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Multi-Terminal DC System line Protection Requirement and High Speed Protection Solutions

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SUMMARY

For long distance and high power transmission, high-voltage direct current (HVDC) transmission is a preferred solution due to its technical and economic advantages. A multi-terminal HVDC (MTDC) transmission system either based on voltage source converters (VSC) or line-commutated converters (LCC) has also been introduced recently. With the development of fast and high breaking capability HVDC circuit breakers, the collapse of the MTDC network voltage resulting from DC line faults can be prevented and the disturbances to the connected AC grid can be minimized by using related protection systems. Therefore, it is required to have a fast and selective DC line fault detection and location methods using initial transient fault signatures.

This paper describes the basic requirements of a line protection system in a VSC based MTDC network such as speed, selectivity, sensitivity and security, etc. with consideration of the expected breaking capability of HVDC circuit breakers. The transient phenomena of DC fault currents and DC voltages for different types of faults are analysed together with the protection requirements for an example four-terminal bi-pole MTDC transmission system.

Based on the fault analysis and high speed operational requirements, fast fault detection algorithms using traveling waves measured at the MTDC terminal stations are proposed. The proposed fault detection algorithms are based on single end measurement. To verify the proposed fault detection algorithms, the example four-terminal bi-pole MTDC network is used to check the performance of the fault detection functions for different types of DC faults, such as pole-to-pole faults and pole to ground faults, at different locations. Finally, conclusions are provided based on the fault analysis and fault detection testing results.

KEYWORDS

DC Grid Protection, Multi-terminal HVDC System, Power transmission.

1 INTRODUCTION

Technology development always brings new innovations in the application areas. One important technology progress in power transmission domain is voltage source converter (VSC) based HVDC transmission during last decade. One of advantages of VSC based HVDC transmission system is the possibility to perform power reversal through current reversal in which an HVDC link could be used similar as an AC link [1]. There are several MTDC systems in advanced planning stage of development in Europe, North America and a couple of practical MTDC systems have been put into operation in Asia [1]. In particular, MTDC systems have been considered technically and economically attractive for

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integration of large-scale offshore wind farms and for reinforcement of interconnected regional power grids over AC transmission solutions.

For a VSC-based MTDC system, there might be different grounding schemes which could influence the fault detection and protection solutions. For high impedance grounded system, the voltage stress during the pole to ground fault period implies higher demand on the insulation systems while the low impedance grounded system might cause high fault current during the fault period [1]. This paper will focus on the fault detection and protection solutions for bi-pole VSC-based MTDC systems with low impedance grounding scheme.

Considering various grid system expansion requirements, a MTDC transmission system could be configured with different network topologies such as radial, meshed or a combination of both. Figure 1 below shows an example four-terminal MTDC system which is connected with four asynchronous AC grids. In the shown MTDC network, each converter station is connected to the other three converter stations by DC cable systems. Each DC cable system has three parallel cables: positive pole cable, negative pole cable and a metallic return. For MTDC network protection purpose, HVDC circuit breakers (not shown) are installed at both ends of the DC power cables.

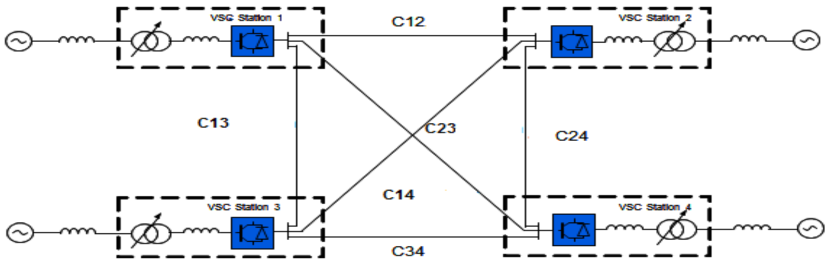

Figure 1- An Example of MTDC Transmission System

2 DC LINE PROTECTION REQUIREMENTS

2.1 Protection Strategies for Handing DC Line Faults

One critical design requirement for any MTDC system is the need of reliable protection strategy, especially fast fault detection and selective protection system for DC lines. When a short circuit fault occurs in any DC line, fault propagation on the MTDC network is very fast and power transmission in all converter stations may become infeasible. It is thus critical to isolate the faulted DC line quickly so that power transmission in the remaining MTDC network can be maintained or resumed as quickly as possible.

