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Analysis of induced components in hybrid HVAC/HVDC transmission lines on the same tower for various fault conditions

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ABSTRACT

The use of Hybrid Parallel HVAC/HVDC Overhead Transmission Lines (HPOTL) on the same tower can improve the power transfer capacity and transmission line stability and reduce power transient swing, but it will also present some challenges. The most important one is the electromagnetic coupling between the HVAC and HVDC lines due to the proximity of the lines. The electromagnetic coupling phenomenon induces different voltage and current components in the lines for different conditions, including the fundamental frequency component in the DC line and the zero sequence component in the AC line. The magnitude of the induced components is much higher in fault conditions than in normal conditions. The electromagnetic coupling between the HVDC and HVAC lines has a significant influence on their equipment and protection systems. In this paper, the induced components in the normal and various fault conditions in HPOTL are investigated with the detailed modeling of the HPOTL. In addition, the effect of faulty phase(s) or pole(s) for AC, DC, and AC/DC intersystem faults, fault location, and fault resistance on the induced component in transmission lines are investigated. Simulation results show that the electromagnetic coupling can cause the mal-operation of the protection system in healthy lines.

1. Introduction

1.1. Motivation

High voltage direct current (HVDC) technology is an effective system for power transmission. HVDC transmission systems have many advantages over HVAC transmission systems, especially over long distances. These advantages are due to the voltage drop and operating costs reduction for long distances. A presented idea to increase transmission capacity through cost management is to use Hybrid Parallel HVAC/HVDC Overhead Transmission Lines (HPOTL) on the same tower. The use of HPOTLs can also improve stability and reduce power transient swings. In addition, with the development of technology and the greater use of DC transmission lines in the power transmission industry, the possibility of creating paths where the AC and DC lines are parallel increases. In such paths, the transmission lines may be on the same tower, or they may be separated from each other, i.e., on separate towers. Other reasons for the construction of HPOTL can be environmental concerns and the difficulties and public concerns about the erection of new transmission lines. HPOTLs on the same Right-of-Way (ROW) are another type of hybrid parallel transmission line where the AC and DC transmission line towers are separate. It is clear that the electromagnetic coupling in the HPOTLs on the same tower (due to the close distance of the conductors to each other) is greater than the HPOTLs that are on the same ROW but separate towers. Therefore, it is very important to check the electromagnetic coupling between the lines in the first case (on the same tower).

The use of HPOTLs on the same tower will also present challenges. The most important of which is the electromagnetic coupling between the HVAC and HVDC lines. Electromagnetic coupling between lines causes the transients created in each transmission line (AC or/and DC) to strongly affect the adjacent transmission line and can sometimes activate the protection system of healthy transmission lines [1].

1.2. Literature review

Several papers have considered electromagnetic coupling between transmission lines in order to provide an accurate transmission line model for use in power system studies [2,3]. Investigating electromagnetic coupling in HPOTLs is important because in HPOTLs transmission lines with two different topologies are adjacent to each other and influence each other. Several papers have analyzed the electromagnetic

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coupling in parallel transmission lines on separate towers [1,4-15] and on the same tower [16–26]. Interaction between transmission lines in HPOTLs in normal condition has been discussed in [1,4-7,16-18,22,23]. In [9] the parameters that affect the magnitude of induced voltage and current components are investigated. In [10] the effects of parameters such as AC/DC separation distance, paralleled length, the effect of line transposition, and VSC operating points on the DC component induced in the ac line are investigated. In [11] methods for limiting the electromagnetic coupling on the DC line, such as AC and DC line transposition, using a 50 Hz blocking filter and firing angle modulation are discussed. It is shown in this paper that blocking filters can sometimes result in increased DC side overvoltage and the induced 50 Hz voltage would still exist at the DC line terminal. In [13] electromagnetic coupling of AC cable section partly installed in parallel with DC lines in one corridor is analyzed. The focus of this paper is more on the induced components in the non-parallel part of the DC line.

In [14], field-effect limits and design parameters for HPOTL corridors, and in [24] accurate transmission line modeling for accurate estimation of DC components induced in the AC lines of HPOTLs are investigated. Some papers have suggested converting the HVAC line to an HPOTL to increase the efficiency and capacity of the transmission line. In [21] the general principles of converting the existing HVAC line (Gibe III – Wolyita-Addis Ababa) to HPOTL to upgrade the power transmission capacity (from 1500MVA to 2500MVA) were investigated and it was shown that by doing this conversion, the total cost compared to the Increasing transmission power capacity, it has decreased by 49 % and also the efficiency of the transmission line has increased from 91 % to 97 %. In [15], the effects of electromagnetic coupling on MMC—HVDC transmission lines from the adjacent AC line have been studied. The effect of AC line length and AC current on induced components has also been investigated.

The papers reviewed above have studied induced components only in normal conditions and have not considered the effect of faults and transient conditions on these components. As mentioned above, transient conditions such as faults, switching and etc. can have a significant impact on the induced components. In [12] a method for studying the coupling effect on the LCC-MMC hybrid system from the parallel AC line is proposed. In this paper, the effect of the physical parameters of the conductors, the length of the parallel section, and some AC faults on induced components in the DC line have also been investigated. This method has not been evaluated for other AC and intersystem faults. In [17], the effect of AC/DC faults on the DC line overvoltage in HPOTL on the same tower is investigated.

The performance of HPOTL on the same tower has been investigated in [25]. In this paper, the effect of factors such as the location of the parallel section, the capacity of the DC transmission line, the geometric parameters of the transmission tower, and the type and location of the fault on the performance of the DC line has been investigated. But, in this paper, only AC faults are investigated and it is shown that the induced components in the DC line for AC fault, may cause the DC line protection system to malfunction. In [19,26] induced components in HPOTL on the same tower under normal, switching and fault condition are investigated, and in [26] recommendations for configurations of DC conductors to reduce the mutual influences of AC/DC lines and optimize the performance of HPOTLs are presented. In this paper, only single-line faults are investigated and the other fault types such as DC faults, intersystem faults, and other AC faults are not considered.

1.3. Contributions

As mentioned above, the electromagnetic coupling in fault conditions is much more severe than normal conditions and therefore detailed study should be done in these conditions. In some papers presented in this field, only the effect of the physical characteristics of the transmission line and tower on the electromagnetic induction between the lines has been investigated. But in this paper, in particular, the effect of various faults on the components induced in AC and DC lines of HPOTLs are investigated and the most severe faults are analyzed and identified in terms of the effect on the performance of the protection system of adjacent lines. Since the effect of electromagnetic coupling between lines in HPOTL on the same tower is greater than HPOTL on the same ROW, this paper focuses on the electromagnetic coupling and interaction of AC and DC lines on the same tower in fault conditions.

1.4. Organization of the study

Details of modeling the HPOTL in PSCAD software are described in Section 2. Modeling and calculations of mutual induction in HPOTLs are given in Section 3. Simulations of different fault conditions and the conclusions are presented in Sections 4 and 5, respectively.

