Analysis and evaluation of Intersystem Fault in a Hybrid AC/DC Power System and its impact on the Protection System

R.E. Torres-Olguin, M.M. Saha, H.K. Høidalen

Abstract— **Due to increasing environmental burden and other cost related reasons, the transmission network is undergoing major change globally. One way to utilize transmission corridors more efficiently is to have several three-phase systems in the same tower. This can be multiple AC and DC circuits or AC circuits with different system voltages. The transmission of DC and AC on one tower is a challenging technical territory, particularly in case of intersystem faults. In order to cope with this, new technical solutions are required as well as practical testing of the present protection ideas are needed. This paper presents a PSCAD simulation model in order to investigate the intersystem faults in a hybrid AC/DC line, by utilizing four different cases. These cases have been tested to validate the simulation model and the results are presented. The arising phenomena especially the consequences with respect to the protection systems are discussed.**

Keywords: **hybrid AC/DC transmission line, fault analysis, protection, PSCAD simulation.**

I. Introduction

THE growing demand for electrical energy and the lack of appropriate overhead transmission routes require the application of multiple circuit lines often at different voltage levels.

Because the conductors are placed a few meters apart from each other over long distances, not only internal faults in one circuit but also intersystem faults between phases of different circuits may occur. As intersystem faults influence two circuits, they are very complicated for network protection. Previous protection concepts did not concentrate on inter-system faults as there was no reliable information available on the selective detection and location of these faults. Few methods [1, 2] presented a solution for detecting intersystem faults according to distance protection principle. These methods described the discrimination of intersystem faults and double-circuit transmission lines with different voltage levels and different line parameters.

Two decades later, a paper [3] suggested a method to investigate and increase reliability of the distance protection relay during a combined fault of transmission lines carrying two different voltage levels. This study used actual fault records, analytical method and PSCAD simulation studies to analyze combined faults in an existing 400 kV and 150 kV transmission lines of Denmark.

HVDC systems have been connected to AC networks with high short-circuit power ratings compared to the nominal HVDC transmission power. As a consequence, the influence of the HVDC system has to be taken into account before installing high speed line protection.

The impact of HVDC Stations on Protection of AC Systems, was studied by a CIGRE JWG B5/B4 [4]. An HVDC system may bring about different fault characteristics in the HVAC systems, influence the operation of HVAC protection or even cause false operation. When an HVDC scheme is installed, it is recommended that a careful review of protection philosophies and settings in the nearby connected AC networks be made to determine possible adverse risks of maloperation due to the influence of the DC scheme during steady state and transient condition. However, proper design of the protection scheme can prevent false operation of the AC protection. Alternative protection principles need to be considered for some cases.

Due to the strategy to shut down conventional power stations (e.g. coal, nuclear) the balance between generation and load is changed. The wind energy onshore as well as offshore is mainly available a long distance apart. This situation requires necessity of electrical energy transportation. One technical solution is the utilization of present transmission routes and the substitution of AC line with a DC line. If AC and DC are on the same tower the challenge is the detection of intersystem faults. That means faults between the AC and DC systems [5].

A recent paper [6], described the intersystem faults between high voltage AC and DC systems. This is a new type of line fault in which the AC and DC system characteristics are combined. Thus, both systems suffer from undesired frequency components within the current characteristics. In order to handle these intersystem faults reliably, a classification of the present fault is required, which demands an adaption of existing DC protection schemes. For the classification of an intersystem fault the paper used the fundamental frequency component on the DC voltage as an appropriate criterion, since it distinguishes an intersystem faults from a pure DC fault [6].

A hybrid model that combines alternating current (AC) and

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direct current (DC) in the same line length is used in this paper for investigation as shown in the Figure 1. The potential benefits are the following:

- To increase the power transmission capacity of a transmission corridor without major modification of the existing infrastructure.
- Better utilization of the existing corridors
- Minimization of the environmental impact

Steady- state and transients on the AC transmission system influences the HVDC transmission system and vice versa under certain system conditions. Protection system may be influenced adversely. The main challenges is related to Inter-system faults and this have not been studied deeply. Moreover, there is lack of operational experience.