There are at least three main strategies for handling DC faults in MTDC networks [2], [3]. The first strategy is the so-called one protection zone concept which uses AC breakers to disconnect the entire MTDC system from the connected AC grid(s) for all DC side faults. The drawback with this strategy is that it requires an extended period of time to re-establish both reactive power capability of the converters as well as active power transfer on healthy parts of the DC network. The second strategy is a variant of the first, but the converters will remain connected to the AC grid(s). In this strategy, the fault current contribution from the AC side following a DC fault is interrupted by either DC breakers on the DC terminals of half-bridge converters or by reversing the DC voltage with full-bridge converters. The advantage with this strategy, as compared to the previous, is that the converters can provide voltage support throughout the contingency. However, the re-establishment of active power transfer on the healthy part of the MTDC network will take some time. The third strategy is to use HVDC circuit breakers inside the MTDC network to isolate the faulted piece of DC equipment such that the remaining MTDC network quickly can resume normal operation in terms of active power transfer. This strategy is, from a technical perspective, a superior solution since, in line with AC grid line protection philosophy, it does not require the total shutdown of the DC network and thus has minimum impact on the connected AC grid(s). The line protection algorithms presented below will be used for this strategy.

In order to reduce the stresses on HVDC breakers, properly sized DC reactors are needed at HVDC switchyards (not shown in Figure 1) to reduce the rate of rise of fault currents. With recent development of hybrid HVDC circuit breakers, it becomes feasible to achieve maximum breaking currents up to 16 kA and operating times within 2 milliseconds [4].

2.2 Basic Requirements for DC Line Protection System

Based on the third protection strategy discussed above, two basic but highly demanding requirements are imposed on the DC line protection system and are described below.

The first requirement is the fast fault detection function of the DC line protection system. Because the DC fault current increases very fast continuously to a high level during the initial fault period and there is no current zero cross point as in the case of AC fault currents, it is required to interrupt the fault current before it arrives to the maximum interruption capacity of DC breakers. As analyzed in [5], it is necessary to have the total fault clearing time which includes both the fault detection time and fault current breaking time within milliseconds so that the DC fault current can be reliably interrupted before it becomes higher than the maximum current breaking capability of HVDC circuit breakers. Therefore, it is important to keep fault detection time as short as possible, ideally within some hundred microseconds.

The second requirement is the reliability of the DC line protection system, which includes both dependability aspects and security aspects. The dependability (including selectivity and sensitivity) is a performance measure for the certainty of correct operation once a fault occurs within the protection zones. For example, only the faulted line's circuit breaker should be tripped in case of a fault in that line within a MTDC systems with multiple HVDC breakers. For a bi-pole transmission system, if there is a positive pole to ground fault, it is required to just trip the circuit breakers in the faulted positive pole conductor. Also, it is demanded to detect and trip all different types of faults in the transmission line including high impedance faults. The security is a performance measure for the certainty of a given protection system to avoid incorrect operations or trips if a fault is outside the protection zones. In general, a reliable protection system means that only the faulted lines or components should be tripped and all healthy lines will be kept in operation without interruption of power transmission.

An overall DC line protection system that could meet the requirements above shown in Figure 2. Here, Main 1 and Main 2 are two fast protection functions. In addition, there are backup protection and sensitive fault protection functions with different time delays. Breaker failure (BRF) function is also required in case of DC breaker failures so that the surrounding breakers could be tripped. Auto-reclose function is provided for quick service restoration after temporary fault trips. Fault location function is also provided using the same sampling data.