2. Modeling of HPOTL

The model used in this paper, as shown in Fig. 1, is an HPOTL on the same tower, consisting of an HVAC transmission line and a two-pole HVDC transmission line, with common buses at the beginning and end of the transmission line. Electromagnetic coupling is considered between the conductors of the HVAC transmission line and the HVDC transmission line. The HPOTL tower configuration is shown in Fig. 2 [21].

The simulation of HPOTL has been done by using PSCAD software. The simulated HPOTL includes a 400 kV AC transmission line and a 500 kV bipolar DC transmission line. The length of the AC and DC transmission lines is equal and they form an HPOTL on the same tower with a length of 400 km. Both transmission lines are fully transposed. The sampling frequency in the simulations performed in this paper is 20 kHz. The other specifications of the presented model and the filters used in the model and the specifications of the transmission line conductors are presented in [27].

3. Model and calculations of mutual induction in HPOTL

As mentioned in the previous section, in HPOTLs due to the influence of transmission lines on each other (as a result of the mutual induction), AC components are induced in the DC line, and also DC components are induced in the AC line. These induced components are present in normal and fault conditions. But the amplitude of the induced component in fault conditions is usually much higher than the normal condition. In long transmission lines, unlike short transmission lines, the capacitive effects of transmission lines should be considered. Therefore, in order to be able to calculate the mutual induction between transmission lines, we need to have the self and mutual parameters of the transmission line [6, 28]. In [28], long transmission line equations for a single-conductor transmission line and a mutually coupled double-conductor transmission line are provided. It is very complicated and difficult to obtain and solve the equations of these lines [28]. The model presented in Fig. 3, inspired by the model presented in [28], is used to obtain hybrid parallel transmission line equations with five conductors ("A", "B" and "C" for AC and "P" and "N" for DC lines).

According to Fig. 3 and using KVL and KCL, the differential equations of voltage and current can be obtained for the HPOTL. In order to summarize and limit the presentation of the content, and also considering the main purpose of this section, which is only to show the large number of equations of HPOTLs and the complexity and difficulty of solving the equations, only the final form of the equations is presented in a matrix form. These equations are obtained for a healthy transmission line. When a fault occurs in the transmission line, the transmission line is divided from the fault point into two parts with unknown lengths, which greatly increases the complexity of the equations and their solution. The integrated matrix of voltage and current equations of both healthy transmission lines (AC and DC lines) at the distance l from the receiving-end of the transmission line is obtained as follows:

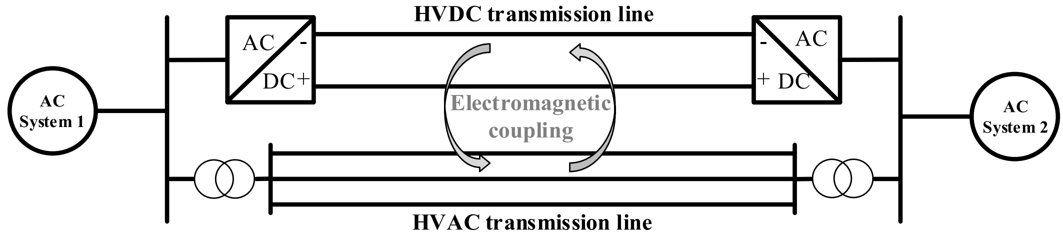

Fig. 1. The studied system for the HPOTL.

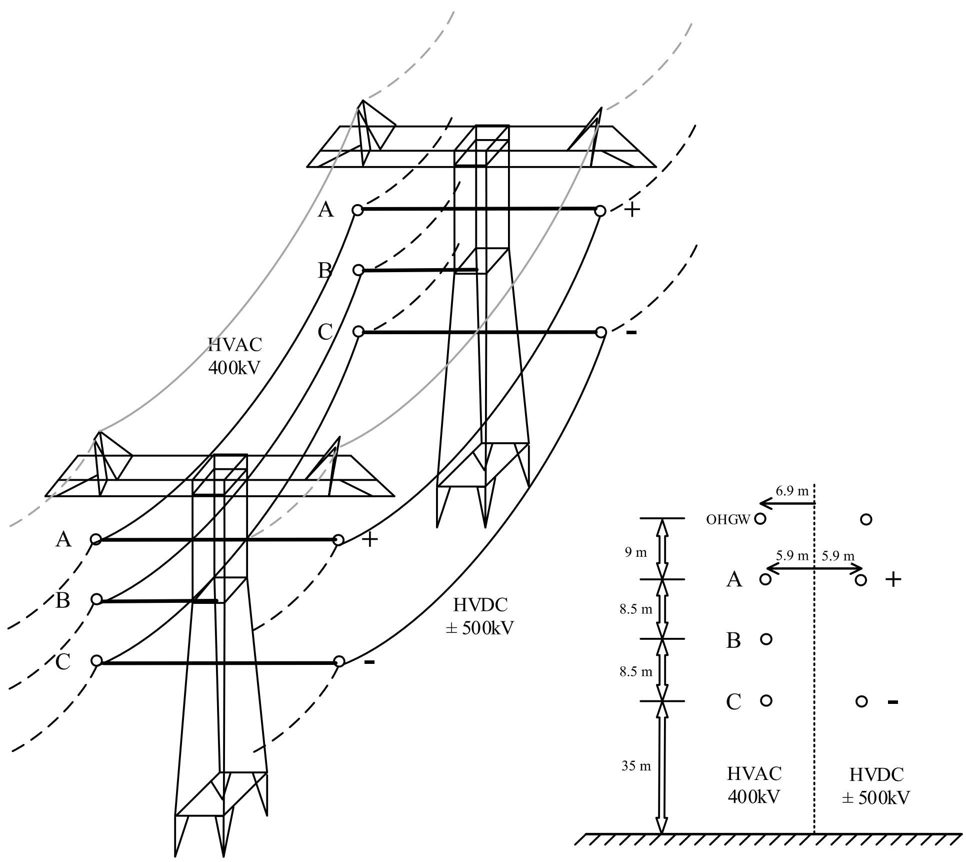

Fig. 2. Specifications of the HPOTL tower [21].

