

Design of Protection Strategies and Performance Analysis of an HVDC Link During Multiple Disturbances

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Abstract- In High Voltage Direct Current (HVDC) transmission system applications, the control and protection system plays an essential role in the overall performance. This paper aims to give solutions to some performance problems that can occur in the HVDC link. In this paper, ways to mitigate this serious malfunction of the commutation failure process in the operation of HVDC converters are studied and protection functions like the Commutation Failure Prevention (CFPREV) have been used. Furthermore, HVDC transmission systems are vulnerable to DC faults and its protection becomes ever more important with the fast growth in the number of installations. In this context, the DC fault protection function is one of the most important challenges to the development of HVDC transmission systems. The dynamics of the studied power system including the HVDC link are thoroughly investigated in this paper through various simulation scenarios.

Keywords- commutation failure; control strategies; protection functions; HVDC; faults; performance

I. INTRODUCTION

High Voltage Direct Current (HVDC) transmission systems are an excellent asset in modern power systems, mainly for their ability to overcome problems of AC transmission, such as the interconnection of asynchronous grids, stability of long transmission lines, and use of long cables for power transmission [1-4]. Due to environmental, technical, and economical reasons [2-6], the HVDC system is a mature technology but it has certain constraints such as the risk of commutation failures [3]. Commutation failures following AC system disturbances may occur in HVDC systems, especially in the inverter station. This fault is the result of the failure to complete commutation before the commutation voltage

reverses its polarity [5]. Furthermore, faults in the DC transmission system, which are generally pole-to-ground faults, block power transfer and are not likely to be of much significance unless voltage reduction occurs [7].

The objective of the current paper is to demonstrate ways to improve HVDC system performance, especially during large disturbances, such as three-phase faults on the AC side of the inverter and DC line faults at the rectifier side. Therefore, in this paper, the DC fault protection (DCPROT) is inserted to detect faults on the line and take the necessary actions to clear them [8]. The protective function Commutation Failure Prevention (CFPREV) is used in the inverter [9]. The control subsystem mitigates commutation failures due to AC voltage dips. Finally, in order to improve the dynamic performance of the proposed controller and protection devices, various simulation scenarios are tested. The main conclusion is that the reliability of an HVDC link depends on control and on the protection system.

II. SYSTEM MODELING AND CONTROL

In order to define the needs in terms of control and protection, the first step is to develop a model for the HVDC transmission system. HVDC systems traditionally use the fixed-parameter PI controller to control the DC line current and excitation angle [10], where the rectifier station controls the DC current through the firing angle (α) and the inverter controls voltage through the extinction angle (γ). In general, a typical basic monopolar HVDC system can be configured as shown in Figure 1 [11], where the schematic diagram and the equivalent circuit are shown in (a) and (b) respectively [12].

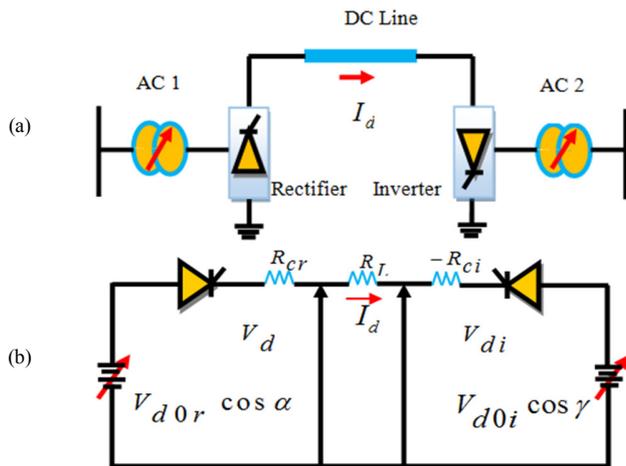


Fig. 1. HVDC transmission link: (a) schematic diagram, (b) equivalent circuit.

The direct current can be expressed using the equivalent circuits as [13]:

$$I_d = \frac{V_{d0r} \cos \alpha - V_{d0i} \cos \gamma}{R_{cr} + R_L - R_{ci}} \quad (1)$$

where R_{cr} and R_{ci} are the equivalent commutating resistances for rectifier and inverter respectively, and R_L is the line resistance. Both impedances are nonlinear and are not pure resistive, referred from converter side AC systems.

$$R_{cr} = \frac{3}{\pi} \omega L_c \text{ and } L_{cr} = L_{co} = L_c \quad (2)$$

where V_{d0r} and V_{d0i} are the ideal no-load rectifier and inverter voltages respectively, referred from converter side AC systems.