This paper presents a PSCAD simulation study in order to investigate the intersystem faults in a hybrid AC/DC line. The arising phenomena especially the consequences with respect to the protection systems are discussed and recommendation for further investigations are given.

II. System description

The investigated hybrid system is a point-to-point HVDC in parallel with an HVAC system as shown in Fig. 1. The total transmission length is 300-km. The AC system is rated at 380 kV, 50 Hz, 1000 MVA and the HVDC system is a bipolar ±400 kV, also 1000 MW. The nominal values of voltages and currents of each system are summarized in Table 1.

The HVDC converter station contain two voltage source converters (VSC) in bipolar configuration, i.e. it contains positive and negative poles that can provide redundancy. Each power converter is a half-bridge modular multilevel converter (MMC) with the converter arm inductance of 15 % and transformer inductance of 18 %. A detail equivalent model (DEM) is used to represent the MMCs. DEM is based on the method of nested fast and simultaneous solution (NFSS). This method breaks the original network into sub-networks, and then solve the admittance matrix of each sub-network. This approach used to reduce the simulation time. MMC converters are connected through long cables, which have been modelled using the frequency dependent phase model for electro-magnetic transients programs (EMTP), which is able to produce the exact DC response. The main focus of this research is to study the intersystem faults, so AC generators are simplified, i.e. all AC systems are emulated by an equivalent AC source voltage of 380 kV which operates at 50 Hz. It is assumed that all AC systems are relatively strong systems with a corresponding short circuit ratio of 5, and X/R= 10.

TABLE I
HVDC/HVAC RATINGS

	HVDC	HVAC
Nominal Voltage	±400 kV	380 kV
Nominal Power	1000 MW	1000 MW
OHL length	300	300
Fundamental Freq.		50 Hz

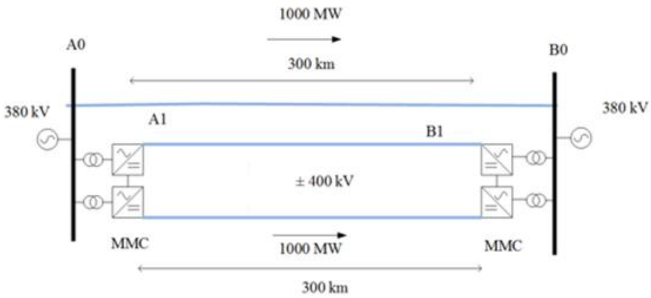


Fig. 1. Reference system Hybrid AC/DC system

The MMC control system contains two control levels: upper level controllers and lower level controllers. Upper level controllers are in charge of the primary objectives such as DC voltage or active power regulation. They use a vector control strategy, which basically divides the controller into two control loop: inner and outer control loops. The inner controller regulates the current at the AC side of the converter while the outer controller regulates DC voltage or active power, and AC voltage or reactive power depending of the control objectives. In this case, converter B1 regulates DC voltages while A1 regulates the active and reactive power. The vector control strategy uses a dq0 reference frame in order to facilitate the control design. The lower level controllers are in charge of the internal objectives such as circulating current suppression, voltage balancing and firing signals.

III. Validation of the simulation model

Several cases have been tested to validate the simulation model. In Case 1, only the AC system is connected while the DC system is disconnected. In Case 2 only DC is connected. In Case 3, both the AC and DC systems are connected but the fault occurs only on either the AC side or the DC side. In Case 4, the intersystem fault scenario occurs.

