Pilot protection scheme for transmission line of a hybrid HVDC system based on polarity characteristics of current and voltage fault components

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Abstract: A hybrid high-voltage direct current (HVDC) system comprises a line commutated converter (LCC) at the rectifier side and a voltage source converter (VSC) at the inverter side, combining advantages of both LCC and VSC systems. However, the asymmetric converters at both ends of line constrain the direct application of line protections used for conventional HVDC systems. This study proposes a polarity-based pilot transmission line protection for hybrid HVDC systems. By digitising the current and voltage fault components, their polarity characteristics are extracted to identify the transmission line fault, which may eliminate the influence of the fault component magnitude differences caused by different converter structures and control strategies. Simulation results show that the proposed protection is valid and feasible and is capable of distinguishing fault with large transition resistance.

1 Introduction

A line commutated converter (LCC)-based high-voltage direct current (HVDC) technology has been utilised for long-distance, bulk power transmission and power grid interconnection for more than 60 years. However, the inverter station of the LCC–HVDC system has inevitable commutation failure problem [1]. By reconstructing the inverter station of the conventional LCC–HVDC system into VSC station, the commutation failure problem could be solved [2, 3]. This LCC–VSC hybrid HVDC system presents great advantages in many applications, especially in a multi-infeed HVDC system. However, due to the asymmetric converters at both ends of line, the application of the line protections used for conventional HVDC systems to the hybrid HVDC system needs further studies.

A pilot protection for the HVDC transmission lines based on current fault component characteristics is proposed in [4]. The fault direction is determined by the integration of current fault component value, which is closely related to the amplitude of the current fault component. However, in the hybrid HVDC system, the amplitudes of the current fault components at two ends of the line are quite different due to the different converter structures and controls. Moreover, the fault current magnitude is attenuated by high transition resistance. These factors would affect the performance of the protection in the hybrid HVDC system.

This paper proposes a novel pilot protection for hybrid HVDC transmission lines based on polarity characteristics of current and voltage fault components. Current and voltage fault components are digitised, while only their polarity characteristics are extracted to identify the transmission line fault. The proposed protection is not affected by the fault component amplitude differences at two ends of the line and has adequate sensitivity under high resistance fault as well.

2 LCC–VSC hybrid HVDC system

Fig. 1 illustrates the schematic diagram of an LCC–VSC hybrid HVDC transmission system built in PSCAD/EMTDC. The rated voltage of the system is ±500 kV, and the transmission capacity is 1200 MW. The rectifier station is the conventional LCC station, the smoothing reactor inductance is 290 mH, and 12/24th and 12/36th double-tuned filter banks are adopted. The inverter station is the VSC station that utilises the modular-multilevel converter (MMC). Each arm contains 400 submodules. The submodule capacitance is 15 mF, and the arm inductance is 80 mH. The reactor located at the inverter side of the line is 20 mH. The dc transmission line, whose length is 1000 km, adopts the frequency-dependent model. M and N are the positions of the installed protection measuring devices.

The LCC-based rectifier adopts a constant dc current control combined with a minimum firing angle control and voltage-dependent current order limiter (VDCOL). During normal operation, the rectifier converter is under the constant dc current control. In the case of fault, VDCOL reduces the dc current order according to the dc voltage drop; thus, the fault current gradually decreases to a new dc current order. Besides the inherent time of the modules in control system, certain inertia time constants are also set to ensure a stable control. Consequently, the control system presents certain response delay to the failures.

The VSC-based inverter adopts direct current control, including inner loop current control and outer voltage control. The inner loop current controller regulates the amplitude and phase of ac current. The outer loop voltage controller includes an active power class control and a reactive power class control, which are chosen as the constant dc voltage control and the constant reactive power control, respectively, in this paper. Limited by the control strategy and the structure of the converter, the inverter side is not able to control the fault current at the dc side. The control trajectory of Ud–Id in a hybrid HVDC system is shown in Fig. 2.

Fig. 1 LCC–VSC hybrid HVDC system
3 Current fault characteristics of the LCC–VSC hybrid HVDC system

According to the superposition principle, when fault occurs, the circuit networks can be divided into the normal network and the fault component network. The current and voltage measured at the protection measuring device, $i$ and $u$, can be described by superposition of the pre-fault current and voltage, $i_0$ and $u_0$, with the fault component current and voltage, $\Delta i$ and $\Delta u$. In the bipolar hybrid HVDC system, as shown in Fig. 1, due to the symmetry of the two poles, without loss of generality, the fault takes place on the positive pole. The positive direction of current is defined as the current flowing from dc bus to dc line.

