

Simulation and analysis of faults in high voltage DC (HVDC) power transmission

Karthikeyan, Manickam; Yeap, Yew Ming; Ukil, Abishek

2014

Karthikeyan, M., Yeap, Y. M., & Ukil, A. (2014). Simulation and analysis of faults in high voltage DC (HVDC) power transmission. In Proceedings of the 40th Annual Conference of the IEEE Industrial Electronics Society 2014 (pp.1786-1791). Dallas: IEEE Industrial Electronics Society.

<https://hdl.handle.net/10356/79430>

© 2014 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works. The published version is available at:
[<http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=7048744&searchWithin%3DSimulation+and+Analysis>]

Downloaded on 23 Aug 2022 22:13:05 SGT

Simulation and Analysis of Faults in High Voltage DC (HVDC) Power Transmission

Manickam KARTHIKEYAN
School of EEE
Nanyang Technological University
Singapore
Email: karthike009@e.ntu.edu.sg

Yew Ming YEAP
School of EEE
Nanyang Technological University
Singapore
Email: yeap0022@e.ntu.edu.sg

Abhisek UKIL
School of EEE
Nanyang Technological University
Singapore
Email: aukil@ntu.edu.sg

Abstract— Modern civilization depends heavily on the consumption of electrical energy for industrial, commercial, agricultural, domestic and social purposes. However, for the current HVDC system, proper protection devices and logic are not yet as mature as the AC counterpart. This paper presents the fault analysis for the protection of the HVDC (65–765 kV range) grid, using PSCAD. Faults in the DC transmission line are analyzed. This paper also looks into the response of the system to each kind of faults. It is observed that the AC and DC faults have different signatures allowing us to tell them apart. The rise time of the fault current is presented here. Analysis of load changes is also done comparatively with the fault cases.

Keywords— Fault currents; Load change; HV Transmission, HVDC, HVDC protection, IGBT, PSCAD, Voltage source converter, VSC.

I. INTRODUCTION

High Voltage Direct Current (HVDC) transmission is the future trend in bulk power transmission [1]. The transmission losses and the capital investments are eventually higher for AC systems beyond certain distance, e.g., typically about 700 KM for overhead and 40 KM for underground lines [2]. Direct connection between two AC systems with different frequencies is rather difficult. HVDC is beneficial in these cases. Moreover, the HVDC systems cause low impacts on the environment compared to the HVAC systems. Integration of renewable energy sources into the grid would be easier using the HVDC system.

There are various methods for controlling the HVDC point-to-point links, but the protection system is still lagging behind the AC systems. There is no suitably rated protection device and logic for the targeted meshed HVDC systems. Designing of the circuit breaker (CB) for HVDC is a challenging task, along with devising a robust fast protection scheme for the future transmission system. This is the theme of the paper.

II. HVDC: STATE OF ART

The modern form of HVDC transmission uses technology developed extensively in the 1930s in Sweden (ASEA) and in Germany. Early commercial installations included one in the Soviet Union in 1951 between Moscow and Kashira and between the island of Gotland and Swedish mainland in 1954 [2]. The previous longest HVDC link in the world was

the Xiangjiaba–Shanghai 2,071 km (1,287 mi), ± 800 kV, 6400 MW link connecting the Xiangjiaba Dam to Shanghai, in the People's Republic of China. Early in 2013, the longest HVDC link has been the Rio Madeira link in Brazil, which consists of two bipoles of ± 600 kV, 3150 MW each, connecting Porto Velho in the state of Rondônia to the Sao Paulo area, over a length of 2,375 km. Rock Island Clean Line was being installed in North America, over a length of 805 km, and power of 3,500 MW which is expected to be completed in the year 2017. This necessitates additional research and development of various components to operate at the extra high-voltage (EHV) levels.

III. PROTECTION OF HVDC GRID

Due to the lack of firm understanding and well-defined standard, the current DC grid protection scenario is still not mature. Hence, the DC transmission networks in the present day are restricted only to the point-to-point connections. For instance, the mechanical DC CB requires very long operating time (20ms–50ms), which is highly undesirable in a DC system. On the other hand, semiconductor (e.g., Insulated-Gate Bipolar Transistor or IGBT)-based DC CB is faster. But it has the particular drawback of high on-state loss. Combining the advantages of both devices, the hybrid DC CB [3] has been proposed, with the capability to provide low loss and quick operation.

