

DC Line-to-Ground Fault Analysis for VSC Based HVDC Transmission System

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Abstract— Voltage Source Converter based HVDC (VSC- HVDC) transmission technology as a kind of new dc transmission, is attracting more and more research. VSCs are susceptible to transmission line to line fault and line to ground fault. This paper focuses on the transient characteristics of electrical quantities in a VSC-HVDC system after the occurrence of line to ground fault. Equivalent circuit and equation is given to calculate the voltage and current in transmission line. Simulations are undertaken in PSCAD. The behaviors of DC voltage and DC current in faulty transmission line after the line to ground fault is studied. According to the characteristics of the fault current circuit when the line to ground fault occurs, the three stages of fault process were presented in detail. Firstly, DC-side capacitor discharge stage and the voltage of capacitor were derived. Secondly, the state equation of grid-side current feeding stage. Thirdly, the distribution of DC-side capacitor voltage in voltage recovery stage was analyzed. This paper also present a propose protection scheme for transmission line in VSC – HVDC system.

Keywords- VSC, Line to Ground Fault, Fault characteristics, Fault Analysis, protection schemes, PSCAD.

I. INTRODUCTION

The world's first VSC-HVDC transmission was put into operation in 1977 in central Sweden. It is a new DC transmission technology based on voltage source converter, full controlled power electronics device and pulse width modulation [1]. Especially the use of voltage source converter (VSC) based HVDC, which draws on pulse width modulation (PWM) control strategies, has provided a number of benefits compared to the classical HVDC, in terms of enhanced flexibility in independent control of active and reactive power. Hence, VSC-HVDC provides a new choice for grid inter-connection, city center infeed and offshore installation, which is a major breakthrough in the field of power transmission and distribution technology [2]. Because of its large capacity and high voltage transmission characteristics, it is often used for long distance transmission. The DC lines become one of the components with high failure probability in the system, and most common fault is pole-to-ground fault. The analysis of its fault characteristics is of practical significance for the protection of power system security operation [3]. Voltage source converter-based-HVDC (VSC-HVDC) systems are considered to be the technology of choice for efficient grid integration which provides the fast and independent control of active and reactive power flow in both directions, low harmonic generation which enhances the power quality and stability of the system [4]. The analysis of its fault characteristics is of practical significance for the protection of power system security operation.

This paper is organized as follows. In Section II, the DC line faults and the fault process is divided into DC-side capacitor discharge, grid-side current feeding and voltage recovery three stages. In Section III, the accuracy and effectiveness of the fault analysis was validated through a two-terminal DC transmission system which was established in PSCAD simulink. In Section IV, recovery methods are proposed to rebalance the capacitor. Finally, concluding remarks are given in Section V.

High Voltage Direct Current (HVDC) transmission has future scope of bulk power transmission. The transmission losses and the capital investments are eventually higher for AC systems beyond certain distance, e.g., typically about 700km for overhead and 40km for underground lines. 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 transmission system, but the protection system is still lagging behind the AC systems. Fig.1 shows the typical topology of two- terminal HVDC system.

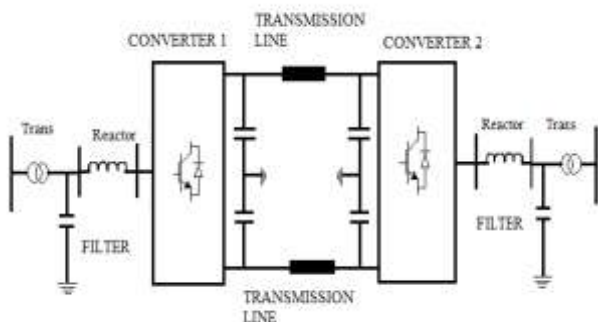


Fig. 1: Typical topology of two-terminal HVDC system

Two-terminal HVDC system corresponding system parameters are listed in Table I.

TABLE I. Model Specification of Simulated HVDC System

Parameter Of VSC-HVDC Model	Rated Value
Steady State Frequency	50 Hz
Rated capacity	100MVA
Rated AC voltage (L-G 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
Transmission Length	100km
DC Capacitor	500 μ F

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-end and the receiving-end.

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. It is also able to prevent the current from entering the system.

Converters - The HVDC converters are the most important part of an HVDC system. They perform the conversion from AC to DC (rectifier) at the sending end and from DC to AC

(inverter) at the receiving end. HVDC converters are connected to the AC system through transformers. The classic HVDC converters are current source converters (CSCs) with line-commutated thyristor switches. A six-pulse valve bridge is the basic converter unit of classic HVDC for both conversions, i.e. rectification and inversion. A twelve-pulse converter bridge can be built by connecting two six pulse bridges.

