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Published in:
2022 International Conference on Electrical, Computer and Energy Technologies (ICECET)

DOI (link to publication from Publisher):
10.1109/ICECET55527.2022.9872770

Publication date:
2022

Document Version
Accepted author manuscript, peer reviewed version

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***Abstract*—HVDC transmission systems are an attractive option for transmitting bulk power through long distance. Protection of HVDC grids plays a major role to have a secure and reliable power delivery to customers. However, design of DC protection has always been a challenge. On the other hand, transient stability of AC/DC grid is important, especially when it comes to situations with faults. The AC/DC grid should keep its stability during and after DC fault interruption. Based on grid characteristics and dynamics, there can be different solutions and circuit breaker selection for different HVDC grids. An effective design of DC protection can reduce system cost, while assuring system security at the same time. This study investigates design of HVDC protection considering system transient stability. The paper presents a method to select appropriate circuit breakers based on transient stability of AC/DC grid. The proposed method can keep transient stability under DC fault condition while avoiding over-qualified and more expensive DCCBs. Different simulation tests have been performed in PSCAD platform and test results are discussed in this study.**

Keywords—HVDC grids, protection system, voltage source converter (VSC), DC protection, transient stability

I. Introduction

HVDC grids are going to become the backbone of electrical power systems in future. HVDC systems can provide power grids with better controllability and stability enhancement [1]. New generation of power converters, Voltage Source Converters (VSC), have remarkable advantages compared to previous Current Source Converters (CSC) [2]. The VSCs can independently control the active and reactive power. [3]. Consequently, VSC-HVDC system becomes an attractive solution for transmitting large-scale renewable energies to main grid. On the other hand, HVDC systems are the only option for connection of two asynchronous AC grids. Having a reliable and effective HVDC protection is vital as bulk power usually is transmitted through HVDC transmission system [4]. AC fault current is usually interrupted in zero crossing, while there is no zero crossing in DC fault current [5]. Recently, DC Circuit Breakers (DCCB) make DC fault interruption feasible in HVDC grids [6]. An effective solution for DC fault interruption is to utilise DCCBs to isolate the faulted link in VSC-HVDC grid. However, there are different types of DCCBs with different fault interruption speed [7]. The faster DCCBs are, the more expensive they will be [8]. DC fault current rising is fast and severe and can damage power components. In the literature, it is usually recommended to use fast DCCBs for HVDC protection systems [9]. However, cost of such fast DCCBs is remarkably high. On the other hand, HVDC converters usually have their own protection systems to protect power semiconductors and the high voltage equipments [10]. This protective function is usually done within microseconds after DC fault occurrence [11]. Therefore, the fastest DCCBs may not always be necessary and it will not be cost effective. On the other hand, HVDC protection system not only must prevent power component damage, but must also secure system stability during and after DC fault occurrence. DC-side system stability is incorporated to AC-side stability. Therefore, instability of one side can lead to instability of another side [12].

With high penetration of Power Electronic Converter (PEC) interfaced Renewable Energy Sources (RES) in the modern power grid, system stability is threatened by reduction in synchronous inertia [13]. Moreover, short-circuit strength of the system is another important feature that can affect transient stability of AC/DC grids under fault condition. An AC grid with low Short Circuit Ratio (SCR) connected to a HVDC system not only can threaten the system stability under AC fault condition, but also threaten the grid stability for DC faults happening on HVDC transmission side. For example, large-scale RES, e.g. offshore wind farms, are usually connected to the main grid via HVDC transmission systems [14]. Characteristics of the AC grid that receives offshore wind energy via a HVDC transmission link can have a big impact on transient stability of the whole grid. Similarly, HVDC transmission systems can be used to connect two or multiple asynchronous AC grids. Characteristics of these asynchronous grids can influence vulnerability of the system to keep its stability under DC fault condition.

