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Study on Improvement of Main Protection for Converter Ground Faults for Some HVDC Projects in China

***Abstract**. The dc differential protection with one stage needs to react all inverter ground faults under various fault conditions in some HVDC projects in China. The protection setting values of action value and delay time are set low and short, respectively, in order to satisfy the protection speedy and sensitivity, which reduces the protection reliability and induces protection mal-operation. Based on the relationship between fault influence level and protection action quantity, this paper improved the dc differential protection from one stage to two stages, in wihich high-value and low-value stages are used to guarantee the protection speedy and the protection sensitivity and reliability, respectively. Then, by using analysis results from the characteristics of inverter ground fault and the influence of ground resistance, this paper obtained the worst fault conditions, which helped setting calculation of the two-stage protection improved. The PSCAD/EMTDC simulation model of Guiguang II HVDC Project was established and used to verify the improvement on the main protection for converter ground faults. The simulation results showed that the improvement was correct and reasonable, and can be helpful to resolve the contradiction among the speedy, sensitivity and reliability of protection performance.*

***Streszczenie.** W artykule przedstawiono ulepszony sposób ochrony różnicowoprądowej dla układów HVDC. W rozwiązaniu zastosowano dwa stopnie ochrony, wysoki i niski, w celu zapewnienia odpowiedniej szybkości, czułości i odporności układu. Na podstawie charakterystyk zwarć doziemnych w falownikach oraz wpływu rezystancji uziemienia, wyznaczono najgorszy przypadek awarii. Wykonano badania symulacyjne, proponowanego rozwiązania, które potwierdziły skuteczność działania. (**Badanie ulepszonego głównego systemu ochrony w zwarciach doziemnych w układach HVDC w Chinach**).*

Keywords: High voltage direct current, Converter ground fault, DC differential protection, Ground resistance, Setting calculation
Słowa kluczowe: HVDC, zwarcie doziemne przekształtnika, ochrona różnicowa DC, rezystancja uziemienia, obliczenie ustawienia.

Introduction

A Converter plays a key role like a heart in high voltage direct current (HVDC) system. Naturally, sustaining its normal operation and protecting it from damage has great significance on the improvement of reliability and availability of HVDC systems [1]. Converter ground faults will cause valves suffering severe overstress, transformers being dc biasing, converter station ground potential rising, auto-control devices mal-operating, and so on [2]. The faults have so heavy influence on power system as to catch up interest of engineers and investigators. At present, researches about fault characteristics [3, 4, 5], protection treatment strategies [6, 7] and fault locating [8, 9, 10] have been investigated widely, and these researches contributed to improve the performance of protection operation and fault treatment.

At some HVDC projects in China, such as Guiguang II HVDC project, the main protection for converter ground faults is applied with a combined way of the high-value stage of the converter short circuit protection and the one-stage dc differential protection [11]. In this way, the high-value stage of the converter short circuit protection probably reacts only to rectifier ground faults. Therefore, the one-stage dc differential protection needs to protect all inverter ground faults. However, the protection action values vary so much under various fault conditions that the setting value and delay time of the one-stage protection are set low and short, respectively. Consequently, the one-stage dc differrential protection is subject to mal-operation. In China Southern Power Grid, there was a mal-operation accident with the one-stage dc differential protection, when there was an operation of disconnection switch in the ac switch yard [11].

The reason for mal-operation of one-stage dc differential protection is that, the protection setting values reduce the protection reliability when the setting values satisfy the protection sensitivity and protection speedy. The paper discussed the relationship between fault influence levels and protection action values, and divides operation characteristics into three parts, every part of which should responds to converter ground faults as soon as possible, fast or reliably, respectively. Hence, there should be at least three protective stages to satisfy the three-part operation characteristics. In view of good fault response performance of the high-value stage of the converter short circuit protection, the paper improved the dc differential protection with its stage from one to two, in which the high-value and low-value stage ensure the protection speedy, and the protection sensitivity and reliability, respectively. Based on the PSCAD/EMTDC simulation model of GuiGuang II HVDC project, the paper analysed the characteristics of inverter ground faults and the influence of ground resistance on protection operation values, and consequently obtained the worst fault conditions. With considering the practice requirement of covering ground resistance for the high-value stage, the paper performed setting calculation of the two-stage protection. Accompanying simulations were carried out to verify the improvement and setting calculation.

