Book Chapter

New Differential Protection Method for Multiterminal HVDC Cable Networks

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Abstract

Ground faults in electrical power systems represent more than 90% of total faults. Their detection, location and elimination are essential and must be carried out in a precise way to allow multiterminal HVDC cable networks to operate in stable conditions by removing only the faulty cable from service. This paper presents a new differential protection method based on the measurement of the currents at both ends of the shields of the power cables. This new method is cheaper and easier to set in operation compared to other protection methods that measure currents circulating in the active conductors. The values of such intensities and their polarities are evaluated to know which cable has a ground fault in a multiterminal HVDC cable network. This method has been successfully validated by computer simulations and successful experimental results have been obtained.

Keywords

Protection Relays; Fault Location; Ground Faults; HVDC
Abbreviations

AC—Alternating Current; DC—Direct Current; HVAC—High Voltage Alternating Current; HVDC—High Voltage Direct Current; IGBT—Insulated Gate Bipolar Transistor; ROCOV—Rate of Change of Voltage

Introduction

Historically, although the first electric distribution networks were operated in Direct Current (DC), the technology at that time made difficult the implantation of this like standard system of transport of energy, due to the expensive installations and the losses in the conductors. This, together with the advantages of Alternating Current (AC) transmission, made it possible to widespread the use of AC systems. The improvements in the design of AC generators and the invention of the transformer allowed generating and transporting electricity in a more economical way through HVAC systems. This way, the generation of AC energy very far away from the loads could be done easily.

However, despite the advantages that in principle the HVAC systems provided, with the increase of the transport distances in the HVAC lines problems associated with stability rise. These problems are, related to the reactive energy between the capacitances and the inductances of the system, additionally quick identification of power quality disturbances must be considered [1]. In this situation the HVDC system presents several advantages compared to the traditional HVAC systems:

- In HVDC systems, the effect of the inductive and capacitive reactance is practically eliminated because the waveforms obtained at the output of the rectifiers contain a low level of ripple [2]. HVDC links have no stabilities problems and the distances are not limited. Figure 1 illustrates a typical point to point HVDC link to interconnect two networks with different frequencies.
In HVDC systems, power can be controlled more quickly than in HVAC systems. For instance, when an imbalance in the AC system (due to any kind of disturbance) is about to occur, the amplitude of the power of the DC line can be changed to counteract and damp the power oscillations. Therefore, an HVDC link can maintain the specified power flow regardless of severe and dangerous electromechanical oscillations present in the network [3-4]. Improvements in DC voltage measurements at different busbars in different substations have been developed and DC power flow control is therefore more precise [5-6].

The disturbances are not transferred from one system to another. Therefore, it is a system that is very useful in case that the generation occurs at variable frequency, as is the case of wind turbines. Meshed AC grids can present problems with high short-circuit currents at times close to the capacity of the installed switchgear with possible current transformers saturation as well [7]. This circumstance is solved with the use of HVDC links since the link to the non-transferring reactive power does not contribute to the increase of the short-circuit power at the connection node. Furthermore, it has been demonstrated that a good VSC control strategy, with adequate PI controllers, allows having a very quick response to disturbances that happen at the AC side [8].

As for the economical costs, the HVDC substation is much higher than the HVAC substation, but the price per km of line is lower in the DC lines, because DC transmission lines require a smaller number of conductors, the supports and towers are smaller. So the width of the street is smaller and therefore the environmental impact is lower. Consequently, DC transmission lines become economically competitive.
with the AC ones when the length of the line is several hundred kilometres [9]. Figure 2 shows the dimensions of towers used in AC and DC to transport the same power.

- Another advantage of the HVDC system is the unlimited use of insulated cable. In the case of AC transmission systems the cable length is limited due to its ground capacitance. This capacitance involves a capacitive current which is proportional to the cable length. So this capacitive current could reach the rated cable current at certain length.