This paper presents design of DC protection and circuit breaker selection for VSC-HVDC systems considering system stability margin. Transient stability of VSC-HVDC systems will be investigated via dynamic relations based on HVDC power value, SCR and inertia time constant values of AC-connected grid. Appropriate fault interruption time under DC fault condition will be discussed considering

This work was supported by the Sino-Danish Center for Education and Research (SDC), University of Chinese Academy of Sciences.

characteristics of AC grids and HVDC power value to avoid the system instability.

II. Incorporated HVDC and AC-Connected System Stability and Dynamic Relations

Schematic of an AC grid connected to a HVDC system is shown in Fig. 1. For LCC-HVDC system, Effective Short Circuit Ratio (ESCR) is defined as Short Circuit Capacity (SCC) divided by HVDC power considering AC filter effect [15]. As AC filter is usually negligible for VSC-HVDC system, ESCR is almost equal to SCR for this type of HVDC system. Therefore, SCR for the VSC-HVDC system can be expressed as follow:

$$SCR = \frac{Short\ Circuit\ Capacity}{P_{HVDC}} = \frac{SCC_{MVA}}{P_{HVDC}} \tag{1}$$

where P_{HVDC} is the HVDC transmitted power. The SCC can be expressed as follow:

$$SCC = \frac{E_S^2}{Z_{SC}} \tag{2}$$

where E_s and Z_{SC} are the Thevenin equivalent voltage and impedance of the AC grid. Using the equation (1) and (2), the following relations can be achieved:

$$SCR = \frac{E_S^2}{P_{HVDC}} \times \frac{1}{Z_{SC}} \tag{3}$$

Generally, power grids can be classified into three groups based on network strength [15]:

$$\begin{aligned} &Strong\ Grid:\ SCR > 3 \\ &Weak\ Grid:\ 2 < SCR < 3 \\ &Very\ Weak\ Grid:\ SCR < 2 \end{aligned} \tag{4}$$

Dynamic relation between electrical angle and electrical power is as follow:

$$\frac{2H}{(2\pi f_s)} \frac{d^2\delta}{dt^2} = P_m - P_{PCC} \tag{5}$$

where H and f_s are the inertia time constant and the power system frequency. P_m and P_{PCC} are the mechanical power and the electrical power at point of common coupling. Also, δ is the load angle.

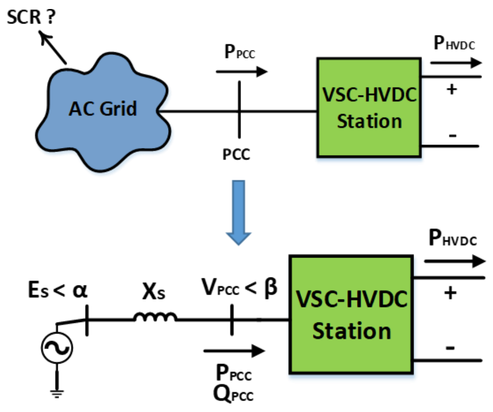


Fig. 1. Schematic of an AC grid connected to a HVDC system.

The parameter P_{PCC} can be calculated as follow [16]:

$$P_{PCC} = \frac{E_s \times V_{PCC}}{X_s} \sin(\alpha - \beta) = \frac{E_s \times V_{PCC}}{X_s} \sin(\delta) \tag{6}$$

where V_{PCC} and X_s are the voltage at the PCC point and the equivalent reactance of the AC grid respectively. The electrical power at the PPC point includes the HVDC power and the power loss of the HVDC station.

$$P_{PCC} = P_{HVDC} + P_{loss} \tag{7}$$

If the power loss can be ignored, the HVDC power is equal to the power at the PCC point as follow:

$$P_{PCC} = P_{HVDC} \tag{8}$$

Therefore, using equation (6) and (8) leads to:

$$P_{HVDC} = \frac{E_s \times V_{PCC}}{X_s} \sin(\delta) \tag{9}$$

Equation (9) shows the relation between the load angle of the AC-connected grid and the HVDC power. As the HVDC power increases, the load angle increases. Therefore, stability margin decreases with more HVDC power.