Converter Ground Faults and Its Protection

A) Converter Ground Faults

There are some high voltage equipment in converter station valve halls, which could be subject to insulation faults The most possible locations of converter ground faults are at phase-to-ground of ac-side windings of converter transformers in the high-voltage and low-voltage valve bridge, named respectively No.1 and No.2 Fault, and high-voltage dc outlet line, middle point and neutral-voltage dc outlet line of twelve-pulse converters, named respectively No.3, No.4 and No.5 Fault. These fault locations are shown in Fig.1

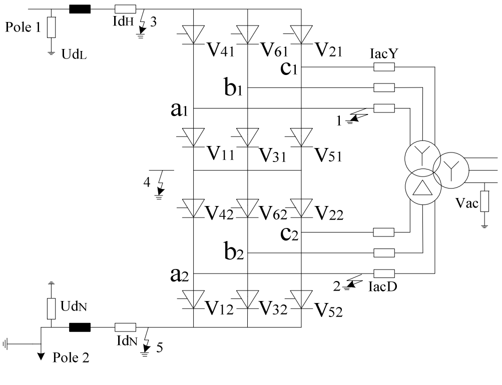


Fig.1. Locations of converter ground faults and Points of protection measurement

B) Main Protections for Converter Ground Faults

Under normal situation, the inflow current is always equal to the outflow current in their amounts. When there is a ground fault in the converter, the equal state is broken. Therefore, the fault can be detected by comparing the difference between these two currents, i.e. |IdH-IdN|. The measurement points of two currents IdH and IdN can be seen in Fig.1. In addition, it will cause big current through valve-side windings of converter transformers, when the ground fault is at some special locations. Hence, by comparing the difference between the currents of both sides of the converter, i.e. Iac-Id, the fault detection can also be achieved. Iac represents IacY or IacD of Fig.1, and Id represents the minimum of IdH and IdN. Both of the protections above are viewed as main protections for converter ground faults

There are two ways of main protection for converter ground faults in China, which can be represented typically by Guiguang II HVDC project and Sanchang HVDC project, respectively. The details of the way represented by Guiguang II HVDC project, which is considered as the combination of the high-value stage of the converter short circuit protection and the one-stage dc differential protection, are listed in Table 1.

Table 1. Main protection for converter ground faults in Guiguang II HVDC project

Operation Principle	Action Setting Value	Time Dleay
$\|IdH-IdN\|>I_{set}$	0.05 p.u.	5 ms
$Iac-Id>I_{set}$	1.5 p.u.	0 ms

Analysis and Improvement of Protection Operation Characteristics

A) Analysis of Protection Operation Characteristics

Table 1 shows the dynamic performance test results of main protection at converter metallic ground faults in Guiguang II HVDC project. In Table 2, the operation results are arranged by the sequence from the high-value stage of the converter short circuit protection to the dc differential protection. When the protection operates, it is remarked by the symbol '+', if not, by the symbol '-'. For example, when there is a ground fault (No.1 Fault) at the rectifier, the high-value stage of the converter short circuit protection will operate, while the dc differential protection not does due to lack of delay time. Then，the operate results are marked with '+/-'.

Table 2. The operation characteristics of main protection for converter metallic ground faults in Guiguang II HVDC project

Fault locations		Operation modes	
		Bipolar Rated Power	Single Polar with Ground Return
Rectifier	1	+/-	+/-
	2	+/-	+/-
	3	+/-	+/-
	4	+/-	+/-
	5	+/-	+/-
Inverter	1	-/+	-/+
	2	-/+	-/+
	3	-/+	-/+
	4	-/+	-/+
	5	-/+	-/+

It can be seen from the results in Table 2 that, the main protection by the combined way can distinguish rectifier ground faults from inverter ground faults, but not further between various inverter ground faults. Then, it should rely on the dc differential protection to react all inverter ground faults in various fault conditions.

Inverter ground faults will be more subject to the influence of fault conditions including system operation modes, fault locations, ground resistance and so on, comparing to rectifier ground faults. When the one-stage dc differential protection needs to respond to all inverter ground faults, its action value and delay time should be set low and short, respectively, in order to satisfy the demand of the sensitivity and speedy of the protection. Consequently, it decreases indeed the protection reliability and induces to mal-operate.

B) The Improvement of Protection Operation Characteristics.