However, the prototype has not yet been utilized to its full potential, and its prospect still remains unclear. Furthermore, DC protection logics, equivalent to the existing AC standards like IEEE C37.90, IEC 60255, are missing. The multi-terminal DC grid will be hard to realize until a set of sound requirement of protection logic (eventually standard) is established, alongside with a reliable DC CB.

The inherent differences in the sinusoidal voltage and current in AC with the unidirectional nature in DC, suggest that the protection devices of both systems are supposed to work differently as well. The existing AC CBs are conveniently designed to interrupt fault current at zero crossing, which is absent in the DC system.

IV. LITERATURE REVIEW

In recent years, the voltage source converter (VSC)-based multi-terminal DC (MTDC) is considered to be one of the suitable methods in structuring the meshed DC grid. There are various methods for controlling the HVDC in the multi-terminal grid but as far as the protection system is concerned, it is still lagging behind the AC systems, without rated protection devices and logic. By employing double thyristor switches, the diode freewheeling effect can be eliminated and the DC-link fault can be freely decayed [4]. This clears the fault quickly without tripping any CB, and can implement fast and automatic power transmission recovery, which greatly enhances the reliability of the HVDC system.

The faulted line in a multi-terminal HVDC can be detected by tracking the changes in some system parameters. An accurate detection can be done, using three parameters, as suggested in [5], initial current change, rise time of the first wavefront of the branch current and the oscillation pattern. As much as fault clearing time is critical, the authors stressed the use of local information at each VSC in their protection scheme instead of telecommunication [5].

In order to clear the DC fault, currently the AC CBs are used with the fast DC switches. This scheme is cheaper than using the DC CBs, which only start to emerge [3]. Two types of faults are of concern: line-to-line and line-to-ground. DC line fault is always the primary concern in a HVDC system as its effect is more prevalent than the AC fault. With the 'handshaking method' proposed in [6], the PSCAD/EMTDC simulation result validates that this method can effectively remove the faulted DC line without telecommunication, and the system is able to restore to normal operation 0.5s after the fault. To meet the requirements of protection applications, the frequency dependent model is separated into the distributed parameter model plus a compensation matrix related to the frequency dependent nature, and FIR filters are adopted to fit the compensation matrix.

The fast DC breaker made up of IGBT and anti-parallel diode is able to add merit in the protection system, whereby the fault isolation can be instantly realized by simply triggering a pulse to the IGBT enforcing the blockage of fault current [3, 7]. Not only it is faster than AC CB, the system also can restart immediately. However, the high on-state loss of the IGBT is of concern. Also, the IGBT might not be available in the higher voltage ratings, required for the HVDC.

Tang and Ooi presented how the MTDC system can survive from DC fault without the expensive DC CB [6]. The AC side CB will clear the DC fault which is already installed in the system on the AC side of the VSCs. The relatively fast and cheap DC switches are used to isolate the faulted line, if the fault is permanent. This is accomplished without any communication channels and is based on local current and voltage measurements. The selection of potential faulted line is based on polling of 3 independent methods to ensure high reliability.

V. HVDC MODEL

Fig. 1 shows the typical topology of two-terminal HVDC system. Its corresponding system parameters are listed in Table I. Generally, the simulated model consists of the following components:

- **AC utility:** It is represented as an ideal AC source behind the impedance, located at the sending- and the receiving-ends.
- **Passive filter:** Each AC source is accompanied by filter in order to eliminate the unwanted harmonics caused by the switching action. The pulse-width modulation (PWM) technique produces a very high order of harmonics, hence simplifying the design of the filter.
- **Transformer:** The grounded wye-delta transformer is needed to step up the voltage level suitable for the converter. The grounding on the neutral point of the wye connection is able to support the loop of the zero-sequence current on the primary winding, preventing the current from entering the system.
- **Converter/Inverter:** Contrary to the conventional thyristor which can be only turned on but not off, gated turn-off thyristor (GTO) has more freedom of control.
- **DC capacitor:** As much as a constant DC voltage with minimum ripple is concerned, a DC capacitor across the converter station can remove such ripple, resulting in smooth DC voltage. The size of the capacitor should not be too large; this is to ensure a stable steady-state performance when the system is interrupted with disturbance.
- **Commutation:** Commutation is defined as the process of turning off the thyristor. The rectification and inversion are accomplished either by natural or forced commutation. In natural commutation, the commutation is achieved without any external device. It cannot be used in DC system because of its unidirectional quality whereas the forced commutation is achieved using an external circuit. This helps to reduce the value of passing current below its normal holding current.