3.1 Internal fault

When internal fault $f_1$ occurs, the fault component network is shown in Fig. 3. The current fault components at two ends of the line flow from the rectifier dc bus and inverter dc bus, respectively, to the fault point under the action of the fault-superimposed voltage source $U_f$.

Due to the large differences in the converter devices and control strategies between the rectifier and inverter, current fault component waveforms at two ends of the line are distinct. Fig. 4 shows the current fault component waveforms at the rectifier side and inverter side when a solid grounding fault occurs on the midpoint of the positive line at 2.5 s. After fault occurs, current at the LCC-based rectifier side increases incipiently, and then decreases gradually under the action of control system. As for the VSC-based inverter side, after the line fault occurs, modular capacitors discharge and large discharging current flows through the protection measuring device. Since the inverter station is unable to control the fault current, the current fault component measured at the inverter side increases continuously.

Although the amplitudes and change trends of the fault currents at the rectifier side and inverter side are different, in the initial transient phase of fault, current fault components at two ends of the line have the same positive polarity, namely $\text{sign}(\Delta i_M) = \text{sign}(\Delta i_N) = 1$.

3.2 External fault at the rectifier side

When external fault $f_2$ occurs at the rectifier side, the fault component network is shown in Fig. 5. The fault current $I_f$ flows from the inverter dc bus to the rectifier dc bus under the action of the fault-superimposed voltage source $U_f$.

Fig. 6 shows the current fault component waveforms at the rectifier side and inverter side when solid grounding fault occurs at the converter side of the rectifier smoothing reactor. When fault occurs, the current fault component at the inverter side increases and its polarity is positive, whereas the current fault component at the rectifier side decreases and its polarity is negative. Since the constant dc current control at the rectifier side is limited by the minimum firing angle control, the rectifier loses the control of the fault current. The fault current magnitude is large and increases continuously. Therefore, the polarities of current fault components at two ends of the line are opposite, namely $\text{sign}(\Delta i_M) = - \text{sign}(\Delta i_N)$.

3.3 External faults at the inverter Side

When external fault $f_3$ occurs at the inverter side, the fault component network is shown in Fig. 7. The fault current flows from the rectifier dc bus to the inverter dc bus under the action of the fault-superimposed voltage source $U_f$.

Fig. 8 shows the current fault component waveforms at the rectifier side and inverter side when the solid grounding fault occurs at the converter side of the inverter smoothing reactor. When fault occurs, current at the rectifier side increases and current at the inverter side decreases. Afterwards, the fault current is controlled by the rectifier control system and decreases gradually. However, in the initial transient phase of fault, current fault component at the rectifier side is positive and current fault component at the inverter side is negative.
The starting unit is to detect the abnormal conditions rapidly and described as follows.

**4 Protection scheme**

Base on the polarity characteristics of current fault components, a pilot protection scheme for hybrid HVDC transmission line is proposed. The sampling rate of the protection is 10 kHz. The data window is chose as 5 ms after the protection starts in order to avoid the influence of the control system. The protection is composed of a starting unit, a line fault identification unit and a faulty pole identification unit. The principles and criteria of each unit are described as follows.

**4.1 Starting unit**

The starting unit is to detect the abnormal conditions rapidly and start the protection. The current gradient is adopted to detect the current changes and determine whether the hybrid HVDC system fault at the inverter side. Base on the polarity characteristics of current fault components, a current fault component changes frequently, which might affect the judgment of the protection adversely. However, the overall characteristic of the fault current variation trend, the sampled window is chose as 5 ms after the protection starts in order to avoid the influence of the control system. The calculation expression and the criterion of the starting unit are as follows:

\[
\begin{align*}
V_i(k) &= \sum_{j=b}^{2} i(k-j) - \sum_{j=3}^{5} i(k-j) \\
|V_i(k)| &> \Delta
\end{align*}
\]

where \(i(k-j)\) is the \(j\)th current value sampled prior to the present moment. \(V_i(k)\) is the calculated current gradient. \(\Delta\) is the threshold value of the starting unit, and it is set to be 0.02 pu.

**4.2 Line fault identification unit**

The aforementioned analysis shows that, under different fault conditions, though the current fault component magnitudes at two ends of the line are quite different, their polarities are obvious, which can be used to distinguish the internal faults from the external faults. In the initial transient phase after fault, the current fault components at two ends of the line have the same positive polarity under internal faults; the current fault components at two ends of the line are opposite, namely the current component at the inverter side is negative. The polarities of current fault components at two ends of the line are opposite, namely \(\text{sign}(\Delta_\text{in}) = -\text{sign}(\Delta_\text{out})\).