AC/AC AC/DC

$$
\begin{bmatrix} V_{Al} \\ I_{Al} \\ V_{Bl} \\ I_{Bl} \\ V_{Cl} \\ I_{Cl} \\ V_{Pl} \\ I_{Pl} \\ V_{Nl} \\ I_{Nl} \end{bmatrix}
=
\begin{bmatrix}
A_{AA} & B_{AA} & A_{AB} & B_{AB} & A_{AC} & B_{AC} & A_{AP} & B_{AP} & A_{AN} & B_{AN} \\
C_{AA} & D_{AA} & C_{AB} & D_{AB} & C_{AC} & D_{AC} & C_{AP} & D_{AP} & C_{AN} & D_{AN} \\
A_{BA} & B_{BA} & A_{BB} & B_{BB} & A_{BC} & B_{BC} & A_{BP} & B_{BP} & A_{BN} & B_{BN} \\
C_{BA} & D_{BA} & C_{BB} & D_{BB} & C_{BC} & D_{BC} & C_{BP} & D_{BP} & C_{BN} & D_{BN} \\
A_{CA} & B_{CA} & A_{CB} & B_{CB} & A_{CC} & B_{CC} & A_{CP} & B_{CP} & A_{CN} & B_{CN} \\
C_{CA} & D_{CA} & C_{CB} & D_{CB} & C_{CC} & D_{CC} & C_{CP} & D_{CP} & C_{CN} & D_{CN} \\
A_{PA} & B_{PA} & A_{PB} & B_{PB} & A_{PC} & B_{PC} & A_{PP} & B_{PP} & A_{PN} & B_{PN} \\
C_{PA} & D_{PA} & C_{PB} & D_{PB} & C_{PC} & D_{PC} & C_{PP} & D_{PP} & C_{PN} & D_{PN} \\
A_{NA} & B_{NA} & A_{NB} & B_{NB} & A_{NC} & B_{NC} & A_{NP} & B_{NP} & A_{NN} & B_{NN} \\
C_{NA} & D_{NA} & C_{NB} & D_{NB} & C_{NC} & D_{NC} & C_{NP} & D_{NP} & C_{NN} & D_{NN}
\end{bmatrix}
\times
\begin{bmatrix} V_{AR} \\ I_{AR} \\ V_{BR} \\ I_{BR} \\ V_{CR} \\ I_{CR} \\ V_{PR} \\ I_{PR} \\ V_{NR} \\ I_{NR} \end{bmatrix}
\quad (1)
$$

DC/AC DC/DC

Eq. (1) is valid for any length (l) of the transmission line. The coefficients matrix presented above is a 10×10 matrix and includes four parts that are shown and separated by colors. Two parts are related to self-equations of AC and DC transmission lines and two parts are related to mutual equations between transmission lines. By solving the equations of the mutually coupled transmission lines, it can be seen that the equations are obtained as hyperbolic sine and cosine functions. Accordingly, each element of the coefficients matrix contains a complex mathematical relationship. Also, the values of the propagation parameters related to both transmission lines are present in these functions and add a lot of complexity to the equations [28]. In some papers [29,30], the double-circuit AC long transmission line model is presented along with the relevant equations for protection and fault location analysis. However, since the HPOTL has AC and DC lines parallel to each other, and the nature of this type of transmission line is different from the double-circuit AC transmission line, it is difficult to obtain transmission line equations and solve them for such lines. According to the explanations given, solving the equations of coupled transmission lines has a very high complexity along with a very high computational load due to the high volume of the equations. For the reasons mentioned, software simulations are used in this paper to analyze the coupling between transmission lines under fault conditions.

4. Simulations and results analysis

In this section, the normal (steady state) and transient interaction of the three-phase HVAC system and bipolar HVDC system are analyzed by

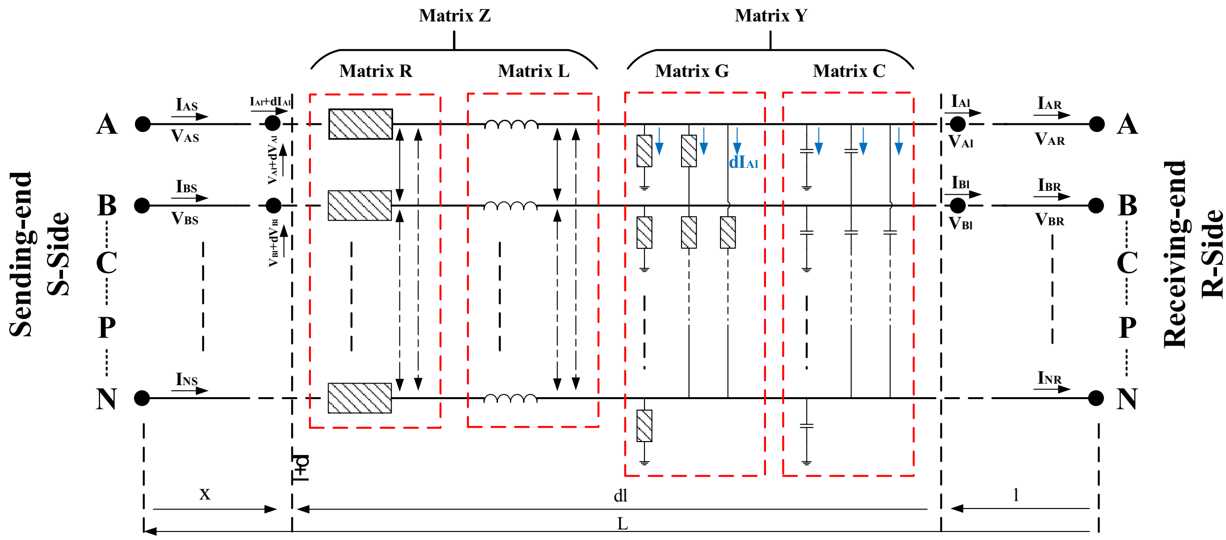

Fig. 3. The model used for extracting the equations of hybrid parallel transmission line.

means of simulation results. Both systems (HVAC and HVDC) are on the same tower and are operated parallel along a length of 400 km (Fig. 2). As mentioned in Section 2, the sampling frequency in the simulations performed in this paper is 20 kHz. In this section, induced components in AC and DC transmission lines at normal and different fault conditions are shown using different simulations. All the waveforms presented in this paper have been measured from the sending-end of the transmission line.

The HPOTL model presented in this paper is a real model that is presented in [21], and the configuration of the transmission line tower and the distances between the AC and DC conductors in the transmission line are presented in Fig. 2. Since the main purpose of this paper is to investigate the induced components in transmission lines under different fault conditions, only the factors such as fault location, fault resistance, and fault type have been analyzed to investigate the parameters affecting the induced components on transmission lines. Therefore, the physical characteristics of the transmission tower (Fig. 2) are considered fixed in this paper. But it should be noted that the effect of these parameters can also be investigated.

4.1. Induced components in normal condition

In the previous sections, the types of induced components in AC and DC transmission lines were mentioned. The fundamental frequency current induced in the DC line, on the AC side of the converter transformer, creates a DC current and a series of harmonic currents that cause great problems for the installed equipment and converter transformer. Transformer core saturation, noise increase, transformer heating, and transformer loss of life are among these problems [1]. Also, due to the saturation of the converter transformer, a broad spectrum of harmonics is injected into both sides of the converter, which makes the design of system filters difficult. From the point of view of system protection, due to the presence of the DC component on the AC side, current transformers (CTs) that measure the value of the line current for protection and control applications may have errors in the measurement. The result of this mistake is the incorrect operation of the healthy system protection. Similarly, the induction of zero-sequence current in parallel AC circuits from DC lines can also cause problems in AC line protection. If this DC current is large enough to saturate the CTs, this can adversely affect the AC line protection [11].