III. DC Protection and Circuit Breaker Selection Based on Critical Clearing Time

DC protection design and circuit breaker selection for the VSC-HVDC systems is a challenging topic. Very fast DCCBs are usually expensive and incur a high cost. These DCCBs may be over-qualified for protection of HVDC systems connected to strong AC grids. On the contrary, slow DCCBs may threaten the system stability during DC fault condition for HVDC systems connected to weak AC grids. Therefore, it is necessary to analyse capability of the power grid to keep its stability under DC fault situation. Critical Clearing Time (CCT) is the maximum time that is allowed to remove the disturbance without loss of synchronism. The system will be stable if the disturbance can be cleared before the CCT time. The critical load angle and the CCT can be expressed as follows [17]:

$$\delta_{cr} = \cos^{-1}\left((\pi - 2\delta_0)\sin(\delta_0) - \cos(\delta_0)\right) \tag{10}$$

$$CCT = t_{cr} = \sqrt{\frac{2H(\delta_{cr} - \delta_0)}{\pi f_s P_m}} \tag{11}$$

where δ_{cr} and δ_0 are the critical load angle and the initial load angle respectively. On the other hand, the following equation can be achieved from (3) and (9):

$$P_{HVDC} = \frac{E_S^2}{X_S SCR} = \frac{E_s \times V_{PCC}}{X_s} \sin(\delta_0) \tag{12}$$

Then, the following equations can be achieved from (12). The initial load angle can be expressed by two alternative relations:

$$\delta_0 = \sin^{-1}\left(\frac{E_s}{V_{PCC} SCR}\right) \tag{13}$$

$$\delta_0 = \sin^{-1}\left(\frac{P_{HVDC} X_s}{E_s V_{PCC}}\right) \tag{14}$$

$$CCT\left(SCR,H\right)=\sqrt{\frac{2H\left(\cos^{-1}\left(\frac{\pi E_s}{V_{PCC}SCR}-\sin^{-1}\left(\frac{E_s}{V_{PCC}SCR}\right)\frac{2E_s}{V_{PCC}SCR}-\sqrt{1-\frac{E_s^{\ 2}}{V_{PCC}^{\ 2}SCR^2}}\right)-\sin^{-1}\left(\frac{E_s}{V_{PCC}SCR}\right)\right)}{\pi f_s P_m}} \tag{15}$$

$$CCT\left(SCR,V_{PCC}\right)=\sqrt{\frac{2H\left(\cos^{-1}\left(\frac{\pi E_s}{V_{PCC}SCR}-\sin^{-1}\left(\frac{E_s}{V_{PCC}SCR}\right)\frac{2E_s}{V_{PCC}SCR}-\sqrt{1-\frac{E_s^{\ 2}}{V_{PCC}^{\ 2}SCR^2}}\right)-\sin^{-1}\left(\frac{E_s}{V_{PCC}SCR}\right)\right)}{\pi f_s P_m}} \tag{16}$$

$$CCT\left(P_{HVDC},V_{PCC}\right)=\sqrt{\frac{2H\left(\cos^{-1}\left(\frac{\pi P_{HVDC}X_s}{E_s V_{PCC}}-\sin^{-1}\left(\frac{P_{HVDC}X_s}{E_s V_{PCC}}\right)\frac{2P_{HVDC}X_s}{E_s V_{PCC}}-\sqrt{1-\frac{P_{HVDC}^2 X_s^2}{E_s^2 V_{PCC}^2}}\right)-\sin^{-1}\left(\frac{P_{HVDC}X_s}{E_s V_{PCC}}\right)\right)}{\pi f_s P_m}} \tag{17}$$

Using (10), (11) and (13), the CCT can be calculated based on the parameters SCR and H as in (15). Also, the CCT can be alternatively achieved from (16). On the other hand, using (10), (11) and (14), the CCT can be calculated based on the HVDC power as in (17). This relation shows that the CCT decreases as the HVDC power increases.