Therefore, the direct voltage V_d at any point on the line and the direct current I_d can be controlled by controlling the internal terminal voltages: $V_{d0r} \cos \alpha$ and $V_{d0i} \cos \gamma$. These two voltages can be controlled by controlling the firing instant of the thyristor or through the tap changing of the converter transformer. Another important control function is implemented to change the reference current according to the value of the DC voltage. This control, named Voltage Dependent Current Order Limiter (VDCOL) [9], automatically reduces the reference current set point when DC voltage decreases during a DC line fault or a severe AC fault. Reducing the reference currents also reduces the reactive power demand on the AC system, helping to recover from fault.

III. CONCEPTS OF THE PROPOSED PROTECTION

In this section, we insert two different protection devices associated with the proposed control strategy to improve the dynamic performance of an HVDC system. The first one, at the rectifier, is the DC fault protection (DCPROT) to detect and remove faults in the DC line. The second protection function is the commutation failure prevention (CFPREV) at the inverter, which controls subsystem commutation failures due to AC voltage dips. In this context, the expected behavior in steady state and stability problems are discussed in order to define the

needs in terms of control and protection. Moreover, the reliability of the HVDC control system depends on the regulators, but also on the protection sub-functions [14]. The actions that are taken by device protection systems when faults or dysfunctions occur are shown. To evaluate the performance of the proposed protection, simulation results are presented.

A. DC Protection Function

The protection is active in the rectifier. It will detect a fault on the DC side and will force the delay angle into the inverter region in order to extinguish the fault current [15]. The fault detection on the DC line is based on the drop in the line to ground voltage. The normal voltage polarity of the line is a parameter as well as the reference level of the fault detection. Delay time is used in the detection to discriminate between a line fault and other disturbances resulting in low DC voltage. A delay time of 200ms is allowed, after the DC system start-up, before activating the detection logic to make sure that the normal operating DC voltage is established. Also, an external signal generated by another protective detection will trigger a forced alpha during an adjustable interval sufficient to allow the deionization of the fault path prior to the re-application of voltage.

B. Commutation Failure Prevention Function

The objective of this device is to develop a control and protection strategy to accommodate large disturbances when an HVDC system is connected to a weak AC system [16]. This phenomenon is the result of the failure to complete commutation before the commutation voltage reverses its polarity, taking into account the need for sufficient extinction time for de-ionization and to re-establish the blocking ability. The protective function, used in the inverter, mitigates commutation failures due to AC voltage dips. After fault detection (three-phase or one-phase) an angle value is sent to the converter delay control in order to be deducted from the maximum delay angle limit. Commutation failure is the most common disoperation of an inverter due to the minimum limit on extinction angle gamma [17]. This puts a limit to the maximum firing angle for a successful inverter operation, as shown by the following equation:

$$\alpha = 180^\circ - (\beta + \gamma) \quad (3)$$

A signal transmitted to the VDCOL indicates the detection of a commutation failure, as this VDCOL function prevents the detection of commutation failure by the CFPREV module, the VDCOL transiently reduces the current in order to prevent the converter from excessive current [18]. To detect three-phase faults abc- $\alpha\beta$ transformation is used where, U_α and U_β may be expressed by:

$$\begin{cases} U_\alpha = \frac{1}{3}(2U_a - U_b - U_c) \\ U_\beta = \frac{\sqrt{3}}{3}(U_b - U_c) \end{cases} \quad (4)$$

The CLARK transformation [19] is used for three-phase fault detection and zero-sequence voltage evaluation. The

detection is based on instantaneous values, which ensure fast reaction of the control system when an AC fault occurs.

IV. SYSTEM STUDY

The HVDC system simulated in this study, is modeled based on the CIGRE HVDC benchmark system [20], as shown in Figure 2. The system is monopolar with a 12-pulse converter. The rectifier is connected to the strong AC system with a Short Circuit Ratio (SCR) of 5. The inverter is connected to the weak AC system with a SCR of 2.5.