Figure 2: HVDC transmission line versus HVAC transmission line.

A typical multiterminal HVDC cable networks with four stations and five cables is illustrated in Figure 3.

Figure 3: Multiterminal HVDC system configuration with four stations and five cable lines.
In such network, when a ground fault happens in any of the cables that connect different HVDC stations, the voltage in the entire system is reduced depending on the severity of the fault and the value of its fault resistance. This circumstance might lead the converters to disconnect their semiconductors, causing a collapse in the grid when all HVDC stations are disconnected. On the other hand, the correct operation of the protection systems should disconnect only the faulty line as shown in Figure 4 when there is a ground fault in the cable A-C.

![Figure 4: Multiterminal HVDC selective ground fault protection in case of ground fault in cable A-C.](image)

It would be convenient to have suitable protection systems that can clear up only the faulty line with full selectivity. For this purpose the fault currents should be carefully studied. Detailed analysis of fault current contribution from AC side to DC side under fault conditions in the multiterminal HVDC cable network is presented in [10].

The protection systems currently used in multiterminal HVDC networks use the following methods to detect and clear up faults:

- Analysis of the initial variation of current di/dt: This method uses the behavior of the capacitor at the DC side when a fault happens. A reduced network equivalent is shown in Figure 5.
With a fault on the DC network, capacitor $C$ will discharge and therefore it will add current to the fault. This current contribution depends on the voltage difference between such capacitor and fault position as well as the inductance along the fault circuit.

- Analysis of the rate of current rise: The use of the rate of current rise to detect faults is mainly due to the very fast increase of the current compared to any other working condition as changes in load, switching-off/on maneuvers, etc. The most important advantage of this type of detection is that the fault current is detected long time before the maximum fault current value is reached. This performance reduces in a great deal the instability created by faults in the HVDC network as well as the breaking capacity for the circuit-breakers to be used.

- Analysis of the Rate of Change of Voltage (ROCOV): this method analyses the rate of change of voltage (ROCOV) at the line side in the coil erected to limit the di/dt value. The variation in ROCOV’s values are used as quick fault detection in the range of some microseconds. ROCOV different values allow the localization of faults with selectivity. ROCOV values decrease significantly as a function of the defect distance to the limiting inductor. The farther the fault takes place, the lower of value of ROCOV. Simulations and research jobs have registered values for ROCOV over 30.000 kV/ms when a fault happens close to the limiting inductors and in the range of 1.000 kV/ms for faults at distances over 500 km [11].
In this paper a new differential protection method applied to multiterminal cable networks is introduced. This method measures the currents circulating at the ends of the shields of the insulated cables employed in HVDC networks and applies a differential criterion to determine which cable has a ground defect.

**State-of-the-Art**

HVDC networks are becoming increasingly important in the connection between systems with different frequencies and in the transmission of high active and reactive powers over long distances. Recent research evaluates the possible implementation of high-temperature superconducting DC cables [12].

Normally, DC power links are one-to-one type and the main protections are included in the AC/DC converter at the AC side although different existing configurations have been evaluated to determine the best possible topology. The selection must evaluate amongst other parameters, the system losses, transient fault currents and postfault contingencies. It can be said that there is no dc topology that can meet all aspects [13].

Thinking in HVDC new multiterminal networks, more protections functions must be developed in order to grant full selectivity in such grids. These protection systems used in HVDC transmission networks must be at least as fast as the protections devices used in HVAC grids or even faster mainly because of the quick developing of high fault currents [14-15]. Some applications use the theory of the two-terminal travelling wave [16]. Others research lines study the short-circuit identification use a wavelet analysis of positive and negative currents in cables to find out the faulty one because the wavelet theory is adequate to analyze transient signals such as travelling waves caused by faults [17].