A. Case 1, only AC circuit is connected

Fig. 2 shows the scenario when DC side is disconnected. Fig. 2(a) shows the steady state behavior. It shows the expected values in power at the sending and receiving end, and the three-phase voltage and current, i.e., 300 kV and 2 kA, respectively. Fig. 2(b) shows three-phase to ground fault behavior. In all cases the fault is applied close to the sending side and lasts for about 10 cycles. Only sending side is displayed. It can be observed that the three-phase voltages drop to zero as is expected while the currents go about 20 kA amplitude in all the phases as is also expected. Fig. 2(c) shows two-phase to ground fault behavior in case 1. As was expected, voltage drops in two phases and overcurrent occurs in two phases. Fig. 2(d) shows the single-phase to ground fault in the system. It can be seen that one of the phase drops almost to zero, and overcurrent occurs in the unhealthy phase.

B. Case 2, only DC circuit is connected

Fig. 3 shows the steady state of case 2 i.e. when AC side is disconnected. Fig. 3(a) shows the steady state situation. The DC voltage is well regulated to ±400 kV as shown in the figure. The DC current is regulated to its reference that is 1 kA. Both sending and receiving sides are displayed.

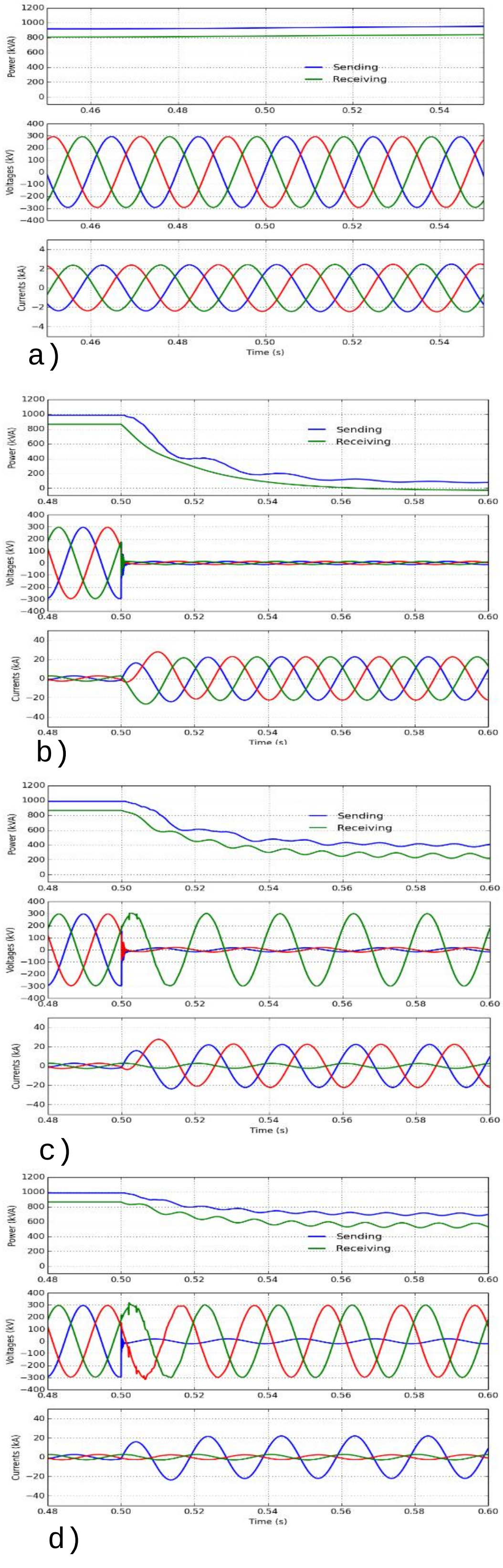


Fig. 2. Case 1: a) steady state behavior b) Three-phase to ground c) two-phase to ground d) one-phase to ground

Fig. 3(b) shows the pole-to-ground DC fault (between positive and ground). The fault is applied close to the receiving side i.e.1 km from bus B0. This side is regulating the DC voltage. The DC voltage drops to half his nominal values as expected. A huge DC current occurs in the positive pole while the negative remains in operation. Fig. 3(c) shows the pole-to-pole DC fault, i.e. a fault between positive and negative poles. The fault is applied close to the sending side. This side is regulating the DC voltage so after the fault, the DC voltage collapses as expected. A high overcurrent occurs in the DC side consequently.