DC Capacitor - HVDC system is concern with a constant DC voltage with minimum ripple at transmission line. So, 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.

Transmission Lines - VSC-HVDC realizes the power transmission from sending end to receiving end by connecting rectifier and inverter through DC transmission line. Considering the high fault probability, radio interference and audible noise of overhead line, most project applications of VSC-HVDC adopt cables as the DC line at present. As the voltage polarity reversal is not needed for VSC-HVDC, this allows new types of cables, such as extruded XLPE DC cables to be used in long distance VSC transmission systems. The situations those the cables cannot be used, the overhead line will be the only choice for DC transmission. Some special demands should be considered such as DC line fault recovery [8].

II. DC LINE FAULTS

Faults in HVDC transmission system can happen for various reasons and they affect the power flow in the transmission system due to disturbances of the transmission line parameters such as DC voltages and currents as well as the voltages and currents of the connected AC Systems. The disturbances depend on following factors such as:

- Type of Faults (Line-to-Line, Line-to-Ground)
- Polarity DC voltage (symmetric monopolar, asymmetric monopolar or bipolar)
- Earthing provided to DC circuit
- Properties of Electrical System (Line length, Resistivity, capacity, reactances)
- The existence of concentrated DC capacitors or DC Filters
- The fault clearing scheme
- Possible additional equipment such as overcurrent limiters.

When a fault (flash-over) occurs on an AC line, there are circuit breakers that disconnect the line. It is then automatically re-connected again. There are no circuit breakers on the DC side in the HVDC converter stations, so when a fault occurs on

a DC line the fault is detected by the DC line fault protection. This protection orders the rectifier to operate in the inverter mode and thus it discharges the line effectively. HVDC transmission lines are prominent due to their unique capacity of transmitting power through underground / under water cables. The faults in HVDC transmission using underground cables are very rare and they are due to mechanical damage. Therefore, submarine DC cables are often buried to prevent damage from anchors and trawls. The same protection action is implemented as for a DC transmission line, but without the restart attempt.

A. Line-to-ground fault

For underground HVDC line, the line-to-ground fault means insulation failure between one DC conductor and ground, and for overhead line, the fault is usually temporary which is caused by lightning strikes and pollution. A DC line-to-ground fault can be expressed by an equivalent circuit shown in Fig.2 where R_1 , R_2 and L_1 , L_2 are the π -model equivalent resistances and inductances of the fault line from the VSC to fault point.

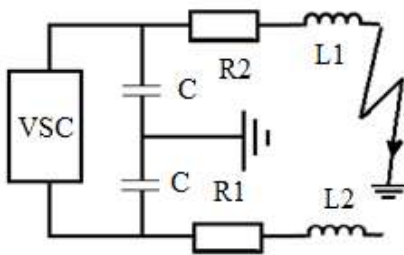


Fig. 2: Equivalent Circuit of DC line-to-ground fault

A DC line-to-ground will produce ground point besides the neutral-ground link of transformer and the mid-point of dc-link capacitor. The line-to-ground fault could be divided to three stages. Usually, the grounding points in a DC network include the neutral-ground link of the transformer and the midpoint of DC- side capacitor. A ground loop will be formed among the grounding points when the fault occurs. The IGBTs can be blocked for self-protection owing to the fault current rising sharply, leaving reverse diodes exposed to overflow. In the initial phase, due to the DC voltage higher than AC phase voltage, the current contribution from AC-side transformer is only freewheeling contribution from the AC reactor. The DC short-circuit current is mostly the DC-side capacitor discharge current. The system will enter the grid-side current feeding stage when the DC voltage drops below the AC phase voltage. The AC power will charge the fault line capacitor through the freewheeling diodes. This stage will not end until the DC voltage becomes higher than AC phase voltage again. The fault line capacitor voltage drops and non-fault line capacitor voltage rising with the capacitor discharging. The DC voltage

gradually restores, so the system enter the voltage recovery stage.

1) DC-Side Capacitor Discharge Stage

The fault process starts from the capacitor discharging. A discharge circuit is formed among the fault pole capacitor and fault impedance through the fault line. After the fault occurs, the system, firstly, experiences the DC-side capacitor discharge stage, and the equivalent circuit is shown in Fig. 3. When the line-to-ground fault occurs, the dc-link capacitor, transmission line inductance, fault resistance and ground point form a loop circuit. The equivalent circuit is represented in Fig.3, where R and L are the equivalent resistance and inductance of the fault line from the VSC to the location of the ground fault, C is the capacitance of dc-link capacitor and R_f is the fault resistance.