The main differences between HVDC and HVAC protection units are based in the different nature of short circuit phenomena. DC fault currents have no zero crossings as AC fault currents and on the other side, DC fault currents reach their maximum
values in extremely low times that implies very fast rising rates [18]. These two main aspects of HVDC fault currents force HVDC protections to eliminate faults very quickly and even faster than HVAC’s and have driven power converters and the DC circuit breakers to be used applying different fault clearing strategies.

The different options to clear faults at HVDC transmission systems are:

- Switching off the HVAC circuit-breakers: This method requires a minimum number of cycles of the AC current signal at rated frequency to detect, identify and release a tripping command to the corresponding circuit-breaker [19]. Unfortunately, this delay time might develop a lack of selectivity in the DC grid. The operation of the AC protection system also implies that the converter in the substation will be out of service. Implementation of converters with blocking options: some converters can block fault currents [20-22] in the time scale of microseconds with the consequent improvement in fault clearing time respect to the previous method.

Use of HVDC circuit-breakers: circuit-breakers based on power electronics can switch-off fault currents in less than 2 ms but have considerable losses in normal operation [23]. Hybrid HVDC circuit-breakers can cut fault currents up to 5 ms with reasonable losses [24-27]. Another option is the use of mechanical circuit-breakers considering breaking times about 10 ms, voltages up to 250 kV and fault currents with values in the range of 8 kA [28]. The fault current contribution from different sources is absolutely necessary to be well estimated in order to determine the proper ratings of the HVDC circuit-breakers [29].

Table 1 illustrates the different time delays in protection relays as well as the in cutting-off elements actually used.
Table 1: Time delays in protection relays and methods of fault current cutting-off.

<table>
<thead>
<tr>
<th>Protection relay</th>
<th>Time delay (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>With communication</td>
<td>5 – 12</td>
</tr>
<tr>
<td>Without communication</td>
<td>0.1 - 4</td>
</tr>
<tr>
<td>Cutting-off elements</td>
<td></td>
</tr>
<tr>
<td>AC circuit breakers:</td>
<td>33.3 – 40</td>
</tr>
<tr>
<td>Mechanical circuit breakers:</td>
<td>4 – 12</td>
</tr>
<tr>
<td>Hybrid circuit breaker:</td>
<td>2 – 6</td>
</tr>
<tr>
<td>Power electronic circuit breaker / converter</td>
<td>0.1</td>
</tr>
</tbody>
</table>

The measurement and evaluation of voltage change is recently getting more importance in HVDC power systems as the principal protection system, which has to detect and clear ground faults in the cables that form such grids [30]. Until now voltage level protection was usually used as a backup protection. Other backup line protections include DC overvoltage protection and DC line differential protection using optical voltage and current sensors along the cables [31-32]. Actually, different fault ride-through schemes based on hybrid fault current limiters are being highly considered for multiterminal HVDC networks that connect large-scale offshore wind parks mainly because those schemes reduce the fault currents and mechanical circuit breakers can be used perfectly [33].

Proposed Method for Differential Protection of HVDC Cable

The research area of this article focuses on the detection of ground faults in multi-terminal DC networks formed by cables. It introduces a novel differential method for the selective detection of ground faults in DC insulated cables that have their shields grounded at both ends. The operating principle of the present method is based on the measurement and analysis of the currents that circulate through the ends of the shields of the cables in case of ground fault. The measurements of intensities in shields have important advantages compared to traditional current measurements in the active conductors. One advantage is the low cost, as there is no necessity for high insulation levels in the
measurement sensors. Another advantage is its ease of assembly as current measurement sensors are ring core type normally. The faulty cable is identified by measuring the polarity of the currents at the ends of the cable shields and comparing such polarities. If the polarities of the currents flowing through the shields are the same, this indicates that the cable has an internal ground fault. However, if the polarities of such currents that circulate through the shields of the protected cable are different, it points out that the cable has no ground fault, so the ground fault is external.