In the simulated model (in normal condition), the values of DC voltage and current components in the AC line are 6.8 V and 10.4 A, respectively, and the values of fundamental frequency components in the DC line are 16 V and 0.6 A respectively. As mentioned in Section 3, the induced fundamental frequency component in the DC transmission line creates the DC and second harmonic components on the AC side of the converter transformer (ASCT). In the normal condition, the second harmonic voltage and current, the induced DC voltage and current ASCT#1, and the induced second harmonic and DC current ASCT#2 are equal to 0.3 V, 0.27 A, 7.1 V, 0.6 A, 0.5 A, and 0.7 A respectively.

4.2. Induced component in fault condition

Transmission Line faults in HPOTLs on the same tower include AC, DC, and intersystem faults. Intersystem faults are faults between AC and DC transmission lines that can occur due to the close distance between the lines and their position on the same tower. In the following, these faults and their effect on healthy lines are examined. As mentioned in Section 2, the HPOTL is 400 km and the simulation of transmission line faults has been done for the entire transmission line. All the figures presented in this section for the induced components in different fault conditions correspond to the sending-end of the transmission line.

4.2.1. AC faults

In this subsection, AC faults are investigated and the effect of these faults on the operation of the DC line is examined. The types of AC faults can be divided into the following:

- Single line to ground fault (SLGF)
- Line to line fault (LLF)
- Line to line to ground fault (LLGF)
- Three-phase fault (LLLF)

In this section, at first, the SLGF is examined and the induced components on the DC line are investigated. Then, the induced components for the other faults are presented. Fig. 4 shows the AC and DC waveforms for an SLGF at $x = 142$ km.

As shown in Fig. 4, the AC fault occurred in phase "A" and the DC line is healthy, but due to the electromagnetic coupling between the transmission lines, the DC voltage and DC current also changes due to this fault. The induced components in the DC line are so large that they can cause the mal-operation of the DC line protection system, even though the DC line is in normal condition. Fundamental frequency components induced in the positive pole of the DC line (V1 and I1) and DC and second harmonic components of voltage (V-dc and V2) and current (I-dc and I2) induced in the ASCT under different AC line faults are presented

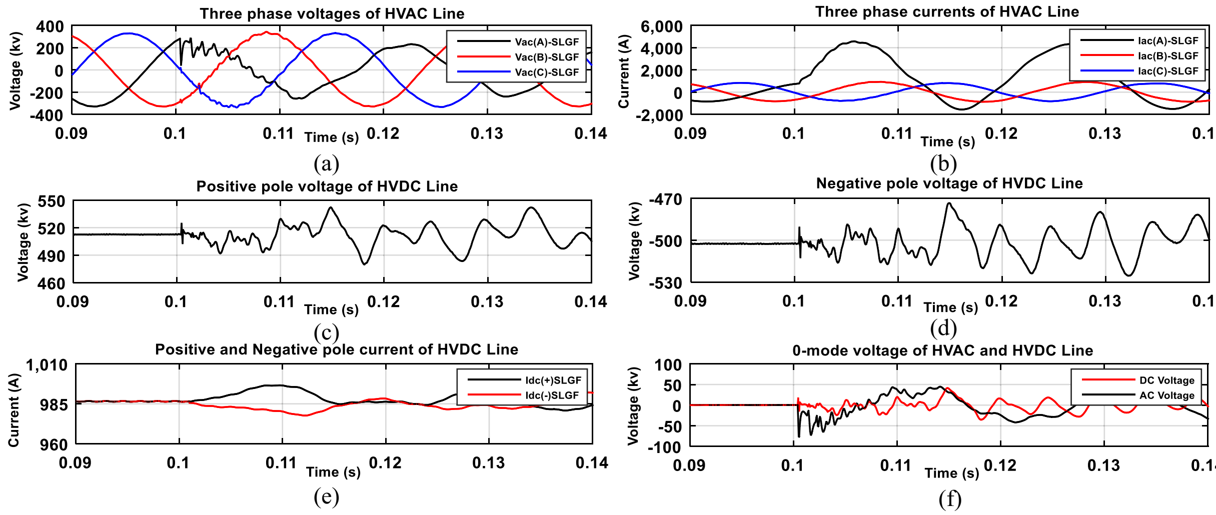

Fig. 4. AC and DC waveforms for an SLGF ("A" to ground fault) at $x = 142$ km, a) AC line voltages, b) AC line currents and c) DC line positive pole voltage, d) DC line negative pole voltage, e) DC line currents and f) 0-mode voltage of AC and DC line.

in Table 1. It should be noted that for SLGF and LLF, phase "A" to ground (AG) and phase "A" to phase "B" (AB) faults are considered, respectively. Therefore, due to the arrangement of the transmission line conductors (Fig. 2) and the fact that the positive pole is the nearest pole to the faulty phase, the induced components in the positive pole are more than the negative pole. The induced components in the positive pole are presented in Table 1. Although, for other faults, the amplitude ratio of the induced components at the positive and negative poles can be different.

As can be seen in Table 1, the SLGF in the HVAC line induces the most components in the adjacent HVDC line and therefore has the greatest impact on the HVDC line performance. After SLGF, LLGF has the greatest impact on the adjacent HVDC line. It should also be noted that the induced components in the HVDC line for ground faults in the HVAC line such as SLGF and LLGF (due to the existence of a path for zero sequence current) are much larger than the ungrounded faults such as LLF and LLLF. Therefore, in HPOTLs protection system studies, special attention should be paid to ground faults. Fig. 5 shows a comparison diagram of induced components in the HVDC line at different fault conditions compared to the normal condition.

Due to the arrangement of conductors in the transmission lines, the fault in phases "B" and "C" can have a different induction than phase "A" in the HVDC line. Fig. 6 shows the effect of SLGF in different phases on the induced fundamental frequency component in the DC line. It can be concluded from this figure that the amplitude of the induced components at the healthy pole is inversely related to the distance from the faulty phase.

Figs. 7 and 8 show the effect of the fault location and fault resistance on the induced fundamental frequency components in the positive pole of the HVDC line under SLGF in phase "A". To investigate the effect of these factors, the SLGF has been selected as the most severe AC line fault from the induced components point of view of the HVDC line. In the figures shown, the fault location changes from 0 km to 400 km and the fault resistance changes from 0 to 500 Ω.

As shown in Figs. 7 and 8, for SLGF at the sending and receiving end of the HVAC line, the induced components in the HVDC line have the highest value, and for middle-of-line faults, the induced components have the lowest value. The reason is that when a fault occurs in the AC line, the direction of the current changes on one side of the fault point, and this change in the direction of the current causes a change in the direction of the induced current in the adjacent DC line, and the result of the induced current in the adjacent DC line reduces (see the Fig. 9). According to Fig. 9, a fault near the sending- or receiving- end of the transmission line causes the induced components on one side of the fault point to be larger than on the other side. Since the induced components with a larger amplitude are much larger than the induced components with a smaller amplitude, the resulting induced components increase from the point of view of the measuring end of the line. This makes the induced components for faults close to the transmission line terminals to be larger than the induced components for middle-of-line faults.