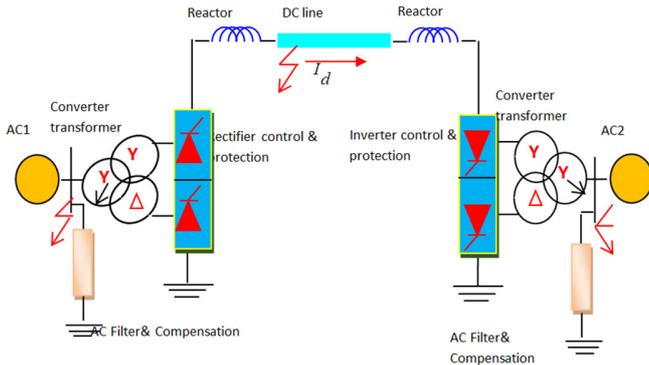


Fig. 2. Basic configuration of the HVDC transmission system.

The model description follows [20].

The AC side of the HVDC system consists of a supply network, filters, and converter transformers. The AC supply network is modeled by a Thevenin equivalent with equivalent source impedance [22]. The filters are added to absorb the harmonics generated by the converter and to supply the reactive power needed by the converter. The DC side of each converter consists of a smoothing reactor. The DC transmission line connected to each converter station is represented by a T network. The 12-pulse converter station is configured by two universal bridge blocks in series. The universal bridge block implements a universal three-phase power converter that consists of up to six power switches connected in a bridge configuration[23]. The system parameters of the HVDC system are given in Table I.

TABLE I. HVDC SYSTEM PARAMETERS

Parameter	Value		
	AC side 1	AC side 2	DC side
AC voltage	500 kV	345 kV	-----
Reactive Power	5000 MVA	10000 MVA	-----
Frequency	60Hz	50Hz	-----
DC voltage	-----	-----	500 kV
DC current	-----	-----	2 kA
Active power	-----	-----	1000 MW
DC cable length	-----	-----	300 km
Smoothing reactors	-----	-----	0.5 H

V. SIMULATION RESULTS AND ANALYSIS

In this section the behavior of the HVDC transmission system is analyzed. In order to test the controllers and the proposed protection functions, two different scenarios will be simulated in order to analyze the dynamic performance. During

the first scenario, a DC line fault on the rectifier side is applied to observe the DC fault protection action. In the second one, a three-phase-to-ground fault on the AC side of the inverter is studied to evaluate CFPREV control. In both scenarios, the waveforms for electrical quantities like DC voltage, DC current, and firing delay angle α are presented and analyzed during the application of faults, at rectifier and inverter side, and finally, the corresponding inverter side AC voltage and AC current waveforms are shown.

A. First Scenario: DC System Faults

The scenario is shown in Figure 3. This fault is applied at $t = 0.7s$ for a duration of 50ms. The DC current increases quickly until 2.22p.u., and it is cancelled at the inverter side.