The influence levels of converter ground faults are related to system operation modes, fault locations, fault time, ground resistance and so on. For most rectifier ground faults, their fault mechanisms are similar to that in the fault situation of valve short circuit. Moreover, the constant dc current controller in the rectifier side is out of usage to decrease fault current. Consequently, the faults can result in severe valve overstress even in wide range of ground resistance, and need to be cleared as soon as possible. For some inverter ground faults at the system operation mode of bipolar rating power, due to the modulation of the constant dc current controller in the rectifier, the faults may cause minor damage to valve overstress compared to the faults in the rectifier. However, the fault current into ground may still cause transformer dc biasing and converter potential rising. Hence, the faults need to be cleared fast, the speedy of which is allowed slower than that in the situation of rectifier ground faults. Under fault conditions such as in the minimal power level of system operation mode or with big ground resistance, the influence level is smaller than the two fault situations above. Then, these faults need to be cleared reliably in order to ensure the safety of power system.

Generally, the requirement of protection operation characteristics depends on the level of fault influence. In view of the difference among influence levels under various fault conditions, the paper divides operation characteristics of main protection for converter ground faults into three parts. The first part is applied to respond to those faults resulting in valve overstress, the second to transformer dc biasing, and the third to threatening system security operation. Since the fault influence level generally depends on the amount of protection operation value, it is natural to require at least three protection stages corresponding to three parts of operation characteristics.

Based on the operation characteristics divided above, and in view of good operation performance of the high-value stage of the converter short circuit protection, the paper proposes two-stage dc differential protection for all inverter ground faults. In the two-stage protection proposed, the high-value stage is applied to protect the fault causing transformer dc biasing, which can satisfy the requirement of protection speedy, and the low-value stage to protect the fault causing minor influence, which can satisfy the requirement of protection sensitivity and of protection non-mal-operation reliability for external faults and system disturbances. The setting values of the two-stage dc differential protection will be obtained through analysis about fault characteristics of inverter ground faults and researches of setting calculation in the next.

Analysis of Inverter Ground Fault Characteristics

In order to obtain reasonable setting values of the two-stage dc differential protection, the worst fault conditions, at which the protection action value is maximum or minimum, must be defined firstly. It is meaningful to study the fault characteristics of inverter ground faults and the amounts of the protection action value at various fault conditions. The PSCAD-EMTDC simulation model of Guiguang II HVDC project is built in the paper, and all the following simulation results are from it.

The bipolar rating power operation mode is the most common operation mode, and inverter ground fault under this mode will have most typical failure process. Naturelly, this paper analyzes general characteristics of inverter ground faults under this mode. A inverter ground fault is supposed to occur at the phase a_1 (or a_2) when it is at the ac-side of inverter.

A) Ground Faults at The AC-Side of The High-Voltage Bridge

When a ground fault occurs at the ac-side of the high-voltage bridge, named No.1 Fault in this paper, its fault process and fault characteristics are related to the state of common-anode valves of the high-voltage bridge at the fault moment.

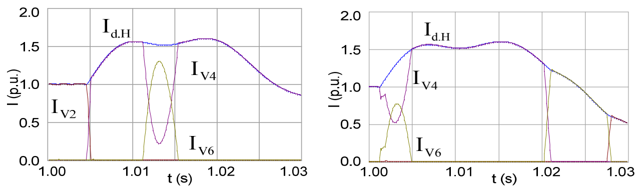
a) Fault occurring at the valve V_{41} on-state

When No.1 Fault occurs at the valve V_{41} on-state (including the periods of the valve V_{21} commutating to the valve V_{41} and the valve V_{41} commutating to the valve V_{61}), the rectifier and dc line will discharge directly to the earth through the valve V_{41} and fault location. Under the combined action of the rectifier dc voltage and line capacitance discharge, there is an apparent overshoot in the dc current IdH. IdH represents the current injecting into the inverter high-voltage outlet line.