Table 1
Induced components in DC line for different types of AC faults.

Fault type		Normal condition	SLGF	LLF	LLGF	LLLF
DC line data Positive pole	V1 (kV)	0.016	12.38	4.93	8.48	8.99
	I1 (A)	0.6	50.2	13.3	37.5	21.16
ASCT data pole (+) side,Tr#1	V-dc (kV)	0.0071	0.693	1.097	1.097	2.28
	I-dc (A)	0.6	18.1	6.5	15.1	7.5
	V2 (kV)	0.0003	0.472	0.968	0.968	1.21
	I2 (A)	0.27	19.6	6.4	13.4	7.4
ASCT data pole (+) side,Tr#2	I-dc (A)	0.7	15.9	4.4	15.3	5.4
	I2 (A)	0.5	19.3	6.5	13.1	8.5

4.2.2. DC faults

In this subsection, DC faults are investigated and the effect of these faults on the operation of the AC line is examined. Therefore, the types of DC faults can be divided into the following:

- Single-pole to ground fault (SPGF)
- Pole to pole fault (PPF)
- Pole to pole to ground fault (PPGF)

In expressing the process of DC faults in this section, there is no fundamental difference between positive and negative poles. Hence for the SPGF, the fault on the positive pole has been investigated. The waveforms of the HVAC and HVDC transmission lines under SPGF (positive pole to ground fault) at $x = 264$ km (as the fault that induces the most induced components in the HVAC line) are shown in Fig. 10. In the following, the induced components caused by other faults in the HVDC line will also be examined.

As shown in Fig. 10, the AC line is healthy, but due to the fault in the DC line, the AC voltage and current are also affected. The induced components in the AC line are so large that they can cause the mal-

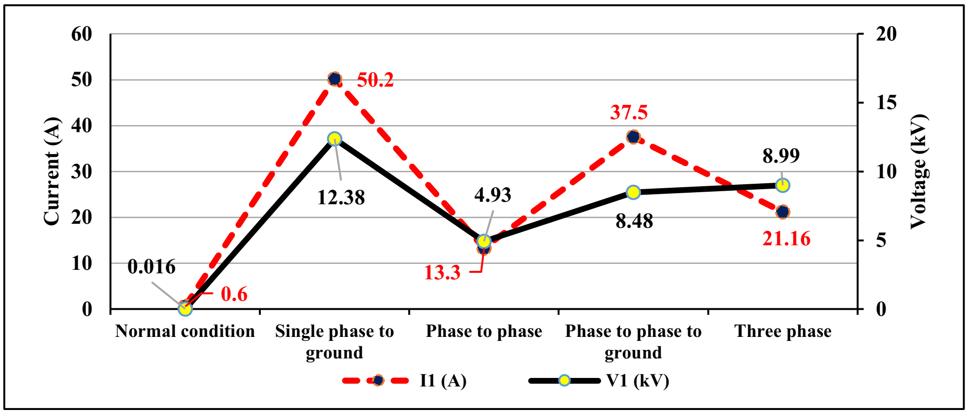

Fig. 5. Comparison diagram of induced fundamental frequency components in the positive pole of HVDC line at different AC fault conditions compared to the normal condition.

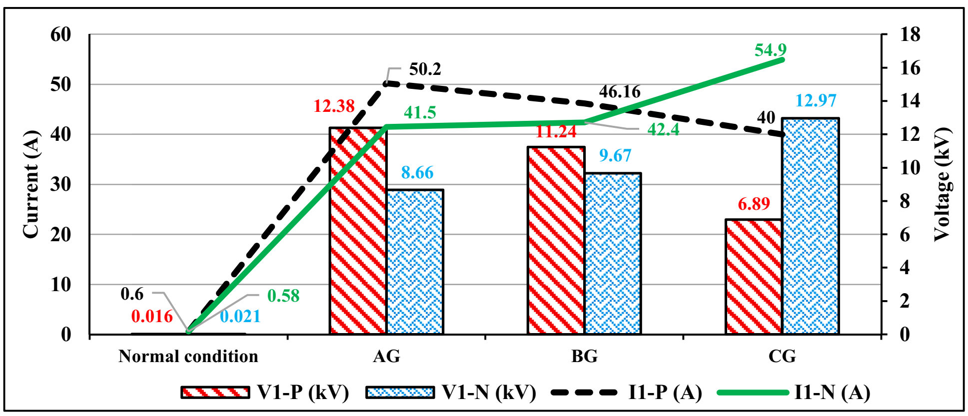

Fig. 6. Comparison diagram of induced fundamental frequency components in the positive and negative poles of the HVDC line for SLGF in different phases in the HVAC line compared to the normal condition.

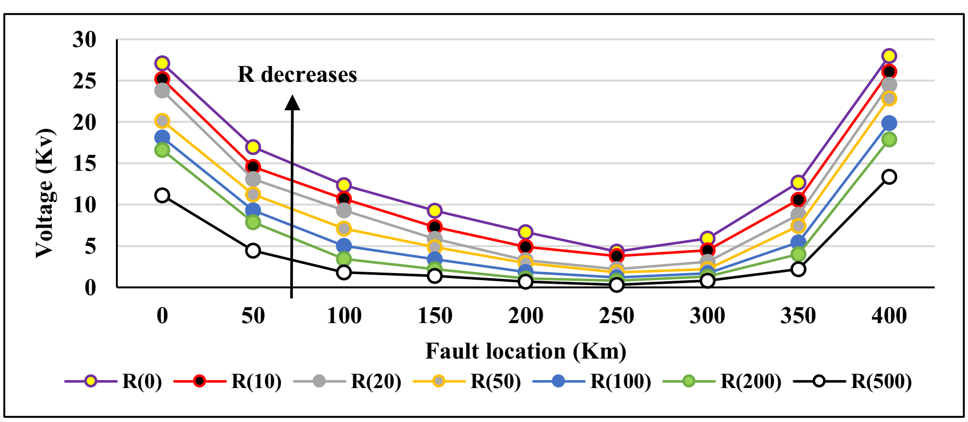

Fig. 7. Variations of fault location and fault resistance and its effect on the induced fundamental frequency voltage in the HVDC line (positive pole) for an SLGF in phase "A".

operation of the AC line protection system, even though the AC line is in normal condition. Fig. 11 shows a comparison diagram of induced zero sequence components in the HVAC line at different DC fault conditions compared to the normal condition. As can be seen in Fig. 11, the SPGF in the HVDC line induces the most DC components in the adjacent HVAC line and therefore has the greatest impact on the HVAC line performance. After SPGF, PPGF has the greatest impact on the adjacent HVAC line. Therefore, in HPOTLs protection system studies, special attention should be paid to ground faults.

