations.

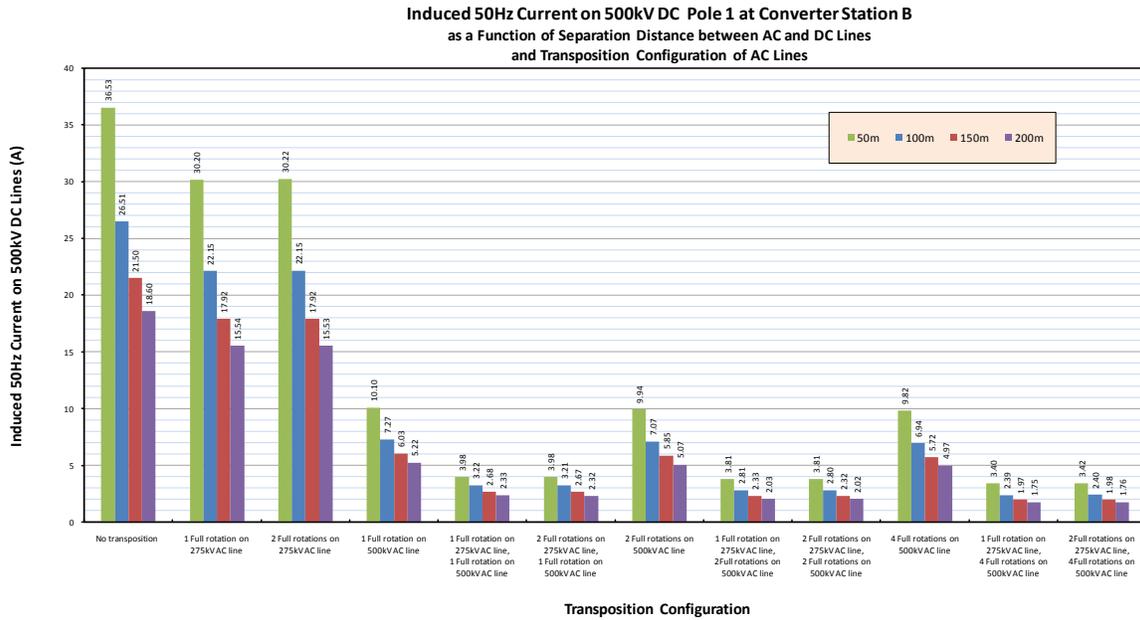


Figure 7- Effect of Separation Distance on Induced 50 Hz Current on 500 kV DC Line