TABLE I. MODEL SPECIFICATION OF SIMULATED HVDC SYSTEM

PARAMETER	VALUE
Steady state frequency	50 Hz
Rated Capacity	100MVA
Rated AC Voltage(L-L RMS)	13.8kV
Rated DC Voltage	120kV
Sending end transformer ratio	13.8kV/62.5kV
Receiving end transformer ratio	62.5kV/115.0kV
Switching Frequency	1980 Hz
Cable Length	100km
DC Capacitor	500 μ F

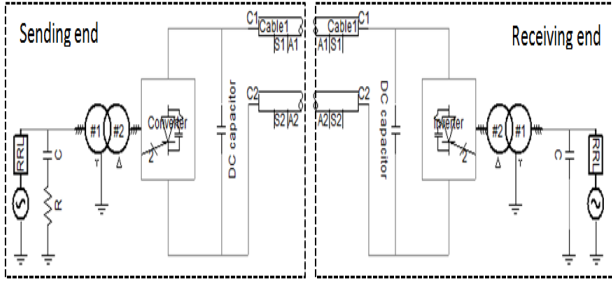


Fig. 1. Two-terminal HVDC system.

VI. CONTROL STRATEGY

The control strategy in this model adopts the Pulse Width Modulation (PWM) technique, whereby the firing signal is generated by comparing the reference waveform with high frequency ($33f_0$) triangular waveform. This kind of technique is responsible to control two independent parameters: modulation index and phase shift. Rectifier and inverter are given different control mode. In any case the model should always fulfill the energy balance as described in the (1), where I_{DC} and I_{CAP} are DC bus current and DC capacitor current respectively.

$$\begin{aligned} P_{ac} + P_{dc} + P_{cap} &= 0 \\ P_{ac} + V_{DC}I_{DC} + V_{DC}I_{CAP} &= 0 \end{aligned} \quad (1)$$

To maintain V_{DC} at certain level, the AC system has to inject enough real power P_{ac} charging up the DC capacitor. The power flow can be manipulated by the DC voltage control by changing the phase shift, which has to agree with (2). This control mode is assigned to the rectifier.

$$P_{ac} = \frac{V_{s1}V_{d1}}{X_1} \sin \delta_1 \quad (2)$$

The inverter is controlled to regulate the AC voltage. To achieve this function, the PI controller calculates the difference between the measured AC voltage and desired set point, the error is then translated into the modulation index.

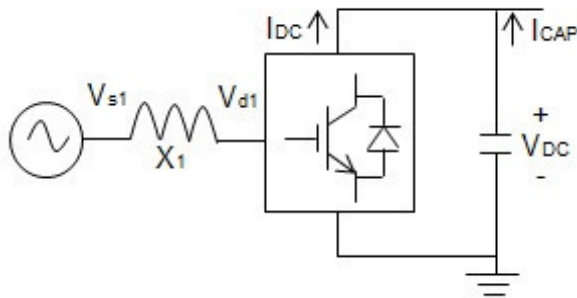


Fig. 2. Control Strategy for the two-terminal HVDC system.

VII. FAULT SIMULATION

We evaluated the dynamic characteristics of the VSC-HVDC system under various operating conditions, such as, AC power system fault as well as steady-state, changing DC power flow, and AC voltage. Therefore, various AC faults are injected at both the sending- and the receiving-ends of the power system, and fault analysis are performed. In order to identify the various fault characteristics of the AC system some simulation results are performed with the help of PSCAD [8]. The simulation tests are done at the sending- and the receiving-end sides with a single phase-to-ground fault (L-G), followed by line-to-line fault (L-L), three phase line-to-ground fault.