In order to have a better understanding of the relation between the CCT, the HVDC power and the characteristics of AC-connected grid, the last equations are implemented in MATLAB software. Fig. 2 shows the CCT value based on the SCR value with different inertia time constant. It can be seen from Fig. 2 that the CCT value increases when the SCR and H values increase. The amount of the CCT is usually less than 200 ms in cases of the grids with the SCR less than 2. The CCT value based on the H parameter with different SCR is depicted in Fig. 3. The amount of the CCT is usually less than 100 ms in cases of the grids with the SCR and H less than 2. The curves in Fig. 2 have the sharpest slope for the grids with the SCR value less than 2.

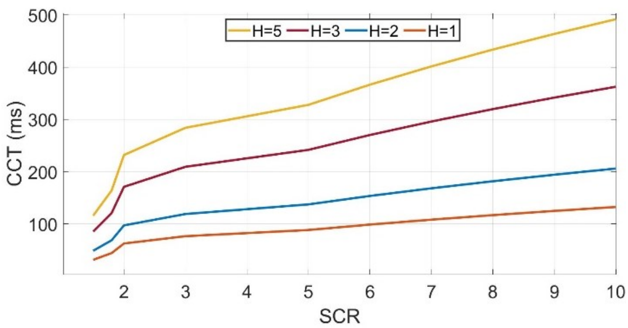


Fig. 2. The CCT value based on the SCR value with different H.

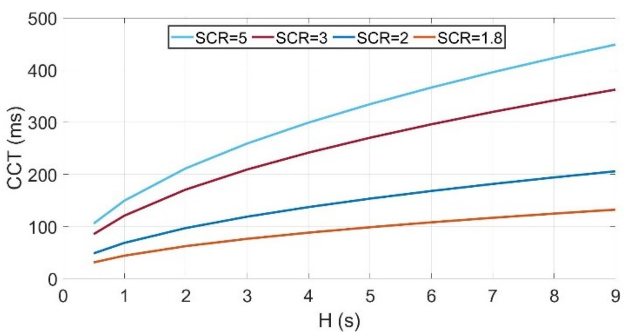


Fig. 3. The CCT value based on the H value with different SCR.

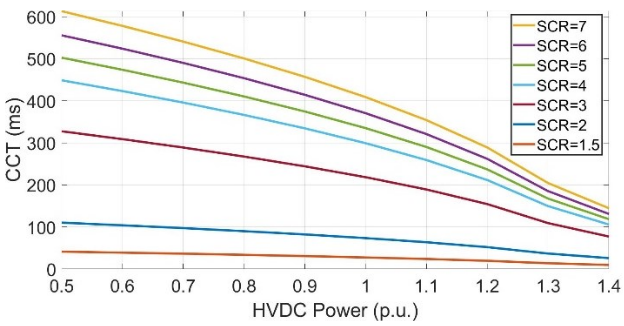


Fig. 4. The CCT value based on HVDC power value.

In other words, sensitivity of the CCT value to the SCR is the highest for very weak grid. Moreover, the relation between the CCT value and the HVDC power per unit is shown in Fig. 4. It can be seen that HVDC power value remarkably affects transient stability of the system. The CCT value significantly decreases with increase in the HVDC power. In addition, the slope of decrease in the CCT value increases with the grid SCR rising.

The CCT time is important when it comes to design of DC protection for HVDC grids. AC-connected grid sees faults on DC side as three-phase faults [18]. DC fault should be cleared before the system becomes unstable. This means that DC protection should be designed so that DC fault is cleared before the CCT time. Therefore, it is necessary to consider transient stability of the system for design of HVDC system protection. Usually, there are two general approaches to interrupt DC faults in HVDC systems [19]. The first one is using AC Circuit Breaker (ACCB) at AC-side of HVDC converter. This approach is quite economical as DCCBs are expensive. The second approach is using DCCB on DC-side to interrupt DC fault. Although, DCCBs are quite expensive, they are much faster than ACCBs. Hybrid and static types of DCCBs are usually able to interrupt DC fault within 5 ms [7]. Mechanical DCCBs can isolate a faulted line in about 10 ms [10]. It takes about several cycles of power frequency for ACCBs to interrupt fault current [20]-[21].