**Figure 3:** Current circulation for an internal ground fault in stretch 1.

As can be seen in Figure 3, in stretch 1 where a ground fault is represented, the polarity of the currents at the ends of the shield in this stretch 1 is the same. For the same ground fault, the polarities of the intensities at the respective ends of the shields in stretches 2 and 3 are different. For an external ground fault outside stretch 1 as represented in Figure 4, the intensities that circulate at the ends of the shield of stretch 1 have different polarities. The basic principles of operation of this new method are the following:

- Measuring of the currents at both ends of cable shield. From these measurements the polarities of the currents are obtained.

- Internal ground fault in case of same polarities.

- External ground fault in case of different polarities.
Figure 4: Current circulation for an external ground fault, outside of the cable.

This new method presented is economical as the current sensors to be used are low voltage insulated; it is simple to set in operation with easy settings and it removes from service in a selective way the cable with defect.

Simulation Model Implemented in Matlab Simulink

Computer Model Description

The model used in Matlab-Simulink considers three different sections of cable with 220 kV as rated voltage and every section has 100 km length. The technical characteristics of the cable used in the model are enclosed in Table 2 and Table 3.

Table 2: Main characteristics of 220 kV cable.

<table>
<thead>
<tr>
<th>Library/Category:</th>
<th>Simscape/SimPowerSystems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Element:</td>
<td>Mutual Inductance + Series RLC Branch</td>
</tr>
<tr>
<td>Parameters:</td>
<td>$\rho_{Al} = 2.82 \times 10^{-8} \ \Omega \cdot m; \ \rho_{Cu} = 1.71 \times 10^{-8} \ \Omega \cdot m; \ \rho_{e} = 100 \ \Omega \cdot m$</td>
</tr>
<tr>
<td></td>
<td>$\varepsilon_{cs} = 2.5; \ \varepsilon_{se} = 2.3; \ r = 3%; \ f = 50 \ Hz$</td>
</tr>
<tr>
<td></td>
<td>Length= 100 km transs</td>
</tr>
</tbody>
</table>
Table 3: Dimensional characteristics of 220 kV cable.

<table>
<thead>
<tr>
<th>Nominal voltage (kV)</th>
<th>Cross section Cu (mm$^2$)</th>
<th>Shield cross section Cu (mm$^2$)</th>
<th>Outer diameter (mm)</th>
<th>Maximum insulation temperature (ºC)</th>
<th>Maximum cover temperature (ºC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>220</td>
<td>2000</td>
<td>165</td>
<td>130</td>
<td>90</td>
<td>70</td>
</tr>
</tbody>
</table>

The equivalent PI circuit of this cable considers the mutual impedance between the conductor and the shield as well as the capacitances conductor-shield and shield-ground. Figure 5 shows such equivalent PI model of the cable.

![Figure 5: PI model of the cable used in simulations.](image)

The simulated circuit model is seen in Figure 6. It consists in one cable A with three cable stretches 1, 2 and 3, an overhead line with two segments A and B with 100 km length each one, another cable B with only one stretch and 100 km length, two HVDC stations A and B as sources, a 50 MW load placed at HVDC generation system B and a fault circuit breaker that allows us to place the ground fault at any position along the cables or overhead line. It considers a HVDC system rated 220 kV and loads from 0 to 50 MW connected. Every stretch in Cable A has 100 km length. At the end of the shields have been included resistance values with 1 mΩ value with the purpose to be able to read the currents that circulate through them. The overhead line has the next parameters are presented in Table 4.
Table 4: Characteristics of 220 kV overhead line.

<table>
<thead>
<tr>
<th>Voltage (kVdc)</th>
<th>$R_0$ (Ω/km)</th>
<th>$R_1$ (Ω/km)</th>
<th>$L_0$ (H/km)</th>
<th>$L_{1}=L_2$ (H/km)</th>
<th>$C_0$ (F/km)</th>
<th>$C_1=C_2$ (F/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>220</td>
<td>0.224</td>
<td>0.12</td>
<td>0.00314</td>
<td>0.00144</td>
<td>5.06·10⁻⁹</td>
<td>7.97·10⁻⁹</td>
</tr>
</tbody>
</table>

Figure 6: Model for analysis of the circulations of ground fault currents in shields of power cables.