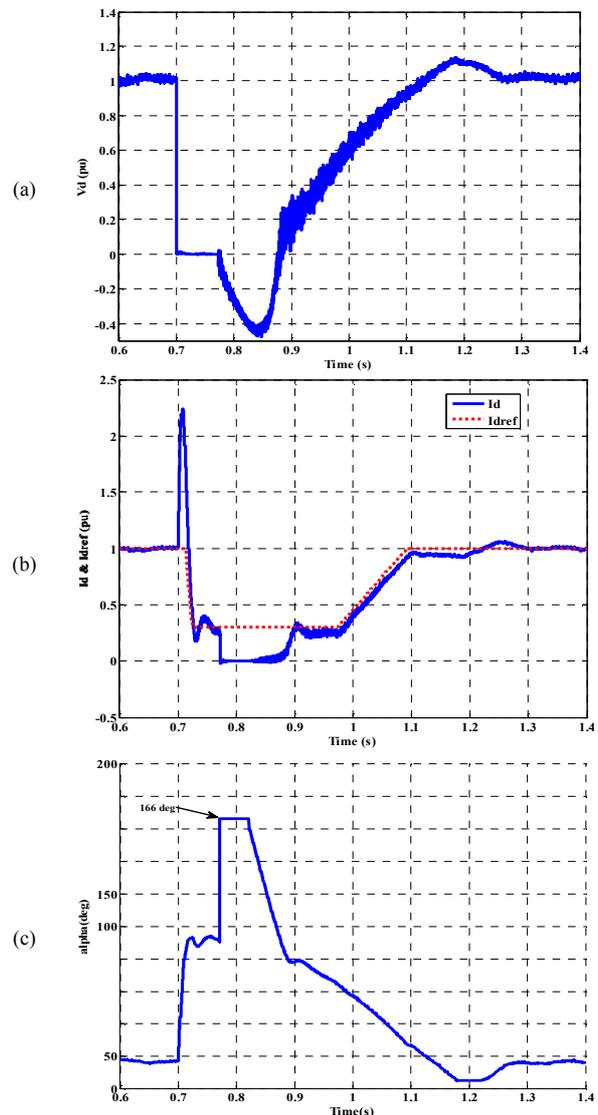


Fig. 3. DC fault on the rectifier side.

The DC voltage falls to zero at the rectifier. This DC voltage drop is seen by the VDCOL through DC fault protection. The VDCOL reduces the reference current to

0.28p.u. at the rectifier. A DC current still continues circulating in the fault. At $t=0.78s$, the rectifier firing angle α is forced to be 166° by the DC protection function after detecting a low DC voltage. In this situation the rectifier operates in inverter mode. The DC line voltage becomes negative and the energy stored in the line is returned to the AC system. Then α is released at $t=0.83s$ and the DC voltage and the current recover in approximately 0.5s.

B. Second Scenario: AC System Faults

Three-phase-to-ground fault is applied at the AC side of the inverter at $t=0.7s$ and is cleared at $t=0.75s$. Figure 4 shows the inverter side, the DC voltage, DC current and firing delay angle during the fault. The oscillation of the DC voltage and current waveform are primarily caused by the controller action.

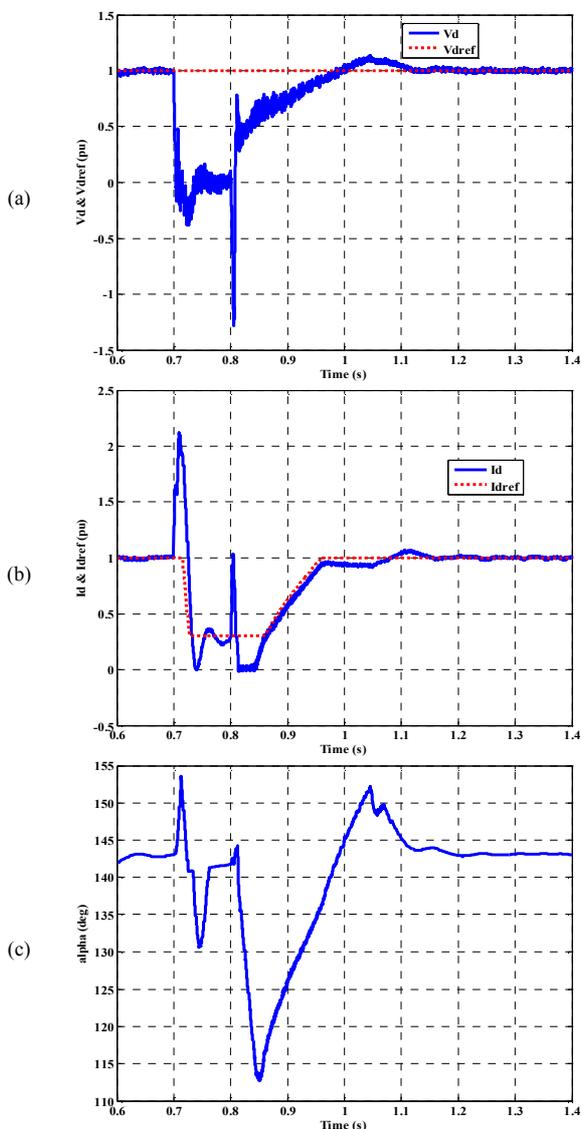


Fig. 4. Three-phase-to-ground AC fault on the inverter side.