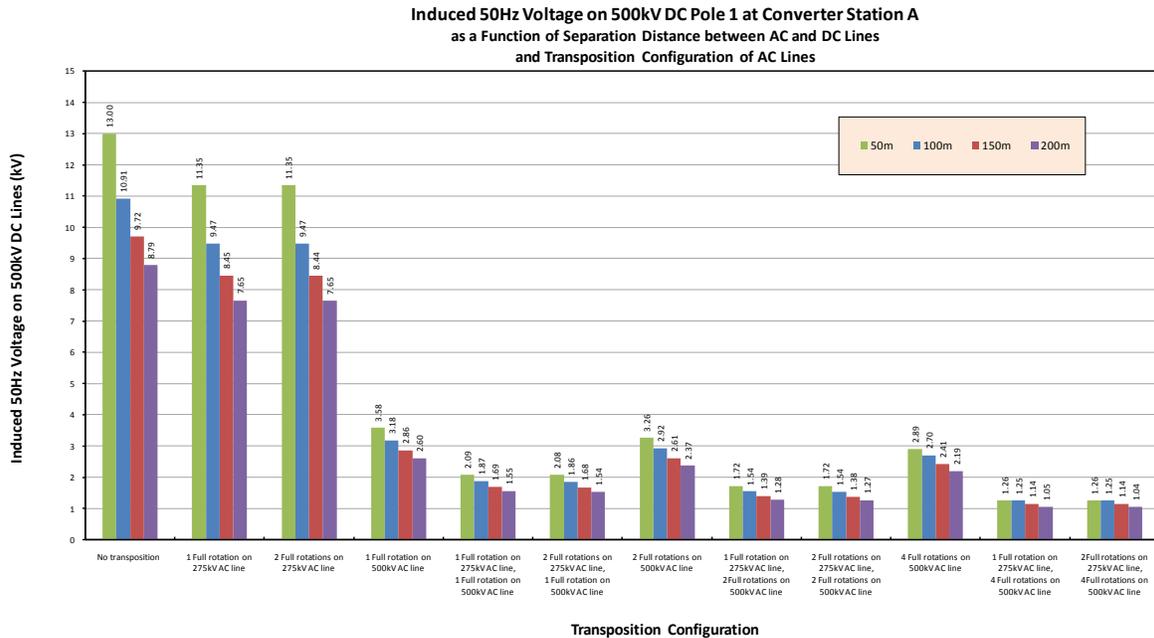


Figure 8- Effect of Separation Distance on Induced 50 Hz Voltage on 500 kV DC Line

The results can be briefly summarized as follows:

- Both the induced current and voltage on the dc conductors are inversely proportional to the separation distance between ac and dc lines. The larger the separation distance, the smaller the induced current and voltage.
- If neither of 275 kV nor 500 kV ac lines are transposed, the induced current under the worst scenario would be reduced to 73% of this figure if the separation distance was increased to 100 m, it would be further reduced to 59% and 50% if the separation distance were increased to 150 m and 200 m respectively.
- The induced current and voltage would also reduce with increased separation distance when the ac lines are transposed. If at least one full rotation is applied to both 275 kV and 500 kV ac lines, the induced current could be decreased to be below 3.2 A (about 0.2% of the rated dc current of 1600 A) when the separation distance is larger than 100 m.

It is noted however, that the magnitude of the reduction of induced current and voltage decreases as the separation distance increases. Separation distance becomes less and less effective in reducing the induced voltage and current level after certain distance. Large separation distances would be required to achieve acceptable levels of coupled voltages and currents if no other measures such as line transpositions are applied.

d). *Effect of Shunt and Series Compensation on 500 kV AC Lines*

The effect of shunt and series compensation on 500 kV ac lines was also investigated with three compensation schemes:

Scheme 1: Both 565 km lines were 45% shunt compensated and 35% series compensated at each end of the line.

Scheme 2: Both 565 km lines were 45% shunt compensated at each end of the line and 70% series compensated 250 km from the converter station.

Scheme 3: Both 565 km lines were broken into two sections, 250 km and 315 km. Each section of the line was 45% shunt compensated and 35% series compensated at each end of the line sections.

Table 1 summarizes the induced 50 Hz currents on dc lines for the above compensation schemes.

Table 1 - Effect of Shunt/Series Compensation on 500 kV AC Lines		
Scheme	Induced 50 Hz Current on DC Lines (A)	
	CS A.	CS B
	Pole 1	
Scheme 1	31.54	37.74
Scheme 2	31.12	38.00
Scheme 3	32.99	38.75
w/o Comp.	32.09	36.53
	Pole 2	
Scheme 1	29.26	33.64
Scheme 2	29.3	33.96
Scheme 3	30.7	34.65
w/o Comp.	28.45	32.58

The shunt and series compensation on 500 kV ac lines could increase the induced 50 Hz current in the dc line slightly if the lines were not transposed. The induced current on Pole 1 increased about 6% in the worst case (Scheme 3).

2) AC/DC Coupling Effect Studied with Detailed Model

a). *Verification and Comparison with Selected Cases from the Simplified Model*

For the detailed system model, the induced currents and voltages were calculated with/without 500 kV ac line shunt/series compensated (Scheme 3, worst case), for all the combinations of 275 kV and 500 kV ac line transposition schemes.

The results summarized in Table 2 indicate that:

- Induced 50 Hz currents calculated with detailed system model were smaller compared to those from the simplified system model. This was due to additional dc circuit impedance in the detailed model from the smoothing reactor and converter transformers.