Simulations Results

Numerous ground fault simulations were performed at different locations and with different fault resistance. Some of them are presented as example and the results of the simulations are showed in Tables.

The currents that circulate in the shield at its both ends when a ground fault is simulated in Cable A (Stretch 1) at 25 km from HVDC-Station A appear in Figure 7 and Figure 8.
In Figure 7 it can be seen the currents in the shield of the faulty conductor when an internal ground fault happens in the time $t=2$ s of the simulation. The fault has been simulated at 25 km distance from the HVDC-Station A. Both currents at both ends of such shield have the same polarity.

Figure 8 shows the currents at both ends of the shield of Stretch 3 in Cable A in case of an external ground fault. Such currents have now different polarity.
Table 5: Polarities of currents in shields with ground fault in Cable A-Stretch 1. Polarity of currents at ends of the shields.

<table>
<thead>
<tr>
<th>Ground fault resistance $R_F$ (Ω)</th>
<th>Ground fault position (km)</th>
<th>Stretch 1: Shield End at HVDC Station A</th>
<th>Stretch 1: Shield End at Stretch 2</th>
<th>Stretch 2: Shield End at Stretch 1</th>
<th>Stretch 2: Shield End at Stretch 3</th>
<th>Stretch 3: Shield End at Stretch 2</th>
<th>Stretch 3: Shield End at HVDC Station B</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-20-40-60-80-100</td>
<td>0-25-50-75-100</td>
<td>positive</td>
<td>positive</td>
<td>negative</td>
<td>positive</td>
<td>negative</td>
<td>positive</td>
</tr>
</tbody>
</table>

Table 6: Polarities of currents in shields with ground fault in Cable A-Stretch 2. Polarity of currents at ends of the shields.

<table>
<thead>
<tr>
<th>Ground fault resistance $R_F$ (Ω)</th>
<th>Ground fault position (km)</th>
<th>Stretch 1: Shield End at HVDC Station A</th>
<th>Stretch 1: Shield End at Stretch 2</th>
<th>Stretch 2: Shield End at Stretch 1</th>
<th>Stretch 2: Shield End at Stretch 3</th>
<th>Stretch 3: Shield End at Stretch 2</th>
<th>Stretch 3: Shield End at HVDC Station B</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-20-40-60-80-100</td>
<td>0-25-50-75-100</td>
<td>negative</td>
<td>positive</td>
<td>positive</td>
<td>positive</td>
<td>negative</td>
<td>positive</td>
</tr>
</tbody>
</table>

Table 7: Polarities of currents in shields with ground fault in Cable A-Stretch 3. Polarity of currents at ends of the shields.

<table>
<thead>
<tr>
<th>Ground fault resistance $R_F$ (Ω)</th>
<th>Ground fault position (km)</th>
<th>Stretch 1: Shield End at HVDC Station A</th>
<th>Stretch 1: Shield End at Stretch 2</th>
<th>Stretch 2: Shield End at Stretch 1</th>
<th>Stretch 2: Shield End at Stretch 3</th>
<th>Stretch 3: Shield End at Stretch 2</th>
<th>Stretch 3: Shield End at HVDC Station B</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-20-40-60-80-100</td>
<td>0-25-50-75-100</td>
<td>negative</td>
<td>positive</td>
<td>negative</td>
<td>positive</td>
<td>positive</td>
<td>positive</td>
</tr>
</tbody>
</table>
Simulation results with ground faults along the three stretches are included in Tables 5, 6 and 7 considering the system loaded with 50 MW. Different fault resistance values (0, 20, 40, 60, 80 and 100 Ω) have been considered at the different positions of the ground fault considered (0, 25, 50, 75 and 100 km) in every stretch in Cable A. Polarities of currents in the shields turned out to be the same when there is not any load connected.