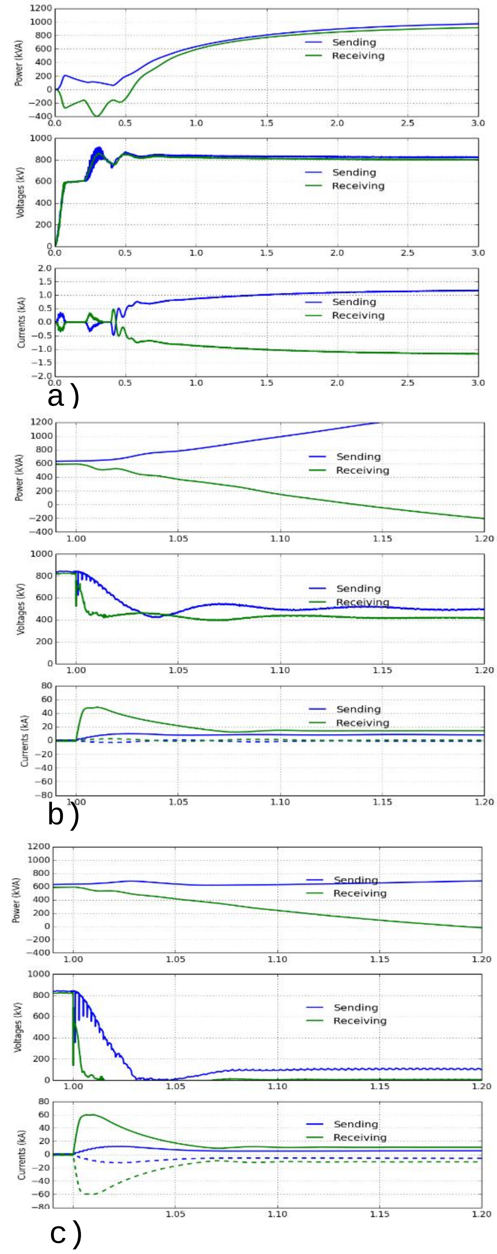


Fig. 3. Case 2: a) system-steady state behavior b) DC system-pole-to-ground fault c) DC system-pole-to-pole fault

C. *Case 3, both AC and DC circuis are connected but faults occur either on AC or DC circuit*

Fig. 4 shows the effect of DC fault on the AC side. This is a pole-to-ground DC fault, which is applied close to the receiving side, i.e. 1 km from bus B0. The short circuit ratio is 5 and the MMC converters are supporting the AC grid providing reactive power. When the DC fault occurs, the converters are unable to support the grid so a voltage drop occurs as shown in the figure. Fig. 5 shows the effect of DC fault on the AC side. A pole-to-ground DC fault, is applied close to the receiving side (1 km from bus B0). It is seen that a DC component is introduced in the AC current as shown in the figure.