On the one hand, the constant extinction angle controller generally adopts the principle of real measuring value of the extinction angle, and cannot adjust immediately the firing angle of the first commutation of the valve V_{41} to the valve V_{61} after fault. On the other hand, according to the equation (1) derived from the commutation formula, the typical critical value of dc current increment, △Id, which can result in commutation failure only because of the increment of commutation current, is just about 0.25 p.u. (When using the equation 1 for the calculation of the typical critical value of △Id, other quantities such as the extinction angle δ, the leading firing angle β, and the minimum extinction angle δ_{min} are valued as 17°，36° and 7°, respectively). Basically, the commutation from the valve V_{41} to the valve V_{61} may fail. Then, the valve V_{41} will continue to be on for one power frequency cycle at least.

$$\Delta I_d = \frac{\cos\delta_{\min} - \cos\delta}{\cos\delta - \cos\beta}\cdot I_d \tag{1}$$

Consequently, for an arbitrary fault moment at the period of on-state of the valve V_{41}, all the fault processes and the curves of IdH are very similar, respectively. By using the simulation model of Guiguang II HVDC project, the paper obtains the curves of IdH and valve currents I_{V2}, I_{V4}, and I_{V6} , corresponding to the valves V_{21}, V_{41}, and V_{61}, under two typical fault times. These current curves are shown in Fig.2. Fig.2(a) shows the current curves with the fault time at the middle of commutation from the valve V_{21} to the valve V_{41}, and Fig.2(b) corresponds to the fault time at the middle of commutation from the valve V_{41} to V_{61}. It can be seen apparently that the two curves of IdH are indeed very similar.



(a) At the middle of commutation from V_{21} to V_{41} (b) At the middle of commutation from V_{41} to V_{61}

Fig.2. The different fault time when the valve V_{41} is on

b) Fault occurring at the valve V_{41} off-state

If the fault occurs at the valve V_{41} off-state, the discharge circuit will include additionally the windings of fault-phase a and phase b or c(corresponding to the valve V_{21} or V_{61} on-state), compared to the situation at the fault time of the valve V_{41} on-state. Then, the inverter will have residual direct voltage, denoted as $V_{d.I}$.

Fig.3 shows the ideal curves of commutation voltages. It can be seen that $V_{d.I}$ will be on the positive half cycle of the winding line voltage e_{ab} (i.e. e_a-e_b) or e_{ac} for the fault occurring after the zero-crossing point c_3. Therefore, the overshoot of IdH will be restrained a bit in the effect of positive voltage $V_{d.I}$. Then, in the initial time of fault, IdH will be smaller, compared to the situation at the fault time of the valve V_{41} on-state.

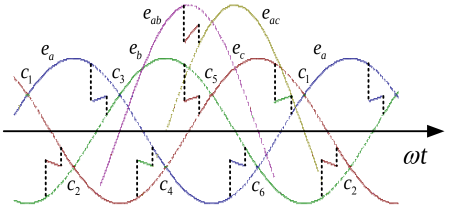


Fig.3. Ideal curves of commutation voltages

As the fault goes on, the fault process will depend on the result of the first commutation for the common-anode valves of the high-voltage bridge after fault. If the first commutation fails, the inverter voltage $V_{d.I}$ will go through the negative half cycle of winding line voltage, which instead promotes the overshoot of IdH. Hence, IdH will be bigger in this period. The commutation failure is likely to undergo for the fault occurring at the time following the commutation completion from V_{41} to V_{61}, which is showed in Fig.4.

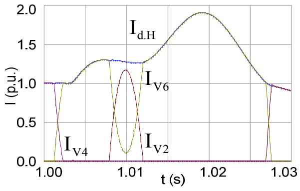
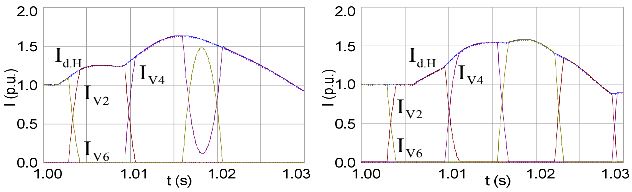


Fig.4. The first commutation for the valve V_{61} to V_{41} after fault

When the fault occurs at the valve V_{61} on-state, and the first commutation succeeds from the valve V_{61} to the valve V_{21}, $V_{d.I}$ will change to the positive half cycle of e_{ac} from the positive half cycle of e_{ab}. It means the sustaining suppression on the overshoot of IdH, and consequently, IdH will be a bit smaller than that in the situation of the fail commutation.