Considering DC protection, the whole time of the system protection, including fault detection time and fault interruption time, should be smaller than the CCT value of grid. Therefore, the following relation must be met for the first approach of DC protection:

- CCT > DC fault detection time + ACCB interruption time

On the other hand, the following expression must be met for the second approach of DC protection:

- CCT > DC fault detection time + DCCB interruption time

Detection time of DC faults is usually within several milliseconds [22]. For the HVDC system connected to AC grid with low SCR, it is vital to use fast and very fast circuit breaker to clear DC fault. Depending on weakness of AC-connected grid, the first approach of DC protection may not be applicable as ACCB is not fast enough to interrupt fault before short CCT time. Therefore, DCCB is usually needed to clear faults for very weak grid with low inertia time constant. For the second approach of DC protection, DCCB selection should be done considering the grid CCT time. For very short CCT, mechanical DCCBs may not be an appropriate choice and faster DCCBs like hybrid ones should be selected. Therefore, a suitable DC protection for a VSC-HVDC grid must be selected based on the system transient stability.

IV. Simulation Results

Fig. 5 shows the case study of a VSC-HVDC grid with symmetric monopole configuration. The nominal voltage of the grid is 300 kV and the case study is simulated using the PSCAD software. The HVDC station 1 and 2 are modelled via VSC converters. The AC grid 1 is modelled using the equivalent synchronous generator machine and the AC grid 2 is modelled by Thevenin equivalent circuit as a strong grid. The rated power of the HVDC system is 300 MW and the length of the HVDC cable is 100 km. The XLPE cable simulated using frequency-dependant model that is suitable for transient studies [23]. Depending on protection system, DCCBs can be installed at both ends of the HVDC link or ACCBs at the back of the HVDC converters to interrupt DC faults. The parameters of the test system and the HVDC cable are given in Table I and Table II respectively in the Appendix [24].

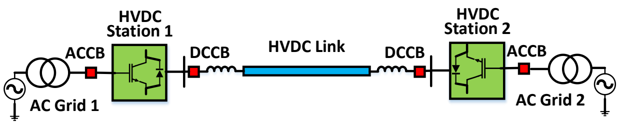
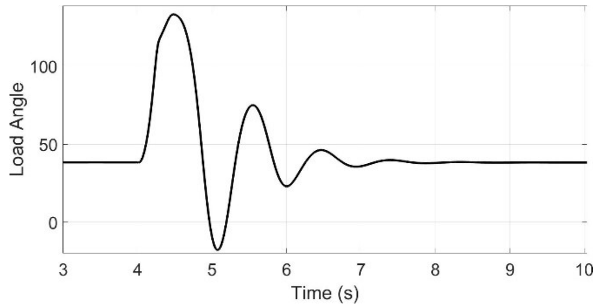
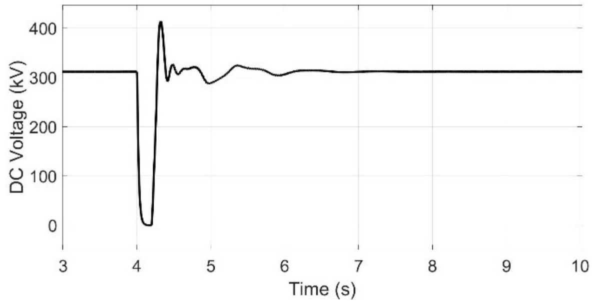


Fig. 5. VSC-HVDC test system.