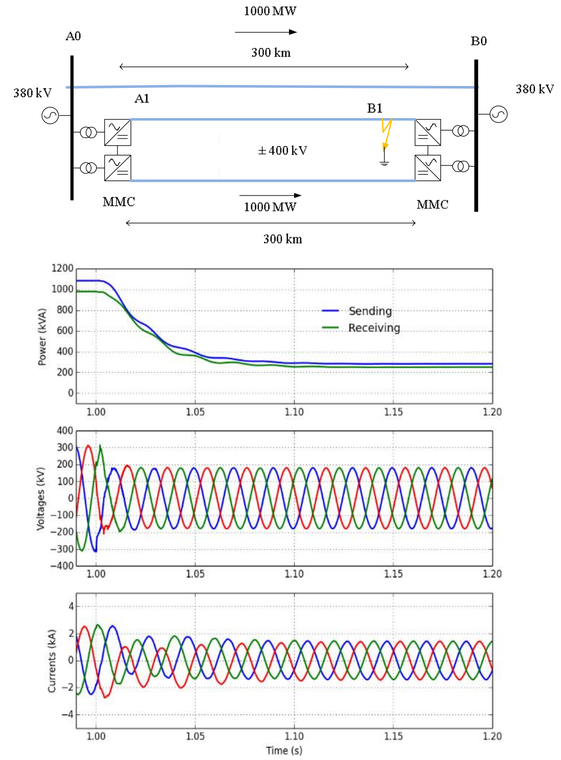


Fig. 4. Case 3: Effect pole-to-ground DC faults on AC side

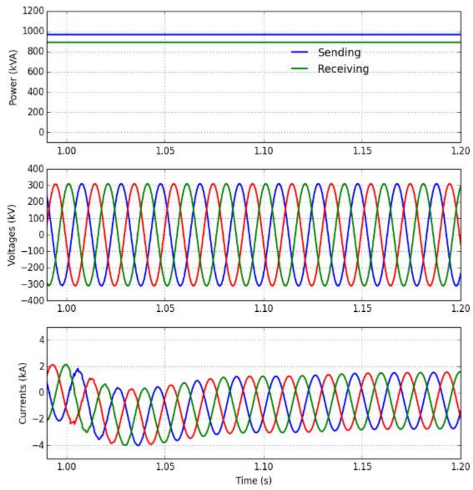


Fig. 5. Case 3: Effect pole-to-ground DC faults on AC side (stiff grid)

Fig. 6 shows the effect of an AC fault on the DC side. A three-phase to ground fault, is applied close to the receiving side (1 km from bus B0) An overvoltage occurs since the converter is unable to regulate the DC voltage, and the converter A1 transfers power into the system which creates a power unbalance which is reflected in the DC voltage.

Fig. 7 shows the effect of an AC fault on the DC side. A single-phase to ground fault, is applied close to the receiving side (1 km from bus B0). An overvoltage occurs since the converter is unable to regulate the DC voltage, and the converter A1 transfers power into the system which creates a power unbalance which is reflected in the DC voltage. A characteristic second order harmonic component appears in voltage and current.

