

COUPLING BETWEEN DC LINES WITH A NEUTRAL CONDUCTOR AND PARALLEL AC LINES

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Keywords: HVDC, AC/DC line coupling, neutral conductor, PSCAD/EMTDC.

Abstract

HVDC lines may have use the same right of way as ac lines. This paper discusses the general study methodology that can be used to investigate any coupling between dc and ac transmission lines that share the same right-of-way. The capacitive coupling and the inductive coupling between a dc line with a long neutral conductor and an ac transmission system running parallel to it were investigated. A digital simulation model of the coupling phenomenon was developed to model the induced fundamental frequency voltage on the dc line and the neutral conductor. The induced dc current in the converter transformer secondary winding was also modelled.

1 Introduction

The number of HVDC power transmission projects under consideration is increasing worldwide. Some of the dc transmission lines in these projects will have to share a right-of-way with an existing ac transmission system, and any coupling between the dc and ac transmission lines will need to be clearly understood. This paper discusses the general study methodology that can be used to investigate this issue. The system configuration used in this study was generally based on a configuration being considered for an actual HVDC scheme. The study results will provide the data for the technical specification of this scheme.

An ac line near a dc line will induce fundamental frequency voltage and current into the dc circuit due to the capacitive and inductive coupling that occurs between transmission lines close to each other. The dc scheme examined in this paper is a bipole system with a long neutral conductor that provides a return path for the dc current. This neutral conductor is likely to be insulated to a low level, and induced voltages from nearby ac transmission lines may cause flashover of its insulation. The induced fundamental frequency current in the dc line could cause dc components in the converter transformer secondary winding, and dc components in the converter transformer may cause transformer saturation and bring about a number of impacts on system performance.

The study discussed in this paper investigated possible interactions between the HVDC transmission system and the existing ac transmission system under steady state and fault conditions. A PSCAD/EMTDC digital simulation model of the coupling phenomenon was developed to model induced fundamental frequency voltages on the dc line and the neutral conductor. Another PSCAD/EMTDC digital simulation model was developed to model induced dc current in the converter transformer secondary winding. Finally, the dc converter was modelled in detail and the impact of the control on the coupling effect was investigated.

2 System description and study methodology

In this study, 257 km of a 354 km dc line was assumed to be in the same right-of-way as various ac lines. A neutral conductor along the whole length of the dc line was used to provide a current return path for the current and was grounded at one end and open at the other end. The various 240 kV ac tower structures and the ± 500 kV dc tower structure with a neutral conductor are shown in Figure 1. The ac conductors were 477 ACSR Hawk, the dc pole conductors were three-bundle Falcon conductors, and the neutral conductor was a single Thrasher conductor. The ac lines were transposed twice along the parallel line sections.

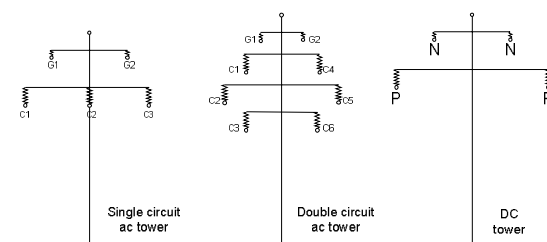


Figure 1: Tower structures of the ac and dc lines

The base case load flow in PSS/E format was used to generate the system operation condition. The HVDC was modelled as 2000 MW under the bipole operation condition and 1000 MW under monopole operation condition. Figure 2 shows the simplified single-line diagram of the coupled lines modelled to evaluate induced fundamental frequency currents and voltages on the dc line. The HVDC bipole system included a neutral conductor with Pole 1 close to the paralleled ac line and Pole 2 a little farther away from the paralleled ac line than Pole 1.

The system and the surrounding network were represented using three-phase models in the electromagnetic transient simulation program PSCAD/EMTDC. The sources and the transmission lines were modelled in sufficient detail to permit evaluation of the electromagnetic and capacitive coupling between the ac lines and the dc line during steady-state and transient conditions. All transmission lines were represented by frequency-dependent distributed parameters.