A. Single phase-to-ground fault

The single phase-to-ground fault is the frequent type of fault (ca. 80%) in the power system which changes the voltage and the current scenarios at both the sending- and the receiving-ends. This fault is caused by voltage fluctuation and sag experienced by the customers. It is observed markedly when a single phase-to-ground fault occurs at the secondary side of the transmission system. A single phase-to-ground fault occurs at 2.10s and lasts for 0.05s, as shown in Fig. 3. This is a temporary fault, getting cleared by itself by 0.05s. When single phase-to-ground fault occurs, phase A voltage and the current become zero. During that period the DC line is also affected, which results in sudden rise in the current and drop in the voltage level (see Fig. 4). Since the voltage at the

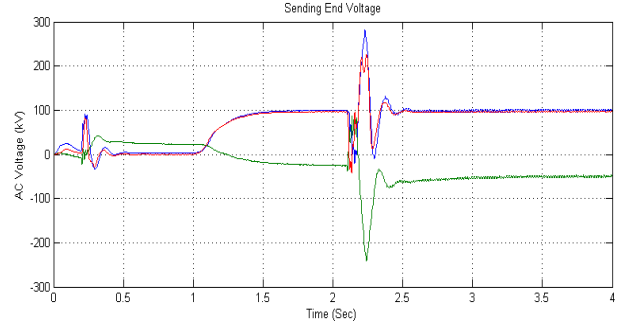


Fig. 3. Result of single phase-to-ground fault at the sending-end.

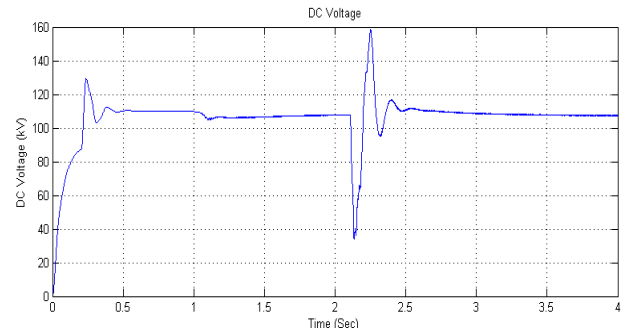


Fig. 4. Result of DC flow during single phase-to-ground fault at the receiving-end.

secondary side of the transformer is changed by single phase-to-ground fault, the converters will generate low quality DC voltage.

B. Two phase-to-ground fault

Two phase-to-ground fault in the system makes the two phase voltages same and makes the system to supply severe unbalanced voltage and current. In this test, the fault is injected at the secondary side of the transformer. Two phase voltages are distorted at the sending-end side, which affects the converter output at the DC transmission side. From the view point of voltage recovery capability, the DC transmission lines have the advantage of RMS voltage sag mitigation. However, the voltage recovery time is large, compared to the AC transmission systems.

Unlike single phase-to-ground fault, in two phase-to-ground fault once the fault is cleared, there will be voltage swell which lasts in the system for 0.05s, and the system tends to be balanced at 2.5s, as shown in Fig. 5. The inverter voltage is gradually lowered to less than 0.2 p.u.. There will not be any oscillations with the limit as the model we obtained for single phase-to-ground fault (shown in Fig. 6). The same fault analysis is carried out at the receiving-end side where the fault is injected after the transformer. During the event of two phase-to-ground fault, the sending-end voltage experiences transient condition, and the voltage at the receiving-end side drops to zero. Meanwhile, the DC current increases and the voltage decreases gradually, due to the presence of capacitor in the DC transmission side.

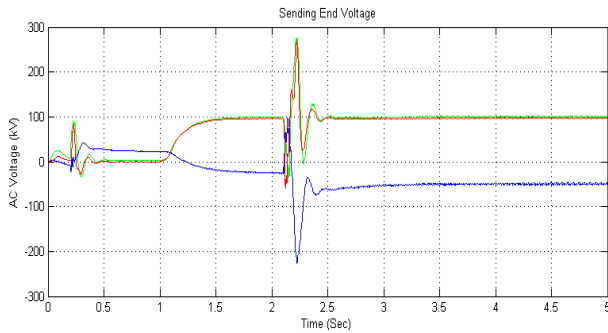


Fig. 5. Result of two phase-to-ground fault at the sending-end.