In [4], a study has been done on a 240 km long HPOTL in the Manitoba Hydro system in Canada. In this study, the cause of operation of the AC system protection and AC circuit interruption after operation of the DC protection system has been investigated. Figs. 12 and 13 show the effect of the fault location and fault resistance on the induced zero sequence components in the HVAC line for an SPGF in the positive pole.

4.2.3. AC/DC intersystem fault

In HPOTLs, the parallel operation of both the AC and DC systems

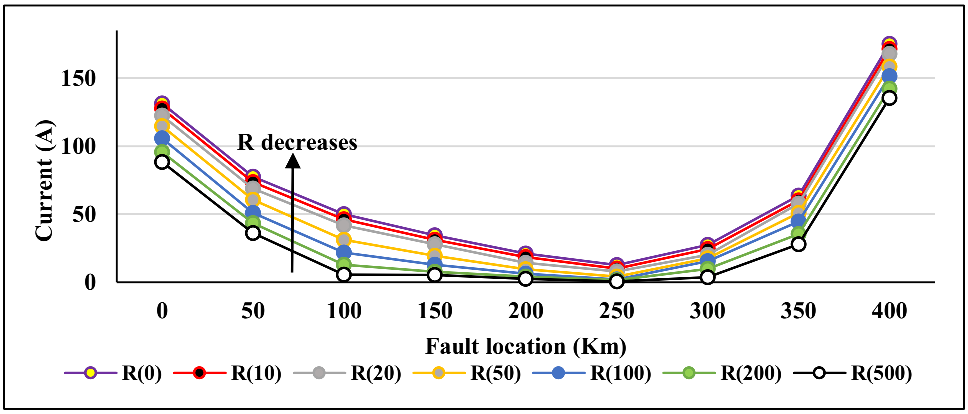

Fig. 8. Variations of fault location and fault resistance and its effect on the induced fundamental frequency current in the HVDC line (positive pole) for an SLGF in phase "A".

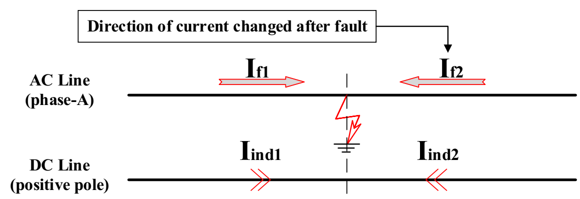

Fig. 9. Sign of the induced current and resulting inductive coupling during an SLGF.

allows a type of fault to occur between the AC and DC systems. This type of fault which occurs as a physical connection between AC and DC conductors is called an AC/DC intersystem fault. In the previous two fault types (AC and DC faults), the electromagnetic coupling issue between AC and DC systems is the root cause of the protection problem. However, in the AC/DC intersystem faults, there is a contact between the two systems. During AC/DC intersystem faults, there is not only a direct influence from the DC pole to the faulty AC phase and vice versa, but also a non-direct influence on the other AC phases through electromagnetic coupling [31].

The main problem with intersystem faults is the fault type variation. In the event of an AC/DC intersystem fault, the AC and DC protection systems must be capable of detecting the fault and must be able to activate the protection. However, the type of AC/DC intersystem fault has a major influence on the HPOTL response. According to the phase/phases and pole/poles involved in the fault, twelve types of faults can be defined for intersystem faults. Different intersystem fault types as grounded and ungrounded faults are presented in Table 2.

During an AC/DC intersystem fault, there are a variety of parameters that affect the development of fault current, such as the faulty phase, or the effective impedance in the fault path [32]. There is also a huge range of phase to pole faults, multipolar faults, and so on. Therefore, only the most severe ones, i.e. line to pole to ground fault (LPGF) and line to pole fault (LPF), are presented and analyzed here. For each one of the LPGF and LPF, there are 6 fault cases, depending on the phase and the pole that are faulty. Figs. 14 and 15 show the AC and DC waveforms for LPGF and LPF (phase "A" and "positive pole") at $x = 100$ km, respectively.

As shown in Fig. 14, the LPGF also affected the healthy phases and pole in addition to the faulty phase and faulty pole. Single LPGF is the same as the simultaneous occurrence of SLGF and SPGF and the analysis of the fault conditions is the same as the analysis presented in the previous sections for SLGF and SPGF. During intersystem faults, high current transients can also occur in the DC system similar to DC faults. Besides, AC components (voltages or/and currents) in the DC system can influence all other parallel AC systems that are not involved in the intersystem fault [31]. Here, distortions in the voltage and current waveforms of faulty conductors are due to the physical connection of the AC and DC system, and distortions in the voltage and current waveforms

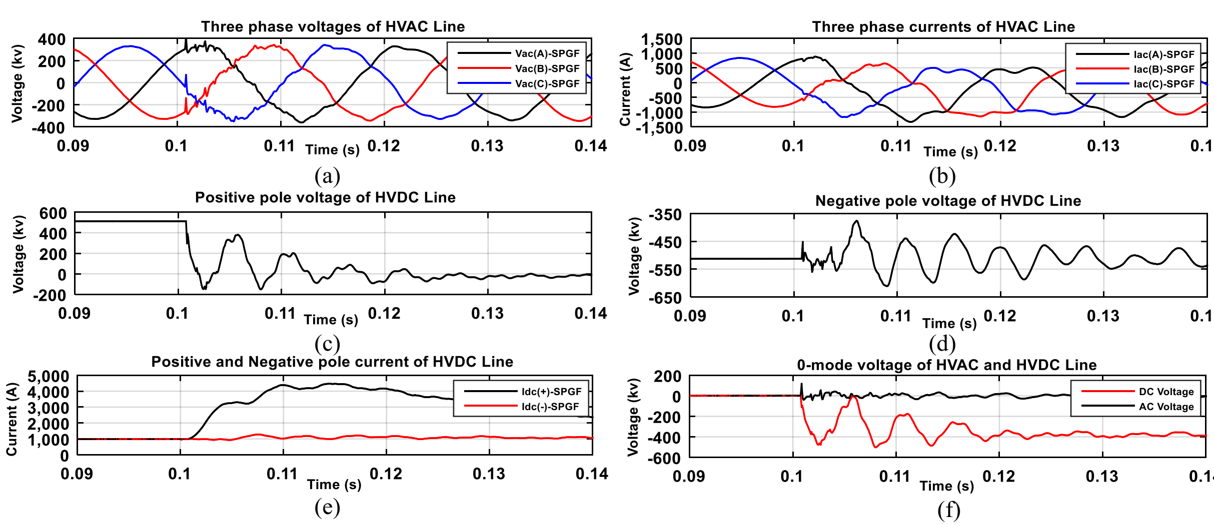

Fig. 10. AC and DC waveforms for SPGF at $x = 264$ km, a) AC line voltages, b) AC line currents and c) DC line positive pole voltage, d) DC line negative pole voltage, e) DC line currents and f) 0-mode voltage of AC and DC line.