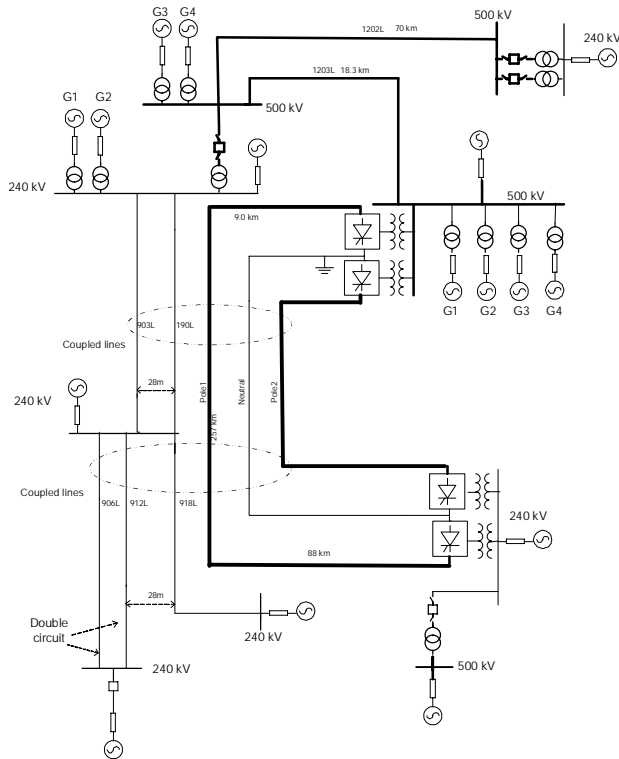


Figure 2: Single-line diagram of the system model

The induced fundamental frequency voltages on the dc line and the neutral conductor were calculated under steady-state and fault conditions by grounding one dc terminal and opening the other dc terminal. Exposure separations between the dc circuit and the nearest ac circuit varied from 50 m to 150 m. The longitudinal potential calculated by this method basically corresponds to the coupling situation between ac and dc circuits.

The induced fundamental frequency current on the dc line was calculated by using the longitudinal potential determined using the method discussed above. The simplified system representation by PSCAD/EMTDC shown in Figure 3 was used to calculate the fundamental frequency current induced on the dc line and the dc offset current in the valve side converter transformer corresponding to the varied longitudinal potentials. The equivalent ac sources at the rectifier and inverter sides, 525 kV and 250 kV, respectively, both with a 25 kA short-circuit level, were used. The converter transformers at the rectifier and inverter side were 500/207 kV and 240/206 kV, respectively, each with a rating of 635 MVA and a 14% leakage reactance. The dc voltage sources were controlled to generate 2 kA dc current and the

maximum longitudinal potential voltage calculated from the induced fundamental frequency voltage calculation was used as the driving series ac voltage source. The dc line and smoothing reactors were also represented in the circuit.

In the sensitivity studies, the induction effects of loading ac lines to their thermal limit and with a 2% zero-sequence current added were investigated. The induced fundamental frequency voltages were calculated by opening both ends of the dc terminal, and by generating a 2 kA dc current on the dc line using dc voltage sources at both dc terminals. The induced fundamental frequency current was calculated by grounding both dc terminals.

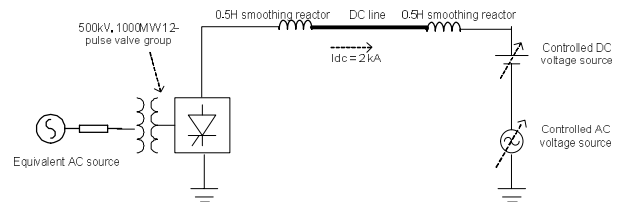


Figure 3: Current induction effect calculation circuit

In order to verify the results, the dc converter was modelled in detail and the dc system and the ac system were fully connected, as shown in Figure 2. The dc control used was the modified CIGRE benchmark control scheme. The ac filters were modelled in detail.

3 Results without the dc converter represented

3.1 Fundamental frequency voltage induced on the dc line and neutral conductor

The maximum induced pole/neutral-to-ground ac voltages with different coupling separations under steady-state operation conditions are summarized in Table 1. The variation curves of the maximum induced voltage with the coupling separations under the bipole operation condition are shown in Figure 4. The results show that the induced ac voltages on the dc circuit are approximately inversely proportional to the coupling separation. For 50 m coupling separation under bipole operation, the induced voltage was 622 V on Pole 1, 476 V on Pole 2, and 484 V on the neutral conductor. Given that the length of ac-dc coupling is 257 km, the induced voltage per kilometre is 2.42 V/km for Pole 1, 1.85 V/km for Pole 2, and 1.88 V/km for the neutral conductor. The induced voltage would be higher under the monopole operation condition due to higher loading on the ac system.