A variety of simulations have been performed to find the CCTs of grids with different SCRs. Fig. 6 depicts the simulation results when a Pole to Pole (PP) fault happens at the terminal of the HVDC station 1 in a grid with SCR=3. The fault happened at the time 4 s and is cleared after 189 ms. The load angle of the grid is shown in Fig. 6 (a). It can be seen that the load angle finally becomes stable after some fluctuations. Also, the DC voltage comes back to the nominal value after transient state as shown in Fig. 6 (b). The simulation results for the same grid with the fault duration of 190 ms are shown in Fig. 7. The load angle becomes unstable after 4 s. Simultaneously, the DC voltage cannot come back to the nominal value and faces increasing fluctuations. Therefore, the results demonstrate that the CCT of the grid is 189 ms. Considering this value of the CCT, it can be concluded that ACCBs are enough for

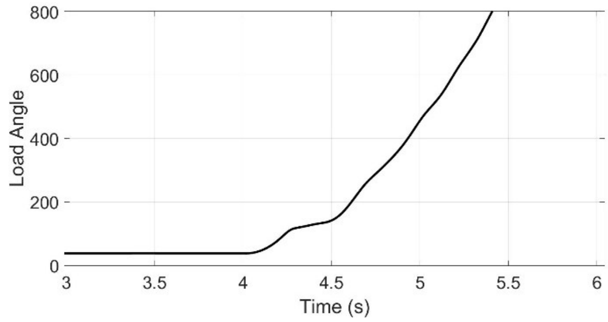


(a)

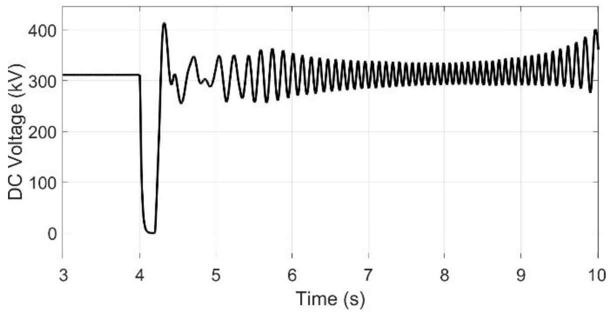


(b)

Fig. 6. Simulation results when a PP fault happens in a grid with SCR=3 and fault interruption time of 189 ms, (a) load angle (b) DC voltage.



(a)

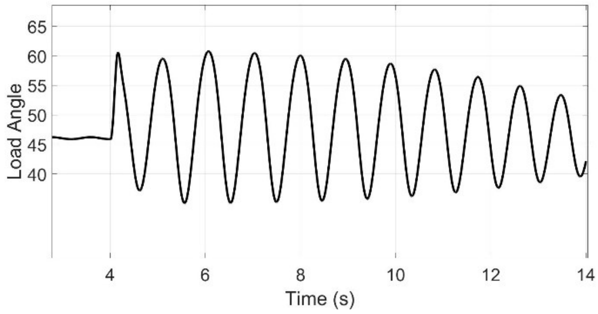


(b)

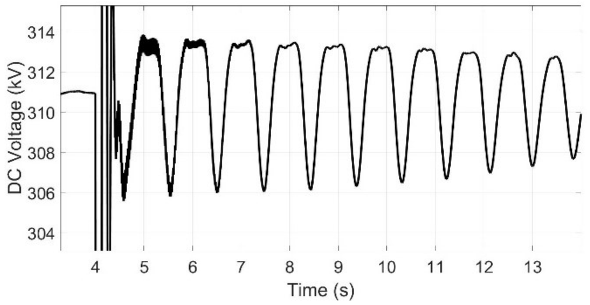
Fig. 7. Simulation results when a PP fault happens in a grid with SCR=3 and fault interruption time of 190 ms, (a) load angle (b) DC voltage.

interrupting DC faults in strong grids with the SCR higher than 3. As mentioned before, it takes about several cycles of power frequency for ACCBs to interrupt fault current. Therefore, they can clear the fault before the CCT and the grid will keep its stability. Consequently, the second approach of DC protection, as an expensive approach, is not necessarily needed in this case.