The equivalent equation of the circuit is,

$$\frac{LC}{2} \frac{d^2 V_c}{dt^2} + \frac{RC}{2} \frac{dV_c}{dt} + V_c = 0 \quad (1)$$

Where V_c is the capacitor voltage between faulty transmission line and ground point and $R = R_1 + R_2$, $L = L_1 + L_2$.

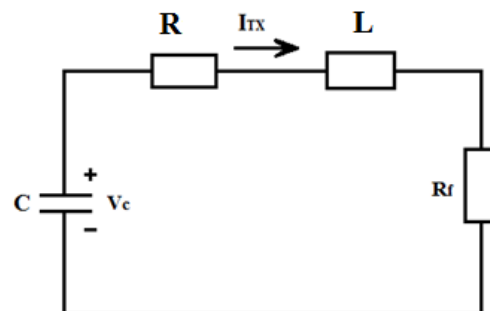


Fig. 3: Equivalent circuit of capacitor discharge stage

The solutions show that when the dc-link capacitor begins to charge, the voltage V_c will drop, but not to zero, so the diode freewheel stage will not occur after a DC line-to-ground fault.

2) Grid-Side Current Feeding Stage

With the DC-side capacitor discharging, the DC voltage drops constantly. Then, the system will experience the grid side current feeding stage when the DC voltage drops to below any grid phase voltage. This stage will not end until the DC voltage becomes higher than AC phase voltage again. This stage is the process of the DC-side capacitor being charged through the fault line by the AC power. The duration of this process is short and the current is small. If the control system can be a timely response, the DC voltage would avoid dropping to below the AC phase voltage. Then the fault process will skip this stage.

3) Voltage Recovery Stage

The fault line capacitor voltage drops and non fault line capacitor voltage rising with the capacitor discharging. The DC voltage gradually restores, so the system enter the voltage recovery stage. A circuit for charging non-fault line capacitor connected with grounding point of fault line. With the fault line capacitor continuously discharging, the charging current provided by the AC current can charge the non-fault line capacitor through this circuit. The voltage of fault pole capacitor drops to nearly zero, while the voltage of non-fault line capacitor increases which is the normal DC voltage of the system without fault after the end of the capacitor discharge. The DC network is not affected and the system will enter the steady state, but it will produce stress on the electrode of this pole. The DC voltage and current change slowly. If the voltage of non-fault pole capacitor increases which is the normal DC voltage of the system without fault, the DC voltage will not drop to below the AC phase voltage. Then the system will directly enter the voltage recovery stage.

III. METHOD USED FOR REQUIRMENT ANALYSIS

This paper focus on the faults analysis of DC line to ground fault for overhead HVDC transmission line. PSCAD simulation software is used to simulate the VSC based HVDC system. PSCAD / MATLAB allow assembling the circuit, running the simulation, analyzing the results, and managing the data in a completely integrated graphical environment. The performance under DC transmission line transients investigated under power system software tool PSCAD. The simulation of circuit by using PSCAD / MATLAB and analysis show out the characteristics of DC line-to-ground HVDC system, and then proposes the recovery demand of temporary faults at overhead line scheme.

For overhead line, the faults are typically caused by lightning strikes and pollution. Fault in the line is likely to be temporary, which demands a fault restoration after the fault clearance which is shown in Fig. 4.