The induced ac peak voltage along the dc line for 50 m coupling separation under the bipole operation condition is shown in Figure 5. The maximum induced ac voltage occurred near the middle of the line.

By adjusting the equivalent ac source phase angles, two paralleled ac lines were loaded to their thermal limit of 499 MW each. The maximum induced voltage was 1321 V on Pole 1, 979 V on Pole 2, and 999 V on the neutral conductor.

By further adjusting the equivalent ac source phase angles to an unbalanced condition, the zero-sequence current in the ac circuit was manually adjusted to 2% of positive-sequence current. The maximum induced voltage was 3608 V on Pole 1, 3258 V on Pole 2, and 3391 V on the neutral conductor. The results show the ac loading and zero-sequence current unbalancing in the system plays a very important role in the fundamental frequency voltage induction effect on the dc line.

Case Description		Coupling Separation				
		50 m (V)	75 m (V)	100 m (V)	125 m (V)	150 m (V)
Bipole	Pole 1	622	430	333	276	238
	Pole 2	475	377	296	252	220
	Neutral	484	379	307	260	226
Monopole	Pole 1	1140	777	596	492	421
	Pole 2	864	657	527	446	389
	Neutral	875	678	544	458	399

Table 1: Summary of maximum induced pole/neutral-to-ground ac voltage under the normal operation condition

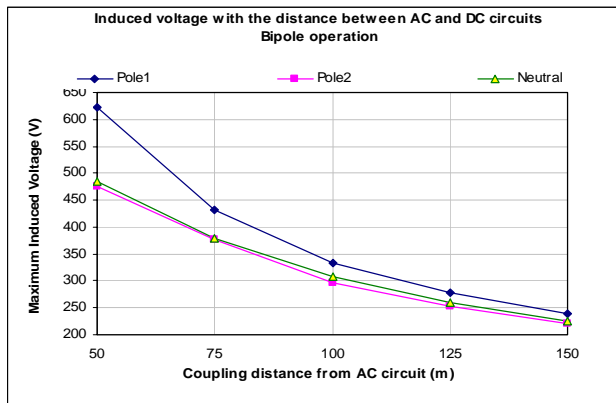


Figure 4: Maximum induced ac voltage verse separation distance under the bipole operation condition

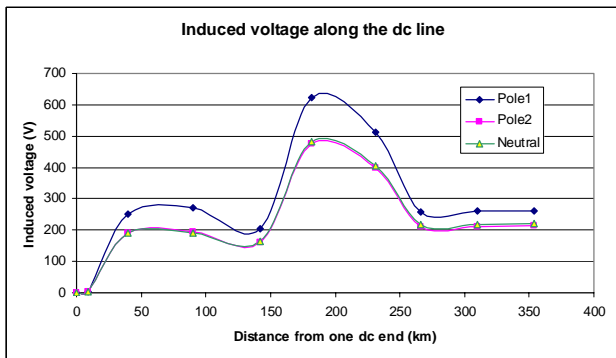


Figure 5: Induced ac voltage along the dc line for 50 m separation distance under the bipole operation condition

The induced fundamental voltages were calculated by opening both ends of the dc terminal and by generating a 2 kA dc current on the dc line using dc voltage sources at

both dc terminals. The maximum induced fundamental voltages on the dc line and the neutral conductor were slightly lower than those induced by grounding one dc terminal and opening the other dc terminal.

On the nearest ac lines, single-line-ground faults were randomly applied at both ends and along the coupling length. The maximum induced pole/neutral-to-ground ac voltages under single-phase-ground fault conditions with different coupling separations are summarized in Table 2. The maximum value of the voltage induced reached 51.6 kV on Pole 1, 47.8 kV on Pole 2, and 45.7 kV on the neutral conductor. Usually, the limited value of the ac voltage component on a 500 kV dc line is about 80 kV. Table 1 and Table 2 show that the maximum induced ac voltage on the dc line and the neutral conductor will not exceed the limited value if the ac lines operate in a steady-state condition or if the ac lines operate in a fault state condition. The neutral conductor insulation should be designed taking this into consideration to prevent a flashover.