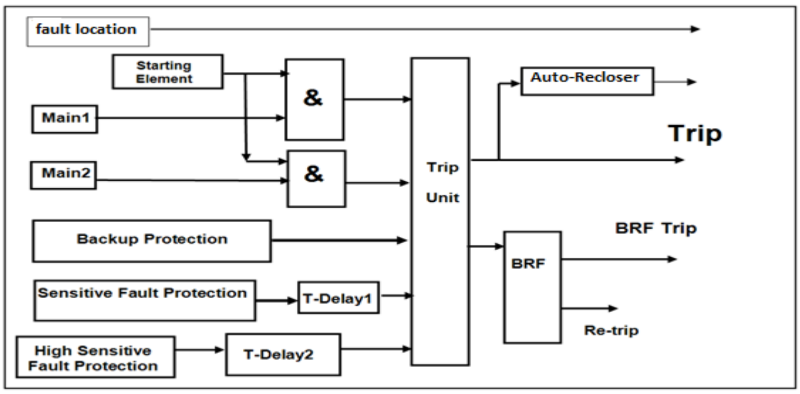

Figure 2-An Overall DC Line Protection System for One End of A DC Line

There are different kinds of faults in the DC transmission lines, such as pole to ground faults, pole to neutral faults and pole to pole faults. Figure 3 shows different line faults in the sample four-terminal bi-pole MTDC system, where R12, R21 … represent the HVDC breakers located at terminal stations and f12, f21 … represent different example fault locations in different DC lines.

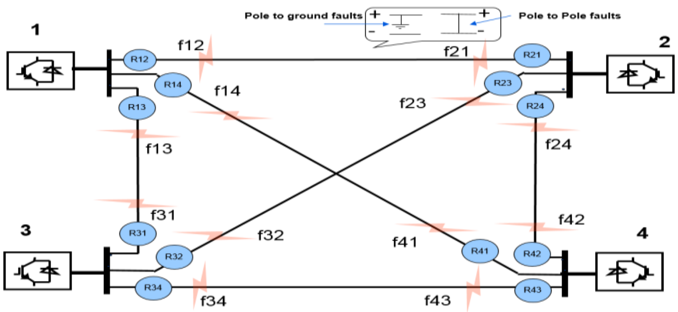

Figure 3-An Example of Fault Positions and Related Protection Systems in a MTDC System

According to the basic requirements for the protection systems, any fault in DC line 12 such as f12 or f21, has to be cleared by R12 and R21 HVDC breakers. The main protection functions associated with R12 and R21 should not trip R12 and R21 for a fault on other DC lines such as f13, f23 … except the faults located in line 12. In addition to the above demand, it is further required to have protection systems in R12 and R21 to trip the faulted pole only in case of pole to ground faults so that the healthy pole could still be kept in operation for the power transmission in that pole. As such, proper pole selection logic (not shown in Figure 3) is required in the DC line protection systems.

2.3 Assumed Breaking Capability of HVDC Breakers

In this paper, the following specification is assumed for HVDC breakers [5]:

(1) Maximum breaking current = 10 kA;

(2) Operating time = 5 milliseconds (ms);

Certainly, there could be different designs of HVDC breakers based on different technologies with different interruption capabilities [5]. It is clear that the protection system needs to isolate the fault before the HVDC breaker maximum interrupting limits. Otherwise, the HVDC breaker will fail to break the current. Figure 4 shows the measured fault current for a cable fault in the example MTDC system described in Figure 3. Here Idcp12 represents the current flow in HVDC breaker R12 for a line fault occurring at 0.5 seconds in position f12 in the simulation. The operating time of the HVDC breaker corresponds to the time delay from receiving the tripping signal from the DC line protection system until the DC line current is interrupted.