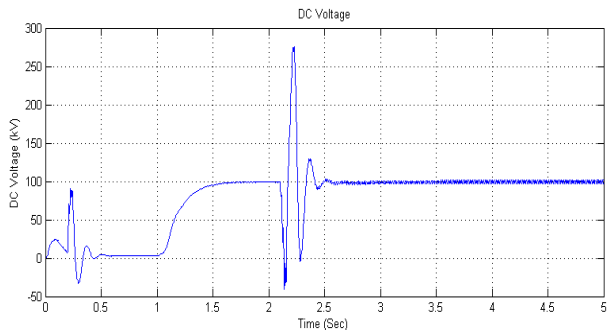


Fig. 6. Result of DC flow during two phase-to-ground fault at the receiving-end.

C. Three phase-to-ground fault

A three phase-to-ground fault is the most severe fault compared to the other two faults. When a three phase-to-ground fault occurs, the three phase voltages are zero at the point when the fault is introduced, as shown in Fig. 7. The output DC voltage does not go to zero immediately because of charging and discharging of capacitors. During single phase-to-ground fault, the receiving-end voltage is not much affected, while in three phase-to-ground fault, it decreases drastically. The transient state in the system lasts till 2.45s, and after that the system becomes balanced, as shown in Fig.8.

During the three phase-to-ground faults, the entire system is unbalanced. This affects the output of the DC system. The output voltage and current of the DC system are shown in the Fig. 8.

D. DC Transmission-line fault

The common faults in the DC transmission lines are line-to-line fault and line-to-ground fault. In this system, a line-to-ground fault is demonstrated and the response of the system is analyzed. As the faults in the cables are usually caused by external mechanical stress, therefore the faults are generally permanent, for which a lengthy repair is needed. The converters should be stopped immediately while a cable fault is detected. For overhead line, the faults are typically caused by lightning strikes and pollution. Faults along the line are likely to be temporary, which demands a fault restoration after the fault clearance which is shown in Fig. 9.

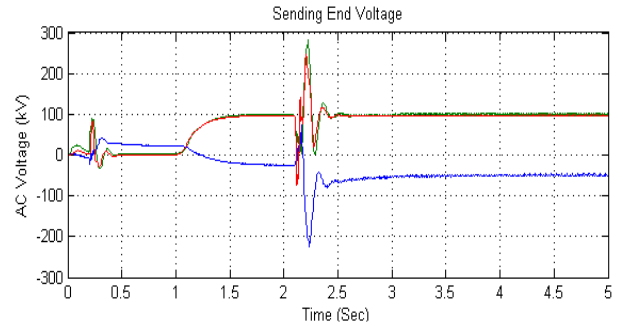


Fig. 7. Result of three phase-to-ground fault at the sending-end.

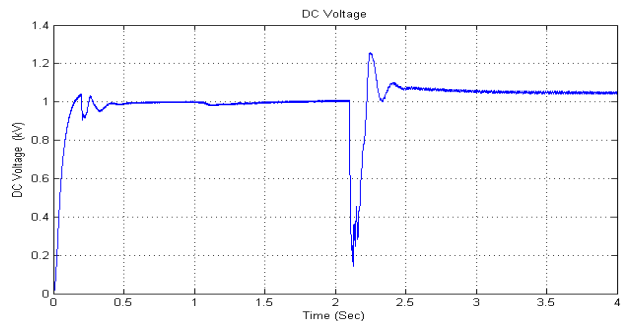


Fig. 8. Result of DC flow during three phase-to-ground fault at the receiving-end.

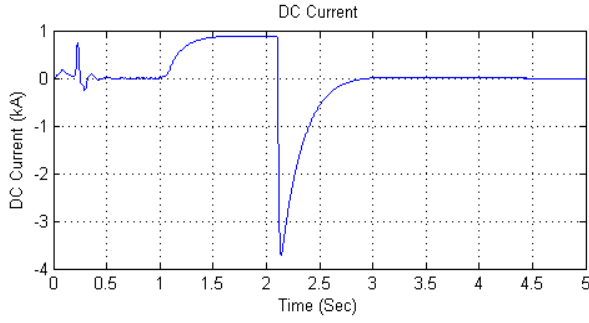


Fig. 9. Result of DC Transmission line fault.