According to the simulation results, the differential protection method proposed operates correctly in any case, with external and internal faults with several fault resistance level.

**Experimental Laboratory Tests and Discussion**

**Experimental Set-Up Description**

The experimental set-up is illustrated in Figure 9. The laboratory set-up used to validate the simulation results is formed by:

- (1) Three phase AC power supply unit: range 0-400 Vac/ 10 kVA.
- (2) Oscilloscope Tektronix TPS2024 with a memory card to save test currents.
- (3) DC rectifying bridge: input range 0-480 Vac.
- (4) Clamps FLUKE I30S for measuring currents in the conductor and in its two shield ends: range 30 A/sensibility 100 mV/A
- (5) One circuit breaker to develop ground faults rated 400 V/ 32 A
- (6) Three cable sections with 100 m length each one. The main characteristics of this cable used are: R=1,8 Ω, L=22 mH and C=4,9 nF with a total cable length of 300 m.
- (7) A load resistor with a range 0-150 Ω.
- (8) One fault resistance with range 0-100 Ω.
- (9) Overhead lines modules: two line modules with equivalent circuit “pi” are used with the next features: R=88.48 mΩ, L=4 mH and C=4 μF each capacitor.

**Figure 9:** Experimental set-up. (1: AC power supply; 2: Oscilloscope; 3: Rectifying bridge; 4: Current measurement units; 5: Fault switch; 6: Cable and Shields modules; 7: Load resistor; 8: Fault resistance; 9: Overhead line modules.

The experimental set-up is illustrated in a schematic way in Figure 10.

**Figure 10:** Lay-out of experimental ground faults positions in cable side (A, B, C and D) and in overhead line side (F and E).
Experimental Results

Many ground fault tests at cable side between positive and shield at positions A, B, C and D were performed. Also ground faults at overhead side were developed in E and F.

Fault resistance has also been considered in the range from 0 to 100 Ω, and the resistive loads from 0 to 150 Ω. The DC voltages used are in the range from 50 to 110 Vdc.

Some of these tests are presented as example. An example of external ground fault is presented in Figure 11. Figure 11 shows the ground fault currents for a defect with fault resistance of 26 Ω in position F at the overhead line side from positive conductor to ground when the circuit is supplied at 105 Vdc from the DC source and has 1 A load current.

It can be seen that the currents in the ends of the shield in cable section 1 have different polarities. It is owing to the fact that the fault is outside the cable in the overhead line side.

For faults inside sections 1 and 2 of the cable, Table 8 shows the current values read by the sensors CH1, CH2, CH3 and CH4 at the end of the shields when there are faults in points A, B, C and D in cable between positive conductor and shield. Polarities of currents in the shields turned out to have the same values when there was not any load connected.

Table 8: Ground fault currents in shield with load connected Test voltage 105 Vdc.

<table>
<thead>
<tr>
<th>Position of the fault</th>
<th>Sensor CH4 (A)</th>
<th>Sensor CH3 (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2.342</td>
<td>0.065</td>
</tr>
<tr>
<td>B</td>
<td>0.924</td>
<td>1.864</td>
</tr>
<tr>
<td>C</td>
<td>1.012</td>
<td>0.735</td>
</tr>
<tr>
<td>D</td>
<td>1.789</td>
<td>0.045</td>
</tr>
</tbody>
</table>
Figure 11: Ground fault currents with external ground fault in overhead line side in E with 1 A load current.

Table 9 shows the polarity of the currents circulating at both ends of the shields for different ground faults placed in A, B, C and D. At every end of any shield, currents leaving the shield have been considered as positive and currents entering in the shield negative.

Table 9: Polarities of ground fault currents in cable without load connected. Ground fault in cable.