The same analysis has been done for a grid with lower SCR, i.e. SCR=2, and the simulation results are shown in Fig. 8 and Fig. 9. In this case, the fault lasts 25 ms and 26 ms for Fig. 8 and Fig. 9 respectively. While the magnitude of the fluctuations in Fig. 8 is decreasing, it is increasing in Fig. 9. The results demonstrate that the CCT of this case is 25 ms. Regarding this value of the CCT, it can be concluded that the first approach which uses ACCBs is not applicable to this grid as it will lead to instability. On the other hand, both mechanical and hybrid DCCBs are appropriate to clear the fault in this case, as their interruption times are less than the CCT.

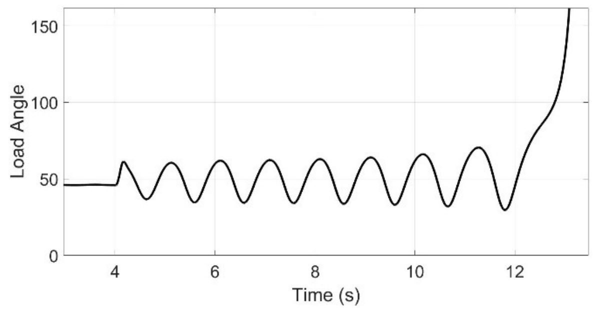


(a)

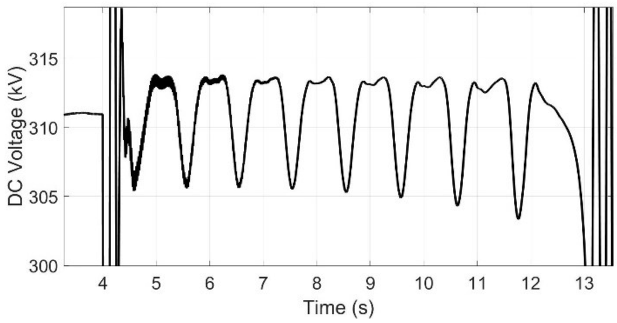


(b)

Fig. 8. Simulation results when a PP fault happens in a grid with SCR=2 and fault interruption time of 25 ms, (a) load angle (b) DC voltage.

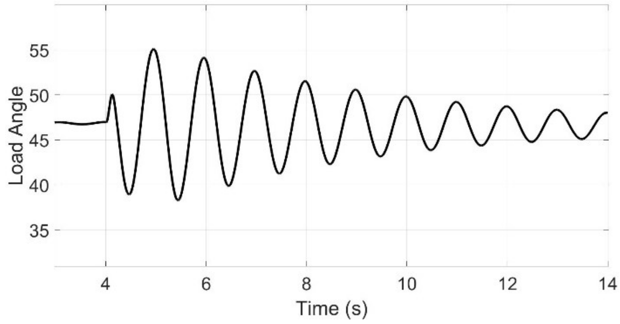


(a)

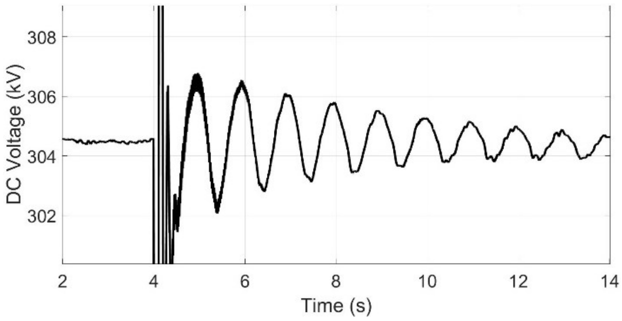


(b)

Fig. 9. Simulation results when a PP fault happens in a grid with SCR=2 and fault interruption time of 26 ms, (a) load angle (b) DC voltage.