The DC voltage at the inverter drops and the DC current increases rapidly to 2.22p.u. on the inverter side. When the

fault is cleared at $t=0.8s$, the control function (VDCOL) operates and reduces the reference current to 0.3p.u.. The system recovers in approximately 0.35s after fault clearing. During the fault period, the DC voltage oscillates around zero due to the commutation failure on the inverter side. The control scheme provides smoother operation of the converter firing angles, which is shown in waveform firing angle.

Furthermore, Figure 5(a)-(b) shows the phase AC voltage and AC current waveforms at the inverter side, for a three-phase-to-ground fault. The AC fault does not affect the rectifier side AC system because the rectifier is connected to a strong AC system. The AC voltage becomes nearly zero, after the fault is cleared, the inverter side AC voltage increased to 1.53p.u.. The AC currents at the inverter shows minor disturbance and high amplitude fault current flows with oscillations.

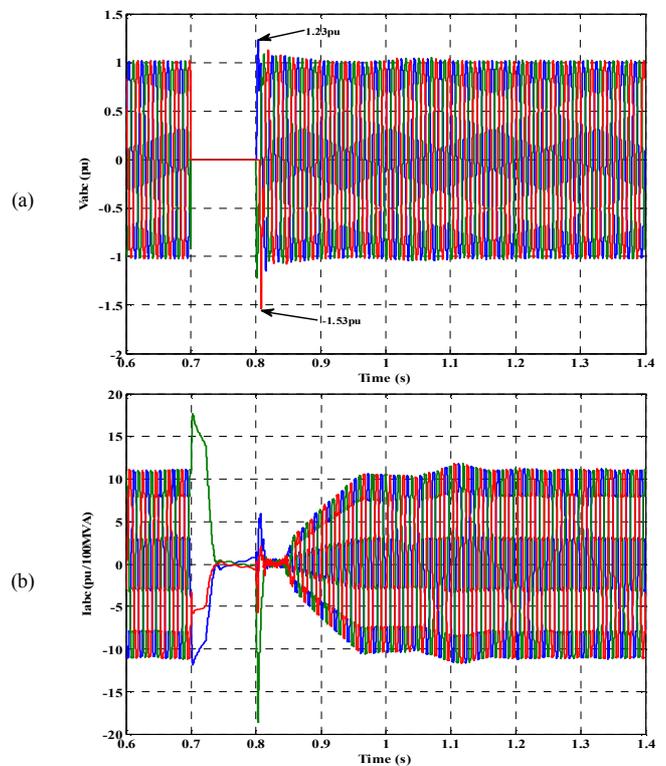


Fig. 5. Voltage and current responses under three phase to ground fault at the inverter.

VI. CONCLUSIONS

This paper focuses mainly on the HVDC performance assessment dynamic state under various scenarios. First, the dynamic response of the HVDC system is analyzed under unbalanced grid conditions. In a typical HVDC link, the rectifier station controls the DC current through the firing angle and the inverter station controls voltage through the extinction angle. The faults associated with an HVDC system are cleared through the action of protection devices. The protection devices thus play a vital role in the satisfactory operation of the HVDC systems. Simulation results show clearly that the reliability of an HVDC control system does not depend only on the

controller, but also on protection functions. In this paper, the actions that are taken by some HVDC link protection systems when faults or dysfunctions occur are presented. The obtained results demonstrate that the DC fault line is eliminated by the rectifier operation in inverter mode through the increase of its firing angle to ensure the extinction of the residual current. This necessary action, is ensured by the DC protection device. For three-phase faults, the commutation failure prevention greatly reduces the risk of repeated commutation failures. Finally, from the simulation results, it can be seen that the system works stably with the purposed protection devices and the fixed parameter PI controller applied to an HVDC system. The protection devices implemented in this paper showed good performance under various scenarios. However, more extensive studies can be conducted in the future. Future work should explore other possibilities and routes in which this paper could lead to. The main perspectives should include:

- The development of a Voltage Source Converter (VSC), with the insertion of these protection devices applied to the conventional HVDC link.
- Protection and implementation of nonlinear control algorithms for VSC-HVDC systems.

APPENDIX

ABBREVIATIONS

AC	Alternating Current
DC	Direct Current
DCPROT	Direct Current Fault Protection
CFPREV	Commutation Failure Prevention
HVDC	High Voltage Direct Current
VDCOL	Voltage Dependent Current Order Limiter

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