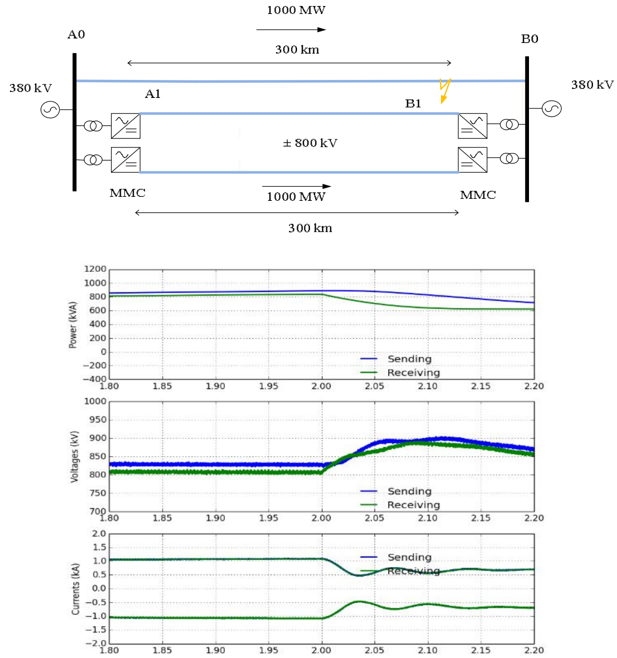


Fig. 6. Case 3: Effect three phase to ground AC faults on DC side

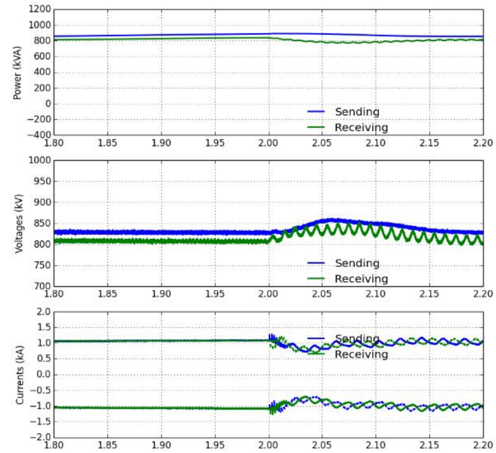


Fig. 7. Case 3: Effect single phase to ground AC faults on DC side

D. Case 4, intersystem faults between AC and DC circuits

Fig. 8 shows the effect of intersystem on the AC side. The fault is applied close to the receiving side (10 km from bus B0). A DC component is introduced in the AC current as shown in the figure.

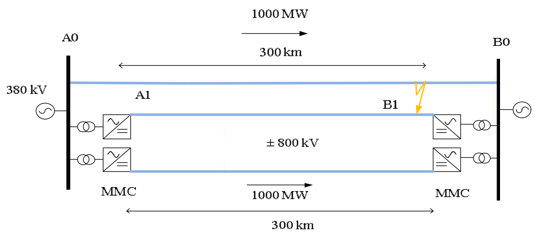
Fig. 9 shows the effect of intersystem fault on the DC side. The fault is applied close to the receiving side (10 km from bus B0). A 50 Hz component is observed in the DC current.

Fig. 10 shows the effect of intersystem on the AC side. The fault is applied close to the receiving side (10 km from bus B0). A DC component is introduced in the AC current in two of the phases as shown in the figure.

Fig. 11 shows the effect of intersystem fault on the DC side. The fault is applied close to the receiving side (10 km from bus B0). A 50 Hz component is observed in the DC current.

Fig. 12 shows the effect of intersystem fault on the AC side. The fault is applied close to the receiving side (10 km from bus B0). A DC component is introduced in the AC current the three phases as shown in the figure.

Fig. 13 shows the effect of intersystem on the DC side. The fault is applied close to the receiving side (10 km from bus B0). No 50 Hz component is observed in the DC current.