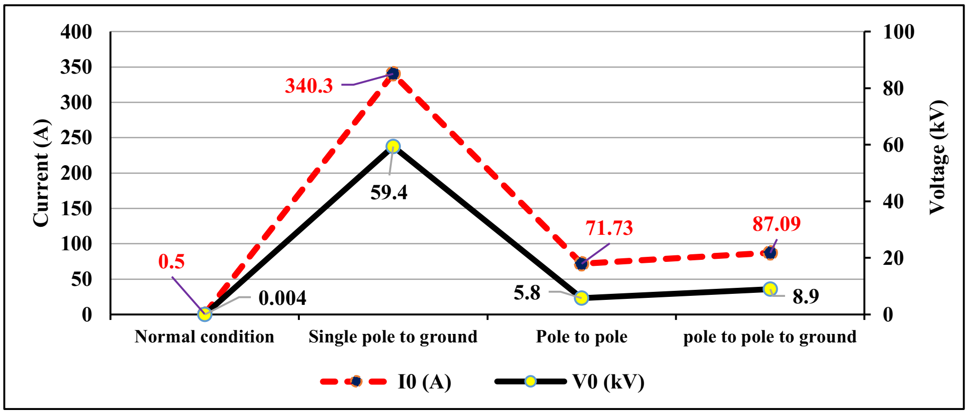

Fig 11. Comparison diagram of induced zero sequence components in the HVAC line at different DC faults condition compared to the normal condition.

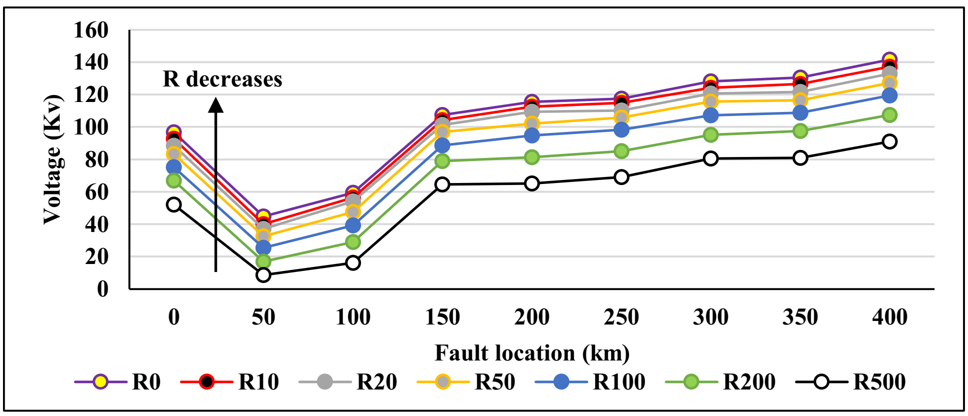

Fig. 12. Variations of fault location and fault resistance and its effect on the induced zero sequence voltage in the HVAC line for an SPGF in the “positive pole”.

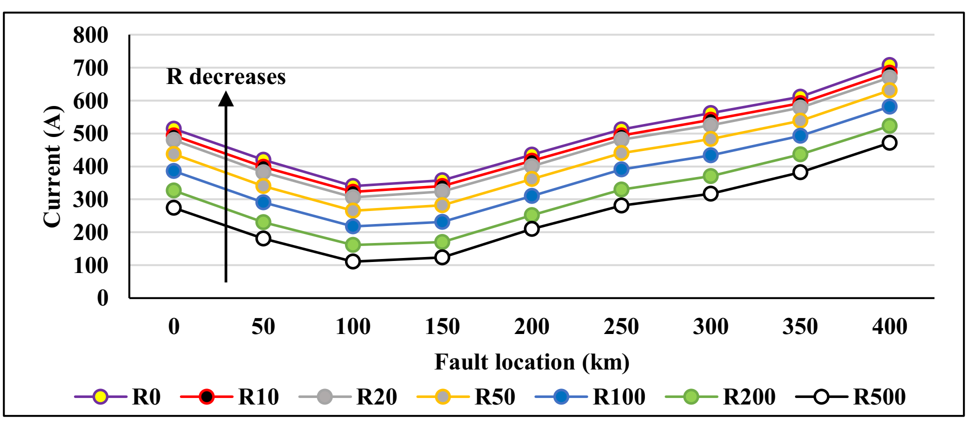

Fig. 13. Variations of fault location and fault resistance and its effect on the induced zero sequence current in the HVAC line for an SPGF in the “positive pole”.

Table 2
Different intersystem faults types.

AC/DC intersystem faults		LPF	LPGF	LPPF	LPPGF	LLPF	LLPGF	LLPPF	LLPPGF	LLLPF	LLLPGF	LLLPPF	LLLPPGF
HVAC transmission line	Single phase	*	*	*	*								
	Double phases					*	*	*	*				
	Three phases									*	*	*	*
HVDC transmission line	Single pole	*	*			*	*			*	*		
	Double poles			*	*			*	*			*	*
Ground			*		*		*		*		*		*

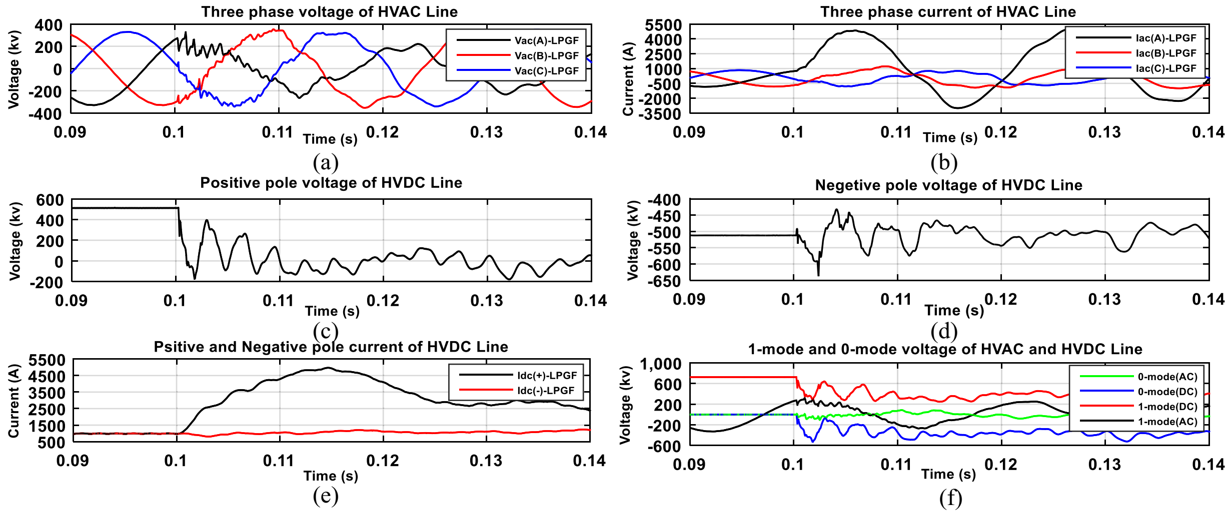

Fig. 14. AC and DC waveforms for LPGF at $x = 100$ km, a) AC line voltages, b) AC line currents and c) DC line positive pole voltage, d) DC line negative pole voltage, e) DC line currents and f) 1-mode and 0-mode voltage of AC and DC line.