Here the fault is introduced at 2.1s, lasting for 0.05s. Since it is temporary fault, it gets cleared by itself. As shown in Fig. 9, the DC current reverses the direction increasing more than 3kA, restoring back to the normal form. On the other end, the DC voltage never gets back to its normal operating state, and the system tends to be unbalanced. So, the receiving-end side will be affected.

E. Load Change

Various test analyses have been made with the VSC-HVDC system and one important case is the system response during the load change. The above faults are attained by the combination of RLC load. Here the analysis is made only with the inductor load (L) and the response of the system is shown in the Fig. 10.

This change in load slightly affects the DC system of the network. The load change is done at 2.1s, lasting for 0.05s. As it is a temporary case, the system gets back to its normal

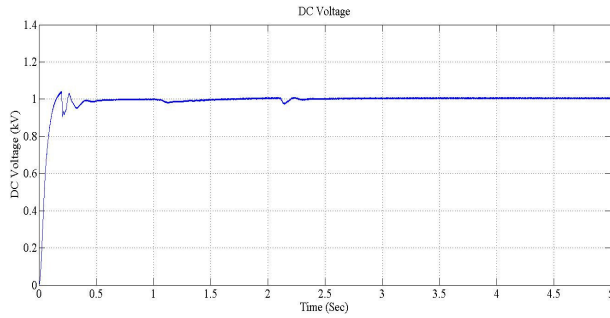


Fig. 10. Results of AC flow during load change.

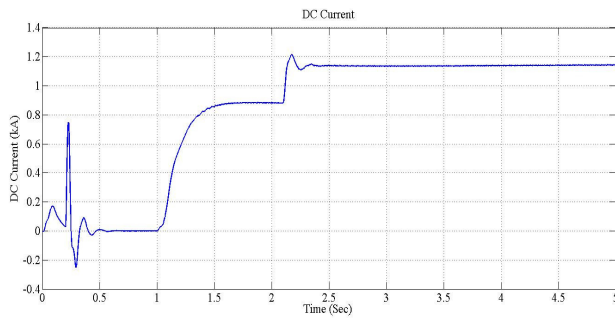


Fig. 11. Results of DC flow during load change.

steady-state operation. The DC voltage drops insignificantly and the current raises to 1.14kA.

VIII. DISCUSSIONS

In the event of fault, we have observed the pattern of the current and the voltage at the AC sending-end and the DC line. The rate of change of the transient DC current is of particular interest because this is a key signature to distinguish different fault cases. The derivative of DC current allows us to see in a clearer manner how fast the current rises when fault happens. The derivation with time constant of 0.001s is performed on the DC current and the result is presented in Table II and Fig. 12.

TABLE II. RATE OF CHANGE OF TRANSIENT CURRENT FOR DIFFERENT FAULT CASES

Type of fault	Maximum rate of change, $ \frac{dI_{DC}}{dt} $ (As ⁻¹)	Time, t (s)
Single phase-to-ground	0.1756	2.113
Two phase-to-ground	0.2081	2.110
Three phase-to-ground	0.2170	2.112
DC line-to-ground	0.3053	2.109
Load change	0.0103	2.120

The result obviously shows that the DC fault results in the transience at the fastest rate. The three types of AC faults produce rather slower transience that sees the rate of change ranging from 0.1756As⁻¹ to 0.2170As⁻¹. Equally important is that the transience due to load change is temporary as has been proven by the corresponding lowest rate of change, hence design of protection logic can take this into consideration and should not raise alarm.

The following comments are cited on the simulation results.