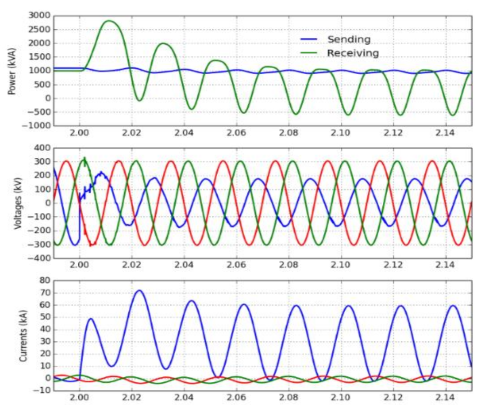


Fig. 8. Case 4: Intersystem faults-1phase to one pole ac side

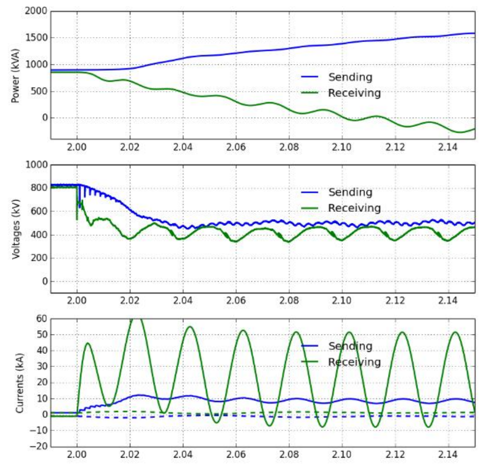


Fig.9. Case 4: Intersystem faults- 1 phase to one pole on DC side

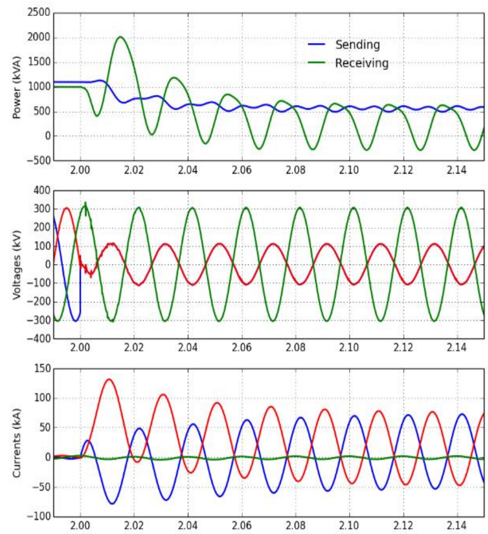


Fig. 10. Case 4: Intersystem faults- 2 phase to one pole on DC side

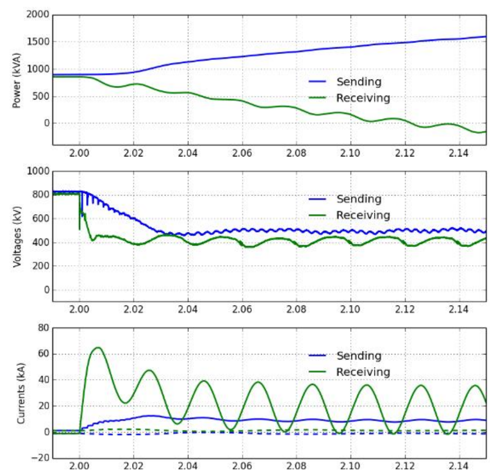


Fig. 11. Case 4: Intersystem faults- 2 phase to one pole on AC side

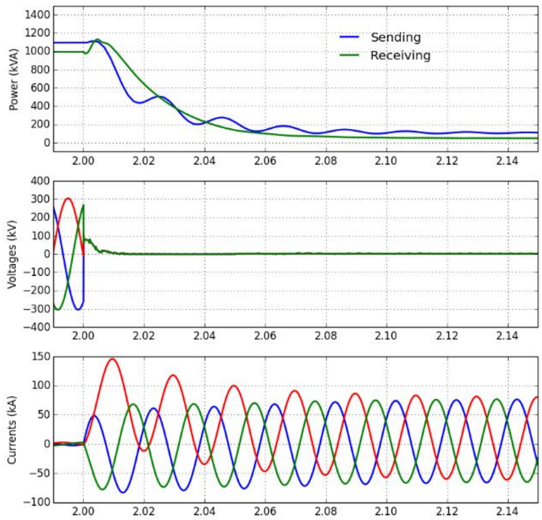


Fig. 12. Case 4: Intersystem faults-3 phase to one pole on AC side

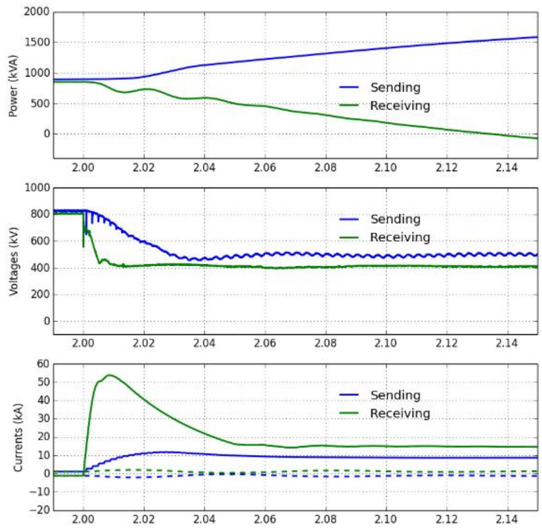


Fig. 13. Case 4: Intersystem faults-3 phase to one pole on DC side

IV. Discussions on Simulation Results

A PSCAD simulation model was developed to study different kinds of inter and intra faults in a hybrid AC-DC transmission line on the same tower. The simulation models have been validated using different scenarios including: case 1 describes the response of the system when the DC line is disconnected as shown in Figs. 2. The case 2 describes the response of the system when AC line is disconnected as shown in Figs. 3. The voltages and currents as shown in Figs. 2 and Figs. 3, justified the validity of the AC respective DC systems.

In case 3, the effects of AC fault into the DC system and vice versa are shown in Figs. 4-7. There are sufficient impact of DC faults on protection of the AC systems and vice versa. The similar phenomena has been described in paper [4]. However, proper design of protection scheme can prevent false operation of AC protections, while in some cases it is necessary to consider new protection algorithms.

Inter-system fault cases are investigated in case 4, which is the main topic of the paper. The steady-state and transient interaction are shown. Three cases were studied: one phase to one pole, two phase to one pole and three phases to one pole. The simulation results are shown in Figs. 8-13. The arising phenomena need further investigations, especially the consequences with respect to the protection systems. The protection of HVDC has been evaluated. Paper [6] mentioned that for classification of an intersystem fault, the fundamental frequency component on the DC voltage is an appropriate criterion, since it distinguishes an intersystem fault from pure DC fault. In Fig. 9, the same behavior has been observed. The differences are the location of fault and fault resistance.