Due to the electromagnetic coupling effect between the parallel transmission lines of the bipolar HVDC system, faults on one line will induce the change in current on the other line, which might cause the maloperation of the transmission line. Research shows that, in the bipolar HVDC system, when single line to ground fault occurs, the voltage of the faulty pole decreases; thus, the voltage fault component of the faulty pole has a negative polarity; but the voltage of the non-faulty pole goes up and downs under the effect of the coupled overvoltage; therefore, the polarity of the voltage fault component of the non-faulty pole is not constant [6, 7]. The polarity characteristic of the voltage fault component could be used to distinguish the faulty pole.

After the protection starts, the polarities of the voltage fault components at each sampling point are judged and the difference between positive ones and negative ones is calculated:

\[
P_{ix}(k) = \text{sign}(\Delta_\text{ix}(k)) = \begin{cases} 
1 & \Delta_\text{ix}(k) > 0 \\
-1 & \Delta_\text{ix}(k) < 0
\end{cases}
\]

where the subscript \(x = M, N\), representing the rectifier side and inverter side parameters, respectively. \(N_{ix}\) is the difference between positive and negative current fault component sampling numbers in the data window. \(k_s\) is the sampling point when the starting unit criterion is satisfied and \(k_l\) is the sampling number in 5 ms. \(P_{ix}\) represents the polarity of the current fault component: 1 for the positive polarity and −1 for the negative polarity. \(\Delta_\text{ix}\) is the filtered current fault component.

At the end of the data window, both the rectifier side and inverter side send the calculated results to each other and add them up:

\[
N_{ix,\text{sum}} = N_{ix,\text{M}} + N_{ix,\text{N}}
\]

If the summation \(N_{ix,\text{sum}}\) is a large positive number, which means the polarities of current fault components at both ends of the line are positive, then the fault is determined as an internal fault. If the summation is close to zero, which means the polarities of current fault components at two ends of the line are opposite, then the fault is determined as an external fault. The criterion of the line fault identification unit is as follow:

\[
N_{ix,\text{sum}} > N_{ix,\text{set}}
\]

where \(N_{ix,\text{set}}\) is the threshold value. It is a positive number and set to be 50% of the total number of samples digitised in the data windows at both ends of the line. In this case \(N_{ix,\text{set}}\) is 50.

**4.3 Faulty pole identification unit**

Due to the electromagnetic coupling effect between the parallel transmission lines of the bipolar HVDC system, faults on one line may cause the oscillation of the current; thus, the polarity of the coupled overvoltage; therefore, the polarity of the voltage fault component could be used to distinguish the faulty pole.

After the protection starts, the polarities of the voltage fault components at each sampling point are judged and the difference between positive ones and negative ones is calculated:

\[
P_{ux}(k) = \text{sign}(\Delta_\text{ux}(k)) = \begin{cases} 
1 & \Delta_\text{ux}(k) > 0 \\
-1 & \Delta_\text{ux}(k) < 0
\end{cases}
\]

where the subscript \(x = M, N\), representing the rectifier side and inverter side parameters, respectively. \(N_{ux}\) is the difference between positive and negative current fault component sampling numbers in the data window. \(k_s\) is the sampling point when the starting unit criterion is satisfied and \(k_l\) is the sampling number in 5 ms. \(P_{ux}\) represents the polarity of the current fault component: 1 for the positive polarity and −1 for the negative polarity. \(\Delta_\text{ux}\) is the filtered current fault component.

At the end of the data window, both the rectifier side and inverter side send the calculated results to each other and add them up:

\[
N_{ux,\text{sum}} = N_{ux,\text{M}} + N_{ux,\text{N}}
\]

If the summation \(N_{ux,\text{sum}}\) is negative with a large absolute value, then the pole is determined as a faulty pole. If the summation is positive or has a small absolute value, then the pole is determined as a non-faulty pole. The criterion of the faulty pole identification unit is as follow:

\[
N_{ux,\text{sum}} < N_{ux,\text{set}}
\]
where $N_{u\_set}$ is the threshold value. It is a negative number and its absolute value is set to be 30% of the total number of samples digitised in the data windows at both ends of the line. In this case, $N_{u\_set}$ is $-30$.

5 Simulation studies

5.1 Internal faults

If a solid grounding fault occurs at 600 km from the rectifier side, the line fault identification results are depicted in Fig. 9. It can be observed that all the samples of current fault components have positive polarities, at the rectifier side and the inverter side. The calculated result of $N_{i\_sum}$ is 100, which is larger than the threshold $N_{i\_set}$. Therefore, the fault is identified as an internal fault correctly.