Case Description		Coupling Separation				
		50 (m) (kV)	75 (m) (kV)	100 (m) (kV)	125 (m) (kV)	150 (m) (kV)
SLG	Pole1	51.6	45.6	41.2	37.8	34.9
	Pole2	47.8	42.9	39.1	36.0	33.5
	Neutral	45.7	41.1	37.4	34.7	31.8

Table 2: Summary of maximum induced pole/neutral-to-ground ac voltage under the SLG operation condition

3.2 Fundamental frequency current induced on the dc line and dc offset current in the valve-side converter transformer

By using the simplified circuit shown in Figure 3, the maximum induced ac current in the dc circuit and the dc offset current in the valve side of the converter transformer were calculated. The maximum induced ac current in the dc circuit with different coupling separations is summarized in Table 3. The variation curve of the maximum induced ac current with the coupling separations under the bipole operation condition is shown in Figure 6. The results show that the relationship between the induced maximum fundamental frequency voltage and the induced fundamental frequency current in the dc circuit is nearly linear, and that the average slope is about 1.1 A(crest)/kV(crest). The induced fundamental frequency currents on the dc circuit are approximately inversely proportional to the coupling separation. For a 50 m coupling separation, the induced current on the dc circuit is 0.69 A, which is 0.035% of the converter rating of 2 kA, a percentage that is below 0.1% of the converter rating. Considering that the length of the ac-dc coupling is 257 km, the induced ac current will be 0.003 A/km. If the induced voltage at the open end of the dc line were used as the driving ac voltage source instead of the maximum induced voltage on the dc line, the calculated ac current on the dc line would be lower, about 0.3 A. Experience with HVDC systems has shown that if the steady-

state fundamental component of dc current ripple is kept below 0.1% of the converter rating, the system performance will not be affected substantially [2].

Case Description	Coupling Separation				
	50 (m) (A)	75 (m) (A)	100 (m) (A)	125 (m) (A)	150 (m) (A)
Bipole	0.69	0.48	0.37	0.31	0.27
Monopole	1.24	0.85	0.65	0.54	0.46
SLG	55.8	49.3	44.66	40.8	37.7

Table 3: Maximum induced ac current in the dc circuit

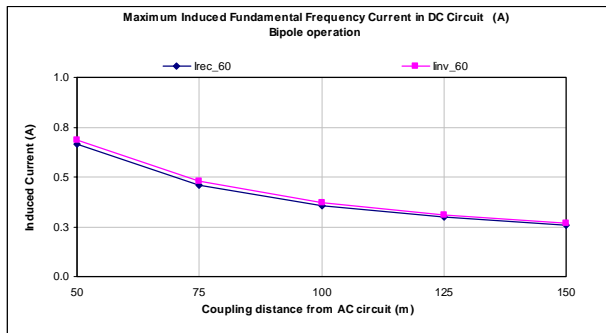


Figure 6: Maximum induced ac current in the dc circuit under bipole operation

The variation curve of the dc offset in the valve side of the transformer under bipole operation with the coupling separations is summarized in Figure 7. The maximum dc offset current in the valve side converter transformer for 50 m coupling separation is summarized in Table 4. The results show that the maximum dc offset is around 0.7 A under the bipole operating condition and 0.0004 pu of the converter transformer rating. If a single-line-ground fault occurs on the ac line, the three-phase wire-to-earth voltages or currents are all badly unbalanced, and the coupling in the dc circuit can suddenly vary. But the duration is short (less than 100 ms in general) so the dc offset current in the converter transformer cannot cause overheating in the transformer.

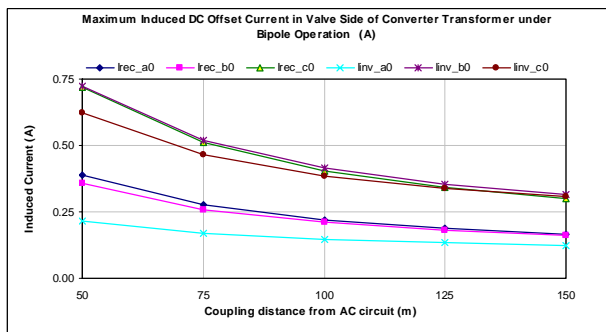


Figure 7: Maximum induced dc offset in the valve side of the converter transformer under bipole operation (A)

Case	Irec_0hz	Irec_0hz_pu	Iinv_0hz	Iinv_0hz_pu
Bipole	0.72 A	0.0004	0.73 A	0.0004
Monopole	1.22 A	0.0007	1.31 A	0.0007
SLG	56 A	0.032	55 A	0.031

Table 4: Summary of maximum dc offset current in the valve side of the converter transformers

The induced fundamental frequency current was also calculated by grounding both ends of the dc terminal in the full system as shown in Figure 2. The dc line in this study was modelled with 0.5 H smoothing reactors and a 0.1 H time average value of the commutating reactance at each end. The maximum induced fundamental current on the dc line was 0.29 A for a 50 m coupling separation under the bipole operation condition. This ac current is mainly caused by the longitudinal potential of the line. It is lower than the 0.69 A ac current conservatively calculated using the maximum induced voltage on the dc line as the driving ac source in the simplified circuit.