- The protection scheme is not discussed in this paper, as the main concern is to understand the different fault characteristics. This would in turn be helpful to develop a robust and quantitative protection logic in future work.
- As AC fault occurs, the DC voltage abruptly decreases to dangerously low level. This is due to the reaction of nearby DC capacitor discharging the current to the fault location at that instant. The current discharging results in drop in voltage, which is apparently experienced by the DC line. In order to maintain the same power, decrease in voltage is accompanied by increase in current, this effect is apparent in our simulation result.
- The magnitude of impact due to the AC fault depends on the DC capacitor size. The DC capacitor can eliminate the DC voltage ripple during steady-state

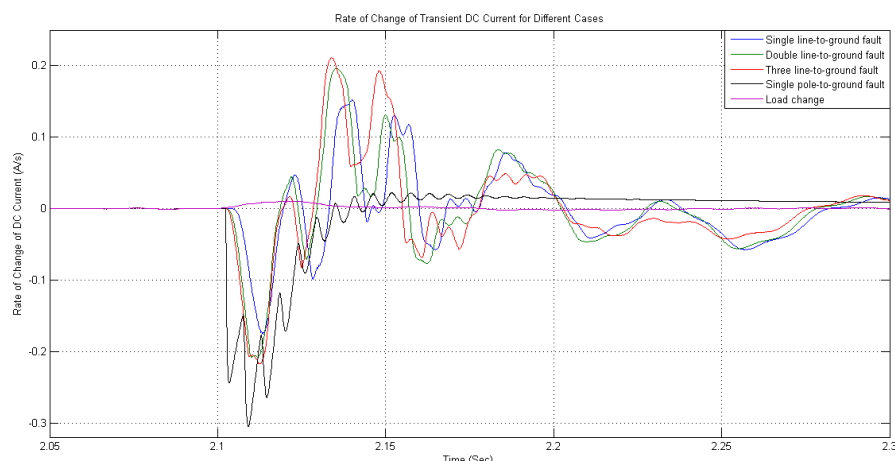


Fig. 12. Comparison of time derivative of DC current under different fault cases

operation. In the event of fault in HVDC system, the DC capacitor is the element that produces the most disastrous effect. The DC capacitor employed in this paper is extremely large, which explains its aggressively negative impact on the DC line.

- The interaction between the AC and the DC parts in the HVDC system can be extended to observe the impact of the DC fault.
- In future works, the system will be tested with DC faults at the multi-terminal network, and various possible fault criteria would be analyzed. This would lead the way to determine the quantitative requirements for the protection logic in the HVDC system.

IX. CONCLUSION

In this paper different fault characteristics of the AC system are analyzed and the response to the DC system is observed, with different faults in the AC side. Furthermore, in the simulation analysis part, diverse fault simulations such as, single, two and three phase-to-ground, and DC line-to-line fault are performed at various points of the test system. Then, the transient response of the DC transmission system under disturbance is compared with that of the AC system. We have also evaluated the rate of change of the transient DC current, with that we can conclude that DC fault results in the fastest transient while load change sees rather slower transient.

REFERENCES

- [1] Y. H. L. J. Arrillaga, N. R. Watson, *Flexible Power Transmission: The HVDC Option*: Wiley, 2007.
- [2] W. Peng, L. Goel, L. Xiong, and C. Fook Hoong, "Harmonizing AC and DC: A Hybrid AC/DC Future Grid Solution," *Power and Energy Magazine, IEEE*, vol. 11, pp. 76-83, 2013.

- [3] M. Callavik, A. Blomberg, J. Hafner, and B. Jacobson, "The Hybrid HVDC Breaker," *ABB Grid Systems Tech. Paper*, Nov 2012.
- [4] X. Li, Q. Song, W. Liu, H. Rao, S. Xu, and L. Li, "Protection of Nonpermanent Faults on DC Overhead Lines in MMC-Based HVDC Systems," *IEEE Transactions on Power Delivery*, vol. 28, pp. 483-490, 2013.
- [5] L. Tang and B. T. Ooi, "Protection of VSC-multi-terminal HVDC against DC faults," in *Power Electronics Specialists Conference, 2002. pesc 02. 2002 IEEE 33rd Annual*, 2002, pp. 719-724.
- [6] L. Tang and B. T. Ooi, "Locating and Isolating DC Faults in Multi-Terminal DC Systems," *IEEE Transactions on Power Delivery*, vol. 22, pp. 1877-1884, 2007.
- [7] C. M. Franck, "HVDC Circuit Breakers: A Review Identifying Future Research Needs," *Power Delivery, IEEE Transactions on*, vol. 26, pp. 998-1007, 2011.
- [8] *User's Guide on the Use of PSCAD*. Available: <http://pscad.com/products/pscad/>