- If 500 kV ac lines were not transposed, the induced current would be slightly higher when they were shunt/series compensated. However, when the lines are transposed the induced current is not affected by the 500 kV series and shunt compensation.
- The induced voltage measured at the converter stations in the detailed system model is much lower than in the simplified system as a path to ground was provided through smoothing reactor, valves and converter transformer and electrode lines in the detailed model and the voltage was divided between the overhead lines and these impedances.
- The magnitude or the reduction of the induced currents calculated with the detailed system depends on the impedances of the smoothing reactor and converter transformer and the electrode lines.

Table 2 - Comparison of Results from Simplified and Detailed System

System Model Configuration	Induced Current (A)	Induced Voltage (kV)
w/o ac line transposition		
Simplified System (500 kV ac lines not Compensated)	32.09	13.00
Detailed System (500 kV ac lines not Compensated)	25.34	2.58
Detailed System (500 kV ac lines Shunt/Series Compensated, Scheme 3)	26.55	2.71
with ac line transposition (1 full rotation on 275 kV lines and 2 full rotation on 500 kV lines)		
Simplified System (500 kV ac lines not Compensated)	4.25	1.72
Detailed System (500 kV ac lines not Compensated)	3.55	0.37
Detailed System (500 kV ac lines Shunt/Series Compensated, Scheme 3)	3.54	0.37

b). Improved Performance with 50Hz Blocking Filter

The effect of 50 Hz blocking filter on the induced 50 Hz current in the dc lines was investigated by adding a simple parallel LC filter tuned to 50 Hz to the neutral of each pole as shown Figure 9. The characteristic of the filter is determined by the values of inductor, resistance (quality factor) and capacitor.

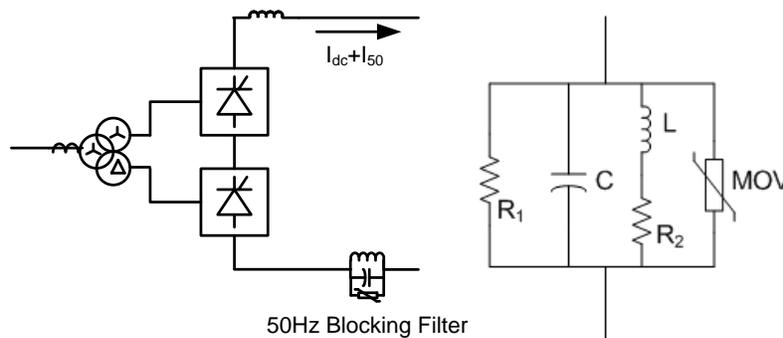


Figure 9 – Location of Blocking Filter in Pole Neutral bus

The calculated induced 50 Hz current and voltages on Pole 1 at Converter Station A are shown in Table 3 assuming an infinite quality factor in the blocking filter.

Table 3 Effect of 50 Hz Blocking Filter

Detailed System , 500 kV ac lines Shunt/Series Compensated (Scheme 3)

System Model Configuration	Induced Current (A)	Induced Voltage (kV)
w/o ac line transposition		
Without Filter	26.55	2.71
With Filter	5.79	13.88
Current Reduction (%)	78	

with ac line transposition		
(1 full rotation on 275 kV lines and 2 full rotations on 500 kV lines)		
Without Filter	3.54	0.37
With Filter	0.81	1.97
Current Reduction (%)	77	

The effect of 50 Hz blocking filters can be summarized as follows:

- 50 Hz blocking filter could effectively reduce the induced current. A reduction of about 77% was observed regardless of whether transpositions were applied on the ac lines.
- If the ac lines were not transposed, the blocking filter could bring the induced current from 26.55 A down to 5.79 A.
- If a blocking filter is combined with 500 kV ac line transpositions (two full rotations), the induced current would be less than 0.1% rated dc current thus meeting the selected performance criterion.
- If a more typical value of Q of 125 is considered for the blocking filter, the induced 50 Hz current would be higher than with infinite Q and the measured current increases to about 1.5 A compared with 0.81 A with infinite Q for the case with ac line transpositions noted in Table 3.