4 Results with the dc converter represented

The detailed dc system and converter control were represented for a 50 m coupling separation. It is well known that low order resonances between the filters and the network occur in HVDC systems and may lead to problems under some system conditions, especially in weak ac systems. If the resonance is close to the second harmonic a resonance condition may be present and the harmonic instability in HVDC system may occur. Impedance scan was performed for the ac system and the scan results showed a resonance just above the third harmonic at the inverter side. Impedance scan was performed for the dc line with a smoothing reactor at each end and the scan results showed a series resonance at the second harmonic. There were small amounts of 2nd harmonic components and 3rd harmonic components on the ac circuit and the dc circuit. It was found that the low order harmonic components were sensitive to the dc converter controller parameters. The parameters of the gamma controller were adjusted so that no additional ac components would appear on the dc line as a result of the interaction of the dc converter with the ac system.

The induced pole/neutral-ground ac voltages at both ends of the dc line and the maximum value around the middle of the dc line are shown in Figure 8. The results were very close to those obtained by grounding one dc terminal and opening the other dc terminal. The induced ac current on the dc line and each phase of dc offset in the valve side converter transformers are shown in Figure 9. The ac current induced on the dc line was close to that which occurs when simplified circuit using induced voltage as ac driving source is used and to that which occurs when both ends of the dc terminal are grounded. The simulation results show that the digital model without the dc converter represented is adequate for investigating the ac/dc coupling phenomena for the system under study.

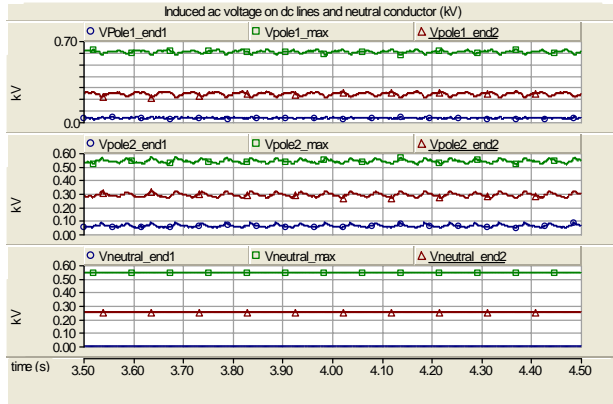


Figure 8: Maximum induced ac pole/neutral-to-ground voltage under the bipole operation condition

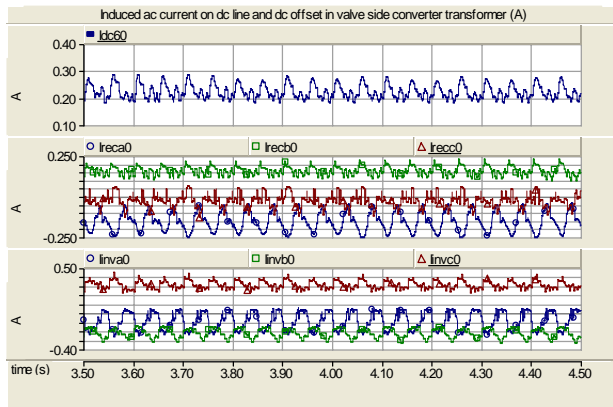


Figure 9: Maximum induced dc offset current in the valve side of the converter transformer under the bipole operation condition

5 Conclusions

Fundamental frequency coupling between parallel ac/dc transmission systems was investigated using the digital simulation program PSCAD/EMTDC. The general study methodology was discussed and the study results will provide data for the technical specification on the design of the neutral insulators and on the converter transformer dc offset withstanding ability.

As long as there is no low order frequency resonance between the ac system and the dc system, if detailed dc system control is not available (such as at the planning stage), the induced voltage on the dc line and the neutral conductor can be calculated by grounding one dc terminal and opening the other dc terminal. The dc offset in the converter transformer secondary winding can be calculated by using the calculated induced voltage as the driving ac source in a simplified circuit, or it can be calculated by grounding both dc terminals along with the smoothing reactor and time average value of the commutating reactance. If there is low order frequency resonance between the ac system and the dc system, the detailed model should be used to show the resonance effect.

References

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