<table>
<thead>
<tr>
<th>Ground fault position</th>
<th>Cable section 1: CH3</th>
<th>Cable section 1: CH4</th>
<th>Cable section 2: CH1</th>
<th>Cable section 2: CH2</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>positive</td>
<td>positive</td>
<td>positive</td>
<td>negative</td>
</tr>
<tr>
<td>B</td>
<td>positive</td>
<td>positive</td>
<td>positive</td>
<td>negative</td>
</tr>
<tr>
<td>C</td>
<td>positive</td>
<td>positive</td>
<td>negative</td>
<td>positive</td>
</tr>
<tr>
<td>D</td>
<td>positive</td>
<td>positive</td>
<td>negative</td>
<td>positive</td>
</tr>
</tbody>
</table>

Figure 12 shows the currents circulating in the shields of cable section 1 when a fault happens in cable section 2. It can be seen that such currents have different polarity.
Figure 12: Ground fault currents in shields of Cable Section 1 with defect in Cable section 2 in point C with 1 A load connected. Fault resistance $R_f=26 \, \Omega$.

Figure 13: Ground fault currents in shields of Cable Section 2 with defect in Cable section 2 in point C with 1 A load connected. Fault resistance $R_f=26 \, \Omega$.

Figure 13 shows the currents circulating in the shields of cable section 2 when a fault happens in the very same cable section 2. It can be seen that such currents have equal polarity, in particular negative, as both currents are leaving the shields to ground. Our reference for currents in shields is negative for currents leaving the shield and positive for currents entering in the shield. The result matches this criterion.
Discussion of Results

The strategy of this novel method described, simulated and tested in laboratory is the measurement of the polarities of the currents that circulate at the ends of the shields of every cable that form a multiterminal HVDC cable network. We have developed many tests to check its performance. Ground faults have been developed in different singular points as follows:

- Faults between active conductor in cable and the corresponding shield in points A, B, E and F (as indicated in Figure 10). Tests developed with voltages 50, 75 and 105 Vdc, fault resistances with 13, 26, 52 and 104 Ω have obtained in all of them equal polarities in the currents circulating in the shields from the faulty points to ground at both ends. Therefore, the results obtained are totally independent from the voltage level used and fault resistance values.

- Faults between active conductor and ground at points C and D (as indicated in Figure 10) in the overhead line. Tests with the same voltage levels and fault resistance values employed are identical as the used in points A, B, E and F. Even when the proximity of the faults in the overhead line to the cable line is remarkable, the polarities of the currents circulating in the shields of the cables are different.

So no matter how close is the ground fault to the overhead line side or cable line side, the results have turned out to be totally satisfactory.

The future research direction points to the study of the currents that circulate through the cable screens to locate the fault in the cable. New mathematical models that include the variation of such ground resistances are underway with the task of not only finding the cable with defect but the position of the fault too.
Conclusions

A new differential ground fault detection method for DC cables is presented in this paper. The method is based on measuring the current at both ends of the cable shields, which circulate only in case of ground faults. By comparing the polarities of these currents, it can be determined if the ground fault is internal or external, and therefore it is a differential ground fault protection. This technique presents the followings advantages:

- Low installations cost
  As the measurement of the currents is performed in the shields no high voltage sensors are required.

- Easy setting
  The operation principle of the protection is the comparison of the polarities of two currents, so no errors in the setting are possible, as in other protection function.

- Suitable for multiterminal HVDC power systems
  This new protection is completely selective, so only the cable with internal ground fault will be removed from service. This is an important advantage in comparison to the AC protections which disconnect the AC/DC power converter.

- Long cables with several section
  This technique could be applied to long cables with several sections. In this way the protection could give information about the faulty section. The proposed protection method has been tested by computer simulations and experimental results with different fault resistance and fault positions results were successfully obtained.
References

10. Bucher MK, Franck CM. Analytic Approximation of Fault Current Contribution From AC Networks to MTDC