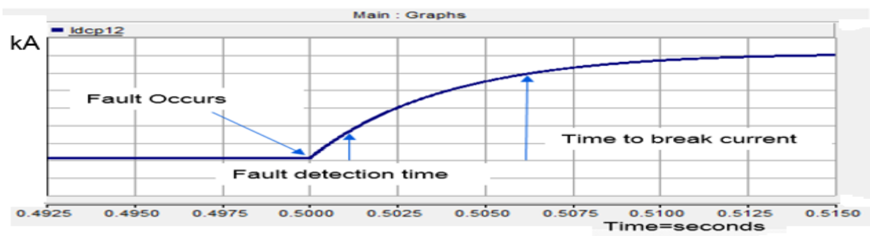

Figure 4-DC Breaker Current during Close-in Pole to Ground Fault in line 12 at position f12

3 DC LINE FAULT DETECTION ALGORITHMS

This section introduces two DC line fault detection algorithms based on transient fault signatures.

3.1 The Basic Concept

The basic concept is to differentiate the local measured fault signal differences between internal faults such as F1 and external fault such as F2 for the cable 12 protection system as shown in figure 5 below.

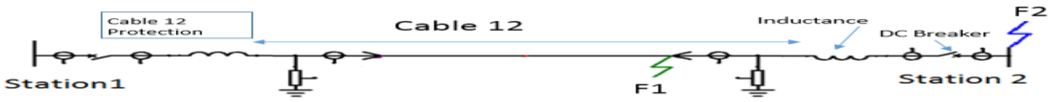

Figure 5-Example DC line with terminal DC reactors in a MTDC system

As shown in Figure 5, the DC inductance has a smoothing effect for the current rising rate [1] so that it is possible to see the difference between internal fault (F1) and external fault (F2) signals (voltage and current measured in Station 1). Figure 6 has shown the simulation results for these two fault cases.

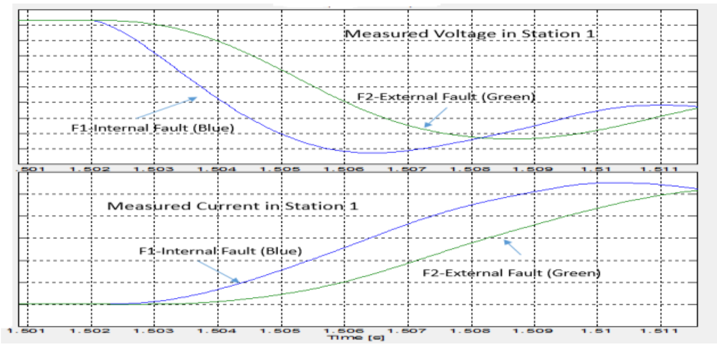

Figure 6-Effect of Inductance Inserted Between DC Breaker and Cable 12 End

The differences between internal and external fault due to the terminal DC inductance could be utilized to detect cable faults as a fast protection function based on only local measurements, which could meet both speed and selectivity requirements.

3.2 Transient Based Fault Protection (TBFP) Algorithm

As it is well known, travelling wave protection has been introduced in power system domain since 1970s [6]. The voltage and current polarity identification algorithms was developed in AC systems in a famous pilot travelling protection system in 1980s [7]. The fault induced travelling wave is explained by considering a transmission line as illustrated in figure 7. The inception of a fault causes a suddenly change in the voltage at the point of the fault and this instantaneous change in voltage can be simulated by inserting an imaginary voltage source at the fault location, which generates a voltage in opposite to the voltage (*U*F) at this point before the fault inception.

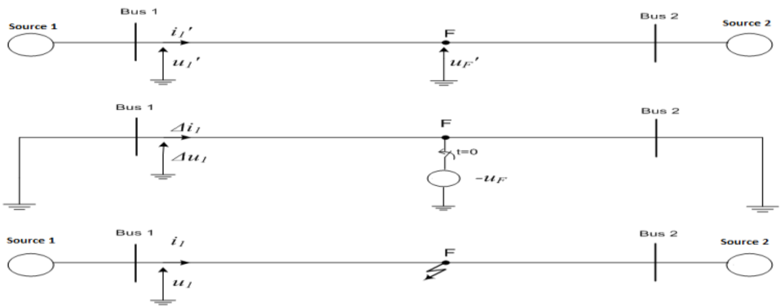

Figure 7-Superimposed Current and Voltage during Fault Inception

According to traveling wave principle this sudden change in voltage level on transmission line at point of the fault will cause the propagation of voltage and consequently current traveling waves on transmission line which reach to both terminals of the line in a very short time. Therefore, the fault currents and voltages at each terminal can be conveniently described using the superposition principal:

$$i_1 = i_1' + \Delta i_1 \quad (1)$$
$$u_1 = u_1' + \Delta u_1 \quad (2)$$

Here, the following notations are used:

i_1 is the measured current after inception of the fault at bus 1;
u_1 is the measured voltage after inception of the fault at bus 1;
i_1' is the measured pre-fault current at bus 1;
u_1' is the measured pre-fault voltage at bus 1;
Δi_1 is the difference in measured current values at bus 1, a fault induced travelling wave current;
Δu_1 is the difference in measured voltage values at bus 1, a fault induced travelling wave voltage;

The fault detection principle of fault induced travelling wave signals can be shown in figure 8 below [6]. Here, the fault induced travelling wave signals are measured by the measurement devices in each end of line (Bus 1 side and Bus 2 side). For internal faults, measured Δi_1 and Δu_1 polarities are in opposite direction and for the external faults behind bus 1, the measured Δi_1 and Δu_1 polarities in bus 1 will have same polarity. For the external fault behind bus 2 side, the measured Δi_2 and Δu_2 polarities in bus 2 will be the same. Therefore, a pilot protection scheme could be formulated by using two side polarity information [6].

Type of the faults	Polarity of u_F'	Bus numbers			
		1		2	
		Δi	Δu	Δi	Δu
Internal	+	+	-	+	-
	-	-	+	-	+
External to Bus 1	+	-	-	+	-
	-	+	+	-	+
External to Bus 2	+	+	-	-	-
	-	-	+	+	+

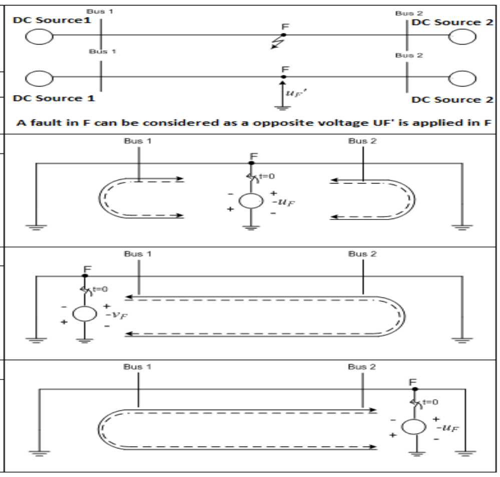

Figure 8-Transmission Line Fault Induced Travelling Wave Polarities for Different Faults

The principle described in Figure 8 cannot be applied for the DC transmission line fault detection because communicating polarity information between two ends of the line will introduce certain time delays which will slow down the protection decision speed. By considering the advantages of DC inductances inserted in each end of DC line, it is possible for one side measured Δi_1 and Δu_1 to see the fault difference between remote end line fault and remote bus fault as given in Figure 5. By using this feature, single end measurement based protection principle can be applied.

Assuming the measured DC current and voltage in Station 1 are *Idcp1*, *Udcp1* respectively by referring to figure 5. In order to capture the travelling wave created by the faults in the transmission line, fast sampling rate is needed and a sampling interval can be denoted as below by using the consecutive sampling time t1 and t2 as given in (3).

$$\Delta t = t2 - t1 \quad (3)$$

Based on the above time interval, the following equations are formed to capture the travelling waves created by faults:

$$\Delta Udcp1 = Udcp1(t2) - Udcp1(t1) \quad (4)$$

$$\Delta Idcp1 = Idcp1(t2) - Idcp1(t1) \quad (5)$$

The multiplication of (4) and (5) will create a signal defined as dP1 as below:

$$dP1 = \Delta Udcp1 \times \Delta Idcp1 \quad (6)$$

For the faults in forward direction along the DC transmission line as fault F1 shown in figure 5, the dP1 value measured at bus 1 will be negative and below certain setting value δ for a short period of time interval Δt as given in (7).