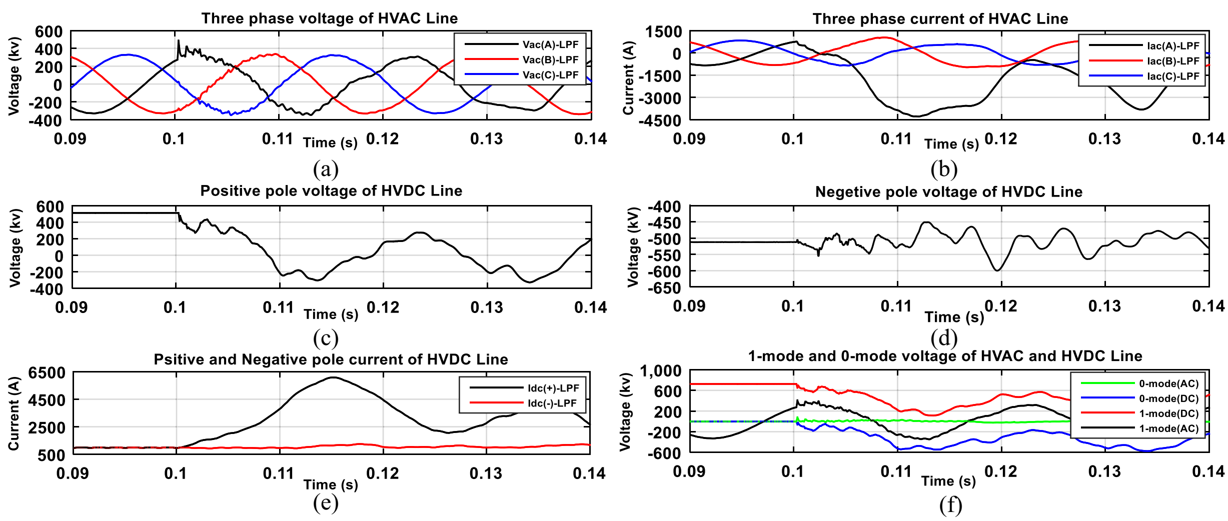

Fig. 15. AC and DC waveforms for LPF at $x = 100$ km, a) AC line voltages, b) AC line currents and c) DC line positive pole voltage, d) DC line negative pole voltage, e) DC line currents and f) 1-mode and 0-mode voltage of AC and DC line.

of healthy conductors are due to the electromagnetic coupling between healthy conductors and faulty conductors.

Another case of a single-pole to phase fault is a fault without ground connection (LPF) as shown in Fig. 15. Since the growth of the fault current in DC systems is very high, after the detection of the DC fault and the blocking the converter, the faulty DC line is opened from both sides. While the faulty phase of the AC system is still energized and is connected to the DC line through the fault path. As shown in Fig. 16, in this condition, the AC fault current is flowing to the ground through the ground capacitors of the DC system. This causes charging of the transmission line capacitors and an increase in the AC voltage at the end of the transmission line [33].

The analysis of the fault conditions for an LPF is different from the LPGF. For an LPF, the DC faulty pole current increases in the first few milliseconds, and in this time period, it appears from the DC system's point of view as an SPGF with a grounding impedance equal to AC system impedance plus neutral grounding impedance of the AC system. During this transient period, the fault current flows from the faulty pole to the faulty phase and closes its loop through the ground of the AC system. After the first transient period, the AC fault current increases

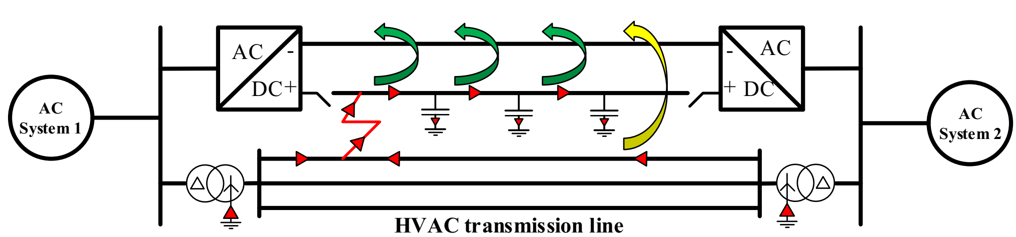

Fig. 16. Induced components under single pole (+) to phase "A" to ground fault.

and the amplitude of the fault current depends on the response of the converter control system. The control system can bypass or block the converter. If the converter is placed in blocking mode, the impedance seen from the AC system is infinite and the fault current flowing from the AC system to the DC system becomes zero. In this case, the voltage of the faulty pole of the DC line becomes equal to the AC system voltage. If the converter is bypassed, the AC fault current flows from the DC system and closes its loop through the DC system ground.

5. Conclusion

Since the use of HPOTLs on the same tower can be one of the effective ways to increase power transmission capacity, all its aspects should be investigated. In this paper, the effect of different fault conditions on the induced components in AC and DC lines in the HPOTL was investigated. The mathematical model of the mutually coupled parallel HVAC and HVDC transmission lines was extracted and the final equations of the transmission line were summarized in matrix form. To analyze the induced components in HPOTLs under fault conditions, a detailed model of an HPOTL was simulated in PSCAD software and various types of faults, including the AC/DC intersystem faults were investigated. The results obtained from simulations are as follows:

- Due to the existence of electromagnetic coupling between transmission lines in HPOTLs, voltage and current components are induced in transmission lines in normal and fault conditions. These induced components have adverse effects on the performance of transmission equipment. For example, they cause converter transformer core saturation, noise increase, transformer heating, and transformer loss of life.
- The amplitude of the induced components in fault conditions is much larger than normal condition, and this can cause the mal-operations of healthy transmission lines protection system in the event of a fault on one of the adjacent lines.
- Among the various DC and AC faults, the SPGFs induce the most zero sequence components of voltage and current in the adjacent AC line and SLGFs induce the most fundamental frequency components in the DC line, respectively.
- Induced components in the AC and DC lines are the highest for faults at near the ends of the transmission line and lowest for the middle of line faults. Induced components also have larger amplitudes at poles (phases) closer to the faulty phase (poles).
- During AC/DC intersystem faults, there is not only an influence from the DC to the directly affected AC phase(s) and vice versa, but also an influence on non-directly involved AC phase(s) and DC pole through electromagnetic coupling. LPGF and LPF are the most critical type of intersystem faults in terms of detection and protection, which must be considered in the protection settings of HPOTLs.

Due to the mutual induction between the lines in HPOTLs, a comprehensive protection system is required for the simultaneous protection of AC and DC transmission lines by considering the electromagnetic coupling between them.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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