Table 1 shows $N_{i\_sum}$ and the discrimination results of the line fault identification unit under different line fault cases, including solid grounding faults, faults with 100 Ω transition resistance and faults with 500 Ω transition resistance at different fault distances on the positive line. It can be obtained from the table that the line fault identification unit of the protection has always worked well under various positive line fault cases. Since the protection criteria are not affected by the current fault component amplitude, the protection has sufficient sensitivity even in the cases of faults with 500 Ω transition resistance.

5.2 External faults

If a solid grounding fault occurs at converter side of the inverter reactor, the line fault identification results are depicted in Fig. 10. It can be observed that, at the rectifier side, all the samples of current fault components have positive polarities; thus, $N_{IM} = 50$; however, at the inverter side, all the samples of the current fault components have negative polarities; thus, $N_{IN} = -50$. Therefore, the calculated result of $N_{i\_sum}$ is zero, which is smaller than the threshold $N_{i\_set}$. The fault is identified as an external fault correctly.

Table 2 shows $N_{i\_sum}$ and the discrimination results of the line fault identification unit of the protection under different external line fault cases. REC and INV represent that the external faults are at the rectifier side and inverter side, respectively. It can be obtained from the table that all these faults are identified as external line faults correctly.
5.3 Faulty pole identification results

To verify the performance of faulty pole identification unit, simulation has been carried out for a solid grounding fault on either the positive or the negative line, at the point of 600 km from the rectifier side. The corresponding results are shown in Figs. 11 and 12.

It can be observed from Fig. 11 that the voltage fault components have negative polarities at both the rectifier side and inverter side. The calculation result of $N_u_{\text{sum}}$ is $-100$, which is smaller than the threshold $N_u_{\text{set}}$. Therefore, the positive pole is identified as the faulty pole correctly. As for the negative line fault case as shown in Fig. 13, the polarities of voltage fault components are not constant. The calculated $N_u_{\text{sum}}$ is 52, which is larger than the threshold $N_u_{\text{set}}$. Therefore, the positive pole is identified as the non-faulty pole correctly.

Fig. 13 shows the $N_u_{\text{sum}}$ calculated by the faulty identification unit of the positive line pilot protection under different line fault cases, including solid grounding faults, faults with 100 $\Omega$ transition resistance and faults with 500 $\Omega$ transition resistance at different fault distances on the positive line and negative line. The simulation results indicate the proposed faulty pole identification method can discriminate the faulty pole and the non-faulty pole effectively, even for the faults with 500 $\Omega$ transition resistance.

6 Applicability analysis

The protection principle proposed in this paper is not affected by the type of the converter station; therefore, it is able to be applied not only to the hybrid HVDC system, but also to the conventional HVDC system. On the other hand, this pilot protection is not limited to the point to point system, and it is applicable to the multi-terminal HVDC system as well.

The performance of the proposed protection when applied to the multi-terminal system is tested, and the test system is as shown in Fig. 10.

| Fault cases                                      | $N_i_{\text{sum}}$ | Result |
|-------------------------------------------------|--------------------|--------|
| REC three-phase fault at the ac bus             | 0                  | external |
| REC three-phase fault at the ac side of the converter | 0                  | external |
| REC grounding fault at the converter side of the smoothing reactor | 0                  | external |
| REC short circuit fault at the outlet of the six-pulse converter | 0                  | external |
| INV grounding fault at the converter side of the smoothing reactor | 0                  | external |
| INV three-phase fault at the ac side of the converter | 0                  | external |
| INV three-phase fault at the ac bus             | 2                  | external |

Fig. 10 Operation result of line fault identification unit under an external fault at the inverter side

Table 2 Test results of external faults

Fig. 11 Operation result of faulty pole identification unit of positive line protection under positive line fault

This prevents the protection on the non-faulty pole from maloperation caused by the coupling current changes.
Various fault conditions are simulated and tested, and Table 3 shows the calculation and judgement results under some typical faults, whose locations are as shown in Fig. 14. The protection has made correct judgements for all of the fault cases, demonstrating that the applicability of the proposed protection in multi-terminal systems.

7 Conclusions

A pilot protection scheme for hybrid HVDC transmission lines is proposed in this paper. This protection only utilises the polarity characteristics of current and voltage fault components to identify the transmission line fault, which eliminates the influence of the fault component amplitude differences. Simulation results show that the protection is able to distinguish internal fault from external fault accurately, identify the faulty pole correctly and hold adequate sensitivity to high resistance fault as well. This protection has low computational complexity, low sampling rate and short data window. Hence, it is easy to realise and has great practical value in engineering. Moreover, the protection principle is not affected by the type of the converters; thus, it is able to be applied to HVDC systems with different converter structures, as well as multi-terminal HVDC systems.

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9 References

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