$$dP1 < -\delta \quad (7)$$

For forward faults behind the bus 2 such as fault F2 shown in figure 5, the measured dP1 value in bus 1 will have negative value too. In this case, a proper setting δ for dP1 is needed to confirm that the bus 1 side dP1 will not trigger in response to the external fault F2. The bus 2 measured dP2 value based on *Udcp2* and *Idcp2* will be positive in this case because the fault F2 is seen as a backward fault by bus 2 protection. In this way, a single end measurement based fast protection algorithm could be formed to meet the speed and selectivity protection demand. Figure 9 shows the results for measured signal of dP1 both for internal fault at F1 and external fault at F2. A clear difference between the two cases can be used.

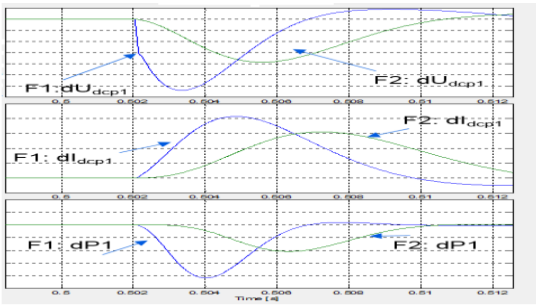

Figure 9-The Signals in Station 1 for the Remote Forward Fault F1 (Blue) and Bus Fault F2 (Green).

3.3 Voltage Derivative Supervised Current Derivative Protection (VDSCD) Algorithm

Voltage derivate related protection solution for HVDC lines has been used for many years [8]. Here, a combination of voltage derivative and current derivative is used for enhanced protection performance. As shown in figure 10, the assumed definition of current direction is positive into the cable from each station. For the internal fault, the rate of changes of both measured currents (I12 and I21) will be positive as the MTDC system feeds into the fault. Note that after the initial current change it is possible that succeeding current response could be oscillatory. But this is not the concern of main protection. In each station, the currents through the un-faulted cables would feed into the fault; some currents would reverse direction while others would maintain same direction. In both cases their rates of change will be negative. A negative current derivative indicates an external fault. A positive current derivative therefore indicates that the fault could be within the protection zone. The currents measured on the other station will also rise proportionately depending on the fault location.

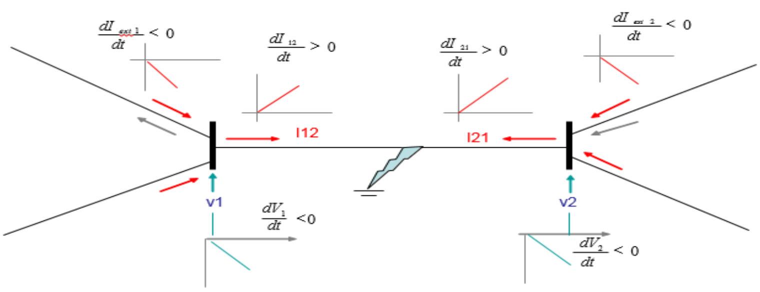

Figure 10- Positive Pole Voltage and Current Derivatives during a Cable Fault

The following rules need to be satisfied for detection of an internal cable fault using this method:

R1: $\frac{dI}{dt} > 0$ -positive rate of change of current

R2: $\frac{dI}{dt} > dI_{operate}, dI_{operate} > 0$ -secure remote relay from tripping forward fault

R3: $\frac{dV}{dt} < dV_{operate}, dV_{operate} < 0$ -added security against external fault

R4: $I > 0$ -security against incorrect operation following fault clearing

On the other hand, the resetting of this function could be done when the fault ceases by using the following resetting rules:

R5: $\frac{dI}{dt} \leq dI_{reset}$

R6: $\frac{dV}{dt} \geq dV_{reset}$

4 DC LINE PROTECTION PERFORMANCE VERIFICATION

4.1 Test System Configurations

The four-terminal MTDC system shown in Figure 1 is used to verify the DC line protection performance. The tests are made with several configurations such as meshed topology, ring, radial and radial with one loop as indicated in figure 11 below. The AC grid strength with different short circuit ratios (3-35) and different cable lengths (100-600km) are also included. The cable line has following parameters: Rc=0.0121 Ω/km, Co=0.2961 μF/km, Lo=0.1056 mH/km, Zo=18.881 Ω.

Figure 11-Test Configurations of example four-terminal MTDC System

4.2 Test Results

For different configurations shown in figure 11, both internal faults and external faults have been tested to check the protection response from both dependability and security points of views. Testing results have shown that the proposed main protection functions can fulfil the demand of fast fault detection and security requirement. Figure 12 shows one of testing results.

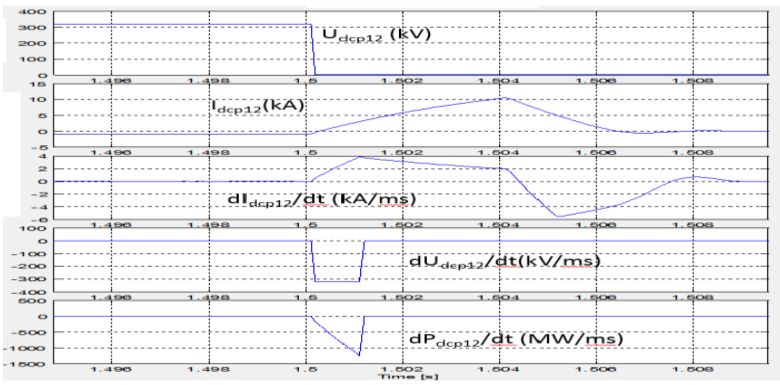

Figure12-Measurments in Station 1 for a close-in internal fault at 1.5 second in Cable C12

Table 1 presents the performance of both protection functions from some example fault cases. Here the remote side trip time includes the fault signal travelling time from the fault location to the measurement station (around 2.1 ms travelling time for 400 km cable line). For example, for fault location f12, station 1 protection will trip first (0.214 ms) and station 2 protection will trip after 3.2 ms because the fault signals created in f12 takes 2.1 ms to arrive to the station 2. Protections at other stations (3, 4) will be kept stable ("x" means no operation) because f12 is an external fault for stations 3 and 4.

Table 1-Testing Results for C12=C13=C14=C23=C24=400 km for MTDC system in figure 1 with different fault positions shown in figure 2 (x=no operation)

Stations	Protection Trip Output	f12	f21	f14	f41	f13	f31	f23	f32	f34	f43
Station1	VDSCD/TBFP Trip Time (ms)	0.214	3.1	0.212	3.0	0.22	3.1	X	X	X	X
Station2	VDSCD/TBFP Trip Time (ms)	3.2	0.22	X	X	X	X	0.212	3.3	X	X
Station3	VDSCD/TBFP Trip Time (ms)	X	X	X	X	3.1	0.25	3.1	0.24	0.23	3.11
Station4	VDSCD/TBFP Trip Time (ms)	X	X	3.0	0.25	X	X	X	X	3.1	0.21

5 CONCLUSIONS

This paper provides requirements and solutions for MTDC system line protection. Two protection algorithms have been proposed as fast protection and selective protection functions based on local measurement signals. The inductance in the HVDC breakers located in each end of line can provide a marginal difference for the local measurement signals to differentiate the line end faults and bus faults so that the single end protection algorithms could meet the high speed and good selectivity demand. The tests have shown that the proposed protection algorithms could detect various DC cable faults in an example MTDC system quickly and selectively. The protection algorithms could also be used for overhead line protection.

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