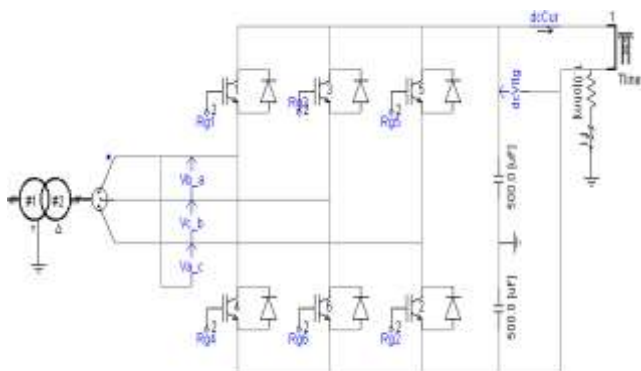
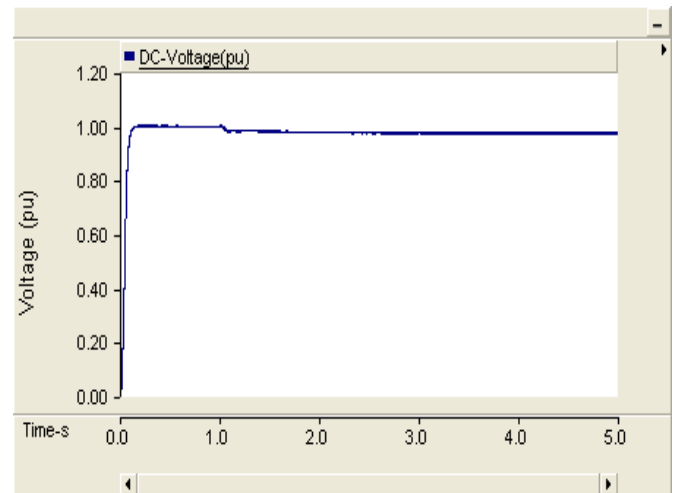
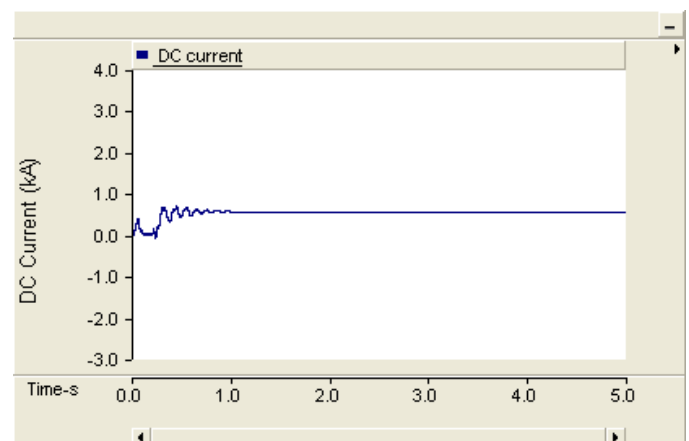


Fig. 4: DC Line-to-Ground Fault model in PSCAD

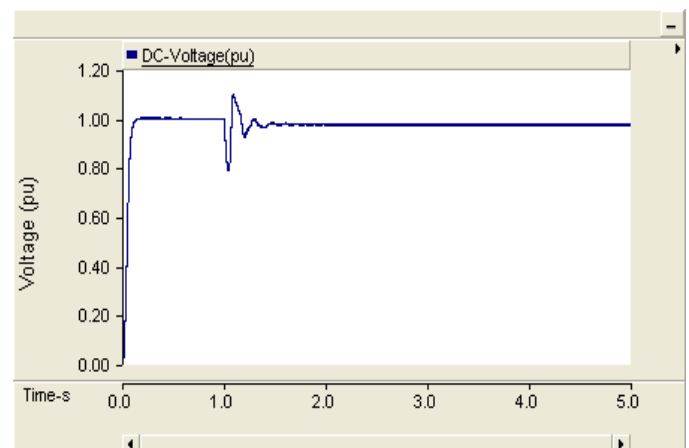
The simulation test is done at the sending end of VSC-HVDC transmission system. Line-to-ground fault is the common fault in the DC transmission system. In this system, a line-to- ground fault is demonstrated and the response of the system is analyzed.



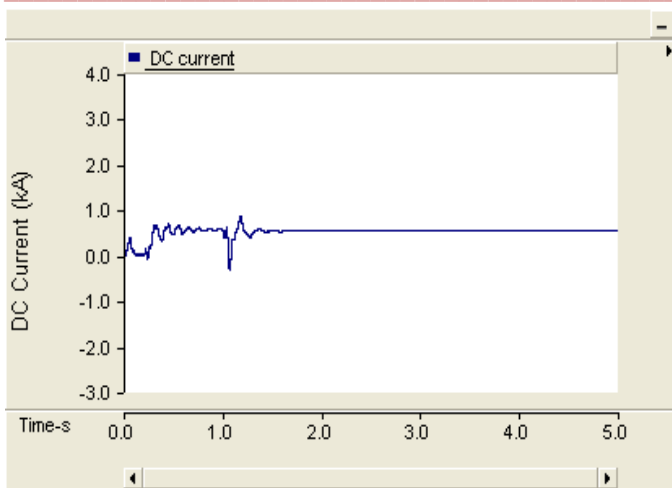
(a) DC line voltage during normal operation



(b) DC line current during normal condition



(c) DC voltage during line-to-ground fault



(d) DC current during line-to-ground fault

Fig. 5: Simulation results for VSC-HVDC System

when a line-to-ground fault occurs at $t=1.0s$ on the sending end of the DC line, the DC voltage of the DC link capacitor rapidly decreases, resulting in a significant rise in DC fault current & after 0.5s isolates the fault so system comes to normal condition as shown Fig.5(c) & Fig.5(d) respectively.