V. SUMMARY AND CONCLUSIONS

A systematic study has been carried out to investigate the ac/dc coupling issues for parallel ac and dc lines. The effects of the variables that affect coupling have been explored using a simplified system model and were compared against results determined for a detailed system model. The study results can be summarized as follows:

- The induced fundamental frequency current is proportional to the coupled line length. The longer the coupled line length, the higher the induced current.
- The induced current is higher on the dc pole conductor closer to AC lines
- The magnitude of induced fundamental frequency is a function of power transfer level on parallel ac lines. The higher the power transfer on AC lines, the higher induced current on DC lines.
- Transpositions of ac lines can effectively reduce the induced current and voltage.
- The induced fundamental current and voltage on the dc pole conductors are inversely proportional to the separation distance. The larger the separation distance, the smaller the induced currents and voltages.
- The induced currents and voltages are not very sensitive to the soil resistivity as the mutual impedances between ac and dc lines are almost the same for both conditions (100 Ohm-m and 5000 Ohm-m) of soil resistivity considered.
- Shunt and series compensation on 500 kV ac lines could increase the induced current slightly if the ac lines were not transposed.
- Induced 50 Hz currents calculated with detailed system model were smaller compared to a simplified system model. This was due to additional impedance from the smoothing reactor and converter transformers.
- The amount of reduction of the induced currents calculated with the detailed system depends on the size of the smoothing reactor and converter transformer and the length of electrode lines.
- 50 Hz blocking filter would effectively reduce the induced current. A 77% reduction was observed regardless of the transposition configuration the ac lines.
- The use firing angle modulation to directly eliminate the dc current in converter transformer has been demonstrated by others [8]. However, this could produce significant levels of some non-characteristic harmonics.

The study results show that the induced 50 Hz current from coupled ac lines can be eliminated by three mitigation methods:

Method 1: AC Line Transposition combined with Increased Separation Distance between ac and dc lines

Method 2: Use of 50 Hz blocking filters in the neutral connection of each pole

Method 3: DC control using firing angle modulation

Table 4 summarizes and compares all the studied mitigation methods giving pros and cons of each method.

Optimizing of AC line transpositions and increasing separation distance between ac and dc lines is the preferred method for mitigating the induced fundamental frequency current on dc lines due to nearby parallel ac lines.

Although this is higher than the selected criteria of 0.1% it may be acceptable given that some existing HVDC transmission systems would allow dc currents in the converter transformer in the order of 10-15 A dc. According to Reference [1] the relationship between I_{50} and the dc current in the converter transformer is $I_{dc} \cong 0.55 \cdot I_{50crest}$. Thus, 10 A crest of fundamental frequency current would result in about 5.5 A maximum value of dc current in the converter transformer.

Values of I_{50} as high as 0.2% of rated current may be acceptable provided they do not result in core instability or leakage flux heating issues. The simulation results did not show any core instability issues in the modelled system under the worst case scenario with about 26 A induced 50 Hz current on dc lines and 17 A (Highest among three phases) dc current in converter transformer secondary side winding. Leakage flux issues would need to be considered by the converter transformer designer.

If it is required to reduce the separation between the dc line and the nearest ac line to less than 100 m then it is considered that a 50 Hz blocking filter would be required. If the separation distance is less than 100m, the blocking filter should always be applied together with optimized ac line transpositions to ensure that the induced current will be limited to less than the selected criteria.