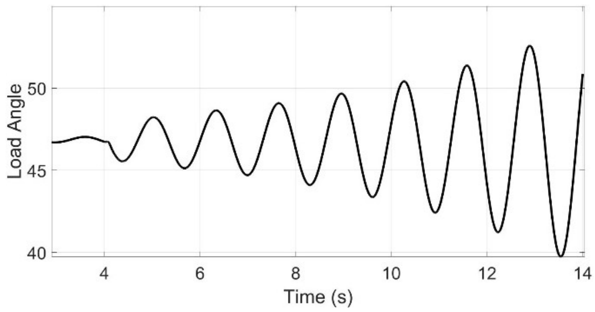


(a)

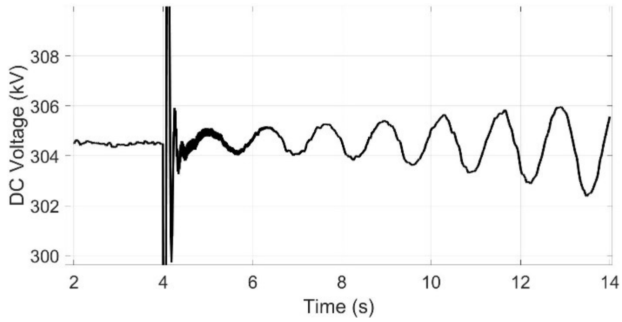


(b)

Fig. 10. Simulation results when a PP fault happens in a grid with SCR=1.5 and fault interruption time of 14 ms, (a) load angle (b) DC voltage.



(a)



(b)

Fig. 11. Simulation results when a PP fault happens in a grid with SCR=1.5 and fault interruption time of 15 ms, (a) load angle (b) DC voltage.

In addition, the simulations have been performed for a very weak grid with SCR=1.5. The simulation results are depicted in Fig. 10 and Fig. 11 with the fault duration of 14 ms and 15 ms respectively. Thus, the CCT for this grid is 14 ms. It is clear that only the second approach of DC protection is applicable to this case. Moreover, it is risky to use the mechanical DCCBs, as summation of fault detection time and the interruption time of this type of DCCB is almost equal to the CCT time. Therefore, the hybrid DCCB is the best choice to clear DC faults for very weak grids. All in all, the simulation results demonstrate that DC protection design should be selected based on the characteristics of AC-connected grid including SCR value to reliably secure the grid against DC faults and keep the system stability.

V. Conclusions

Number of VSC-HVDC projects is going to rise in the world due to its benefits to power grids. A reliable protection system is vital to protect the VSC-HVDC systems against DC faults. An effective DC protection not only interrupts fault current successfully but also secures the system against instability. Therefore, it is necessary to consider the system stability during and after DC fault happening. In this study, dynamic relations for the AC/DC system based on the grid characteristics have been analysed and the CCT calculations considering HVDC power and SCR values have been presented. Sensitivity of the CCT to the characteristics of the AC-connected grid and HVDC power has been investigated in MATLAB software and the results presented in this paper. The results show that the CCT value decreases with increase in HVDC power and decrease in SCR value of the AC-connected grid. Moreover, a case study of the VSC-HVDC grid has been tested with different SCRs in PSCAD platform. The results demonstrate that it is vital to consider short circuit strength of the AC-connected grid for DC protection design and circuit breaker selection of HVDC transmission link.

Appendix

TABLE I
TEST SYSTEM PARAMETERS

Parameters	Value
HVDC rated power	300 MW
AC voltage (line-line)	400 kV
DC voltage (Pole to pole)	300 kV
X/R of AC grid	10
Converter transformer ratio	400 kV / 155 kV
Leakage reactance of converter transformer	0.1 p.u.

TABLE II
PARAMETERS OF XLPE-HVDC CABLE

Parameters	Value
Copper conductor diameter	37.9 mm
XLPE insulation thickness	17 mm
XLPE Permittivity	2.5
Diameter over insulation	78.5 mm
Lead sheath thickness	2.5 mm
Outer diameter of cable	102.2 mm

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