IV. RECOVERY METHODS

As the DC line fault, will induce a significant influence on operation of HVDC, therefore the fault characteristics is necessary for reasonable protection design. Especially for overhead line, the problem in recovery process should be taken into account to ensure that the system can restore rapidly under temporary fault condition. This work demonstrates the DC line fault characteristics and its recovery process. For overhead line, line-to-ground fault is temporary. The rebalance of capacitors can be done by using following methods:

A. Grounding by high impedance branch

In direct grounding system, the unbalance of capacitor is caused by the discharging of the faulty transmission line and the DC voltage controller. In high impedance grounding system, the discharging current is very small so that the voltage of the capacitor can maintain without any overcurrent stress. Fig.6 shows the Grounding by high impedance branch recovery method for line-to-ground fault. The line-to-ground voltage can recover after fault as shown in Fig. 7.

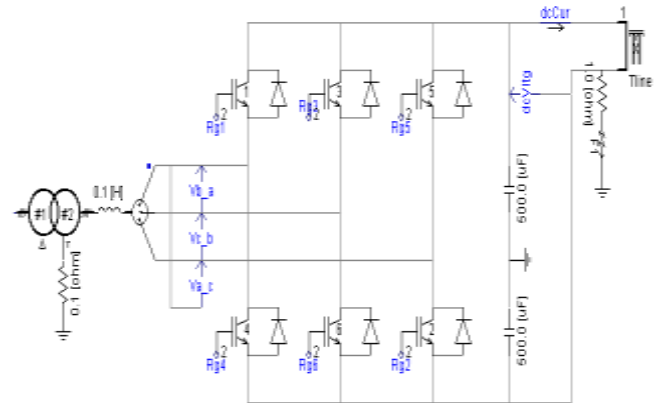


Fig. 6: Grounding by high impedance branch recovery method for line-to-ground fault

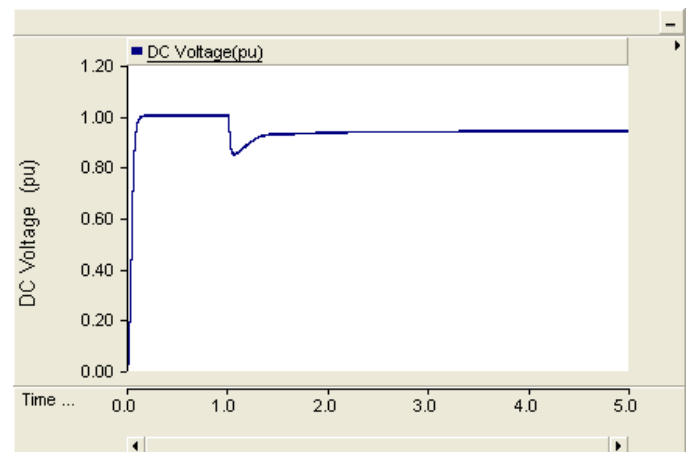


Fig.7: Simulation results of DC link voltage for VSC-HVDC System using Grounding by high impedance branch

B. Change transformer secondary winding to Yn type

By changing the transformer secondary winding to Yn, the unbalance of capacitors will rebalance automatically through the path. However, if there is no suppressing method, the balancing current will be too large for operating securely. According to this, a high resistor can be added to the neutral point of transformer, as in.

C. Monopolar scheme operation

For overhead line system, adopting monopolar scheme has the advantages as follows:

- The system can adopt DC current grounding return arrangement for saving investment;
- The system is generally grounded by positive pole, so The total corona noise and fault probability can be reduced.

Generally, the monopolar scheme is better for overhead line system compared with bipolar scheme.

V. CONCLUSION

VSC-HVDC technology is continually developing and more and more applied in renewable power integration, so it has a broad prospect. DC transmission line faults have a detrimental effect on VSC-HVDC system operation and may make damage to the system components. This paper analyses the transient characteristics of electrical quantities in a two terminal VSC-HVDC system after the occurrence of line-to-ground fault. The results are analyzed in PSCAD detailed.

The analysis and simulation show out the characteristics of DC line-to-ground fault of VSC-HVDC system. The line-to-ground fault leads to the unbalance of DC voltage which is difficult to rebalance; for overhead line temporary line-to-ground faults, the rebalance of capacitors can be realized by using high impedance grounding system. In this recovery method the discharging current is very small so that the voltage of the capacitor can maintain without any overcurrent stress. The over-current after a line-to-ground fault is not very large, so line-to-ground is not serious fault.

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