Table 4 Comparison of Mitigation Methods

Mitigation Method	Pros	Cons
AC Line Transposition Combined with Increased Separation Distance	If neither the 275 kV nor 500 kV ac lines are transposed, the induced current under the worst scenario was reduced to 73% if the separation distance was increased from 50 m to 100 m. It could be further reduced to 59% and 50% if the separation distance were increased to 150 m and 200 m respectively. If at least one full rotation of transpositions was applied to both the 275 kV and 500 kV ac lines, the induced 50 Hz current could be decreased to be below 3.2 A (about 0.2% of the rated dc current of 1600 A) when the separation distance is larger than 100 m.	Increasing separation distance and adding line transpositions cannot eliminate the induced current and voltage. The magnitude of the reduction of induced current and voltage decreases as the separation distance increases. Separation distance becomes less and less effective in reducing the induced level after a certain distance. A significant separation distance would be required to achieve an acceptable coupling level if no other countermeasures were taken such as ac line transpositions are applied. For large separation distances, the ac and dc lines would not be sharing the same right of way and two separate ROWs would be needed.
50 Hz Blocking Filter	Blocking filters are very effective in reducing the induced 50 Hz current. A 77% reduction was observed regardless of the transposition configuration of coupled ac lines. If blocking filters are combined with 500 kV ac line transpositions (two full rotations), the induced current could be less than 0.1% rated dc current (desired level).	Blocking filters can sometimes result in increased dc side overvoltages and the induced 50 Hz voltage would still exist at dc line terminal. The cost of the blocking filter equipment and the associated losses needs to be considered when comparing solutions.
Firing angle modulation [8]	The dc current in converter transformer can be directly eliminated. The control can be simultaneously applied at all terminals of a dc system without controller conflicts Cost would be lower compared to 50 Hz blocking Filters.	It introduces non-characteristic harmonics. The magnitude of some of these harmonics can be significant enough to require changes to the ac filter and possibly dc filter design. The 50 Hz voltage on the dc circuit is not eliminated.

VI. PLANNING OF PARALLEL AC/DC LINES

Although this study was carried out for a particular set of ac/dc line parallel configurations, the parametric presentation of the study results makes them applicable for similar ac/dc line exposures and thus provides useful guidance for future planning of ac and dc lines sharing the same right-of-way. The studies showed the following:

- AC transmission lines should preferably be transposed if running parallel with dc lines. Depending on the configuration, the transpositions would need to be designed to minimize the coupling of fundamental frequency current into the dc line rather than based on normal transpositions that are aimed at balancing the impedances of the three phases of the ac line.
- If optimized transpositions are applied, reasonably small separation distances between ac and dc lines down to about 100 m could be achieved without applying additional mitigation on the dc system to limit fundamental frequency effects due to coupling from the ac lines.
- If it is necessary to reduce the separation distance between the ac and dc line to below about 100 m then it is likely that additional mitigation would be required on the dc system depending on the coupled length and voltage and power transfer level on ac lines. Such mitigation could involve the use of fundamental frequency blocking filters or dc control modulation to directly limit the fundamental frequency current in

the dc line. Both methods would be feasible but the passive solution using fundamental frequency blocking filters if possible increased separation would normally be preferred since it is robust and does not introduce any non-characteristic harmonics.

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BIOGRAPHIES

Jingxuan Hu received her Bachelor's degree in Electrical Engineering in 1995 (China) and her Masters degree in Computer and Electrical engineering in 2001 (Canada). She has over sixteen years experience in high voltage technologies and power equipment; Power system stability and electromagnetic transient (EMTP) studies; SSR phenomena analysis and small signal stability studies; HVDC system control and modeling; Series and shunt compensations; Equipment design studies such as breaker TRV, line and transformer energization, live line maintenance.

She is a registered professional engineer in Manitoba (APEGM), and a senior member of IEEE. She is the Convenor of CIGRE WG B4.61-General Guidelines for HVDC Electrode Design. She is also a working group member of IEEE switchgear HVCB subcommittee and CIGRE B4.51- Study of Converter Voltage Transients Imposed on the HVDC converter transformers and A3.26- Influence of shunt capacitor banks on circuit breaker fault interruption duties.

Bruno Bisewski received B.Sc. (Eng.) degree in electrical engineering from the University of Manitoba, Canada in 1975. He is a specialist with over 35 years of experience in all aspects of the electrical power transmission industry including project management, system studies, specification and design, calculation of electrical effects, design review, cost estimates, equipment testing and commissioning of EHV ac and HVDC transmission systems.

He is a registered professional engineer in Manitoba (APEGM), and a PE in the states of Arizona, Vermont, Minnesota and Wisconsin (USA).