For the protection on HVAC side, new fault identification method and impedance measuring methods must be explored by utilization of better signal processing and relaying algorithms [7]. It is necessary to study more relevant scenarios for the inter-system faults, e.g. high impedance inter-system faults, and study the effect on the standard AC protections. In order to detect the intersystem faults effectively, new protection algorithms are required. It is also necessary to validate simulations with real data.

V. Conclusions

The main purpose of this paper is to describe a PSCAD simulation model suitable to investigate the intersystem faults using a hybrid AC/DC line. The simulation models have been validated using different scenarios and the results are presented in the paper. It is necessary to find more relevant scenarios for the inter-system faults, e.g. high impedance inter-system faults, and study the effect on the standard protections. Further work are required to explore new protection principles for intersystem faults.

VI. References

[1] H. Becker, J. Nilges and H. Dittrich, "Distance protection of double-circuit lines with different rated voltages during intersystem faults,"*Cigre 1990 session, paper 34-206*, 1990.

[2] L. Eriksson and M. M. Saha, "Method and apparatus for detecting flashover between conductors of different voltage levels suspended in parallel from the same tower," *United States Patent, patent number 5352983*, Oct.4, 1994.

[3] C. L. Bak, R. Sigurbjörnsson, B. S. Bukh and R. Post, "Distance Protection Impedance Measurement for Inhomogeneous Multiple-Circuit 400/150 kV Transmission Lines with Shared Towers," *The 13th IET International Conference on Developments in Power System Protection (DPSP) conference, Edinburg, UK,* 7-10 March 2016.

[4] X. Zhao (Convenor), "Impact of HVDC stations on protection of AC systems" *Cigre Joint Working Group, B5/B4.25, TB 484*, 2011.

[5] H. J. Herrmann, "Change in Electrical Energy System-Challenges and Achievements for Protection and Automation,"*Pac World Conference, Zagreb, Crotia*, 23-26 June 2014.

[6] C. Petino, P. Riffing and A. Schnettler, "Intersystem Fault Clearing in Hybrid AC/DC Power Systems with Full Bridge Modular Multilevel Converters," *The 13th IET International Conference on AC and DC Power Transmission (ACDC)* 2017.

[7] M. M. Saha, J. Izykowski, and E. Rosolowski, "*Fault Location on Power Networks*," London, Springer, 2010