(a) Just before the commutation from V_{61} to V_{21} (b) After the commutation from V_{61} to V_{21}

Fig.5. The faults in which the first commutation can succeed

When the fault occurs at the valve V_{21} on-state, and the first commutation succeeds from the valve V_{21} to the valve V_{41}, IdH will be basically the same as the situation at the fault time of the valve V_{41} on-state. Fig.5 shows two kinds of fault processes for the successful first commutation after fault. Fig.5(a) represents the fault at just the beginning of the commutation from the valve V_{61} to V_{21}, and Fig.5(b) corresponds to the fault after the end of the commutation from the valve V_{61} to the valve V_{21}.

It can be seen from the analysis of (1) and (2) that IdH will be relative smaller in its entirety, when the fault occurs at the valve V_{41} off-state and the first commutation after fault can succeed.

Moreover, those on-state valves of the low-voltage bridge and the high-voltage common-cathode bridge will be turned fast off due to the negative voltage of metallic short circuit, and cannot turn on even after a long time. Therefore, the current IdN, which outflows from the dc neutral-voltage bus of the fault polar, will continue to be zero, and IdH is just the action value of the dc differential protection.

Therefore, the amount of IdH, i.e. the protection action value, depends on the conduction state of the common-anode valves at the fault moment and commutation results of these valves. As can be seen from these simulation figures above, if the research interest is only in the fault process after nearly ten milliseconds, the amounts of IdH and protection action value will be relative smaller in their entirety when the fault occurs at just the beginning of commutation from the valve V_{61} to the valve V_{21}.

B) Ground Faults at The AC-Side of The Low-Voltage Bridge

The parameters of dc equipment and the rapid adjustment of dc controllers generally ensure that it will not cause an oversized overshoot of dc current and simultaneous commutation failures of two bridges, when there is a single bridge commutation failure induced by some faults except of ac system faults. The ac-side ground fault of the low-voltage bridge, i.e. No.2 Fault, is similar to commutation failure of the low-voltage bridge. Hence, the increment of the current △Id will be smaller than 0.25 p.u., and the commutation of the high-voltage bridge valves still can succeed.

The characteristics of No.2 Fault and its process also depend on conduction state of common-cathode valves of the low-voltage bridge.

a) Fault occurring at the valve V_{21} on-state

When the fault occurs at the valve V_{12} on-state (including the commutations from the valve V_{52} to the valve V_{12} and from the valve V_{12} to the valve V_{32}), it will cause no influence. The reason is that the winding of the phase a2 has already been connected directly to the ground through the valve V_{12} under the bipolar balance operation mode.

Since there is no sign for the fault, the commutation from the valve V_{12} to the valve V_{32} can succeed. However, the short circuit of the phase a_2 to phase b_2 causing by the commutation will continue with the presence of ground fault, even if the valve V_{12} is turned off after the end of commutation. According to Fig.3, the phase voltage e_b is bigger than e_a before the zero-crossing point c_6. Then, the current of the valve V_{32}, equal to IdN, continues to increase. After c_6, e_b is smaller than e_a and the valve V_{32} will be turned off along with its current decreasing to zero, i.e. IdN=0.

The voltage drop on the ground electrode line caused by the current flow of the healthy polar (the negative polar supposed), enables common-cathode valves to be at negative potential. Then, the valve V_{52} cannot turn on because its anode voltage is at higher negative potential than its cathode voltage, but the V_{12} can normally turn on. Therefore, IdN will continue to be zero at the period from the turn-off state of the valve V_{32} to the next cycle turn-on state of the valve V_{12}. The duration of this period is about 240°-(μ+2δ) electrical angle, i.e. about 10.4 ms, where μ represents the commutation angle and its rated value is about 20°. And the protection action value is just IdH.

As soon as the valve V_{12} turns on again in the next cycle, the current of the dc neutral-voltage bus, IdN, will be built again. A new fault circuit is established and shown in Fig.6. The equation (2) will be derived easily by the established circuit, where R_e and R_f represent the ground electrode line resistance and ground fault resistance, respectively, and I_{d0} represents the dc current of the negative polar. For the metallic ground fault, IdN is equal to I_{d0}. Hence, the protection action value is smaller than 0.25 p.u. after the valve V_{12} turning on.

As the fault goes on, the valve V_{32} will turn on and start the commutation from the valve V_{12}, which implies that the previous fault process will be repeated.

$$\mathrm{I}_{\mathrm{d.N}} = \mathrm{I}_{\mathrm{d.H}} - \frac{R_e}{R_e + R_f}(\mathrm{I}_{\mathrm{d.H}} - \mathrm{I}_{\mathrm{d0}}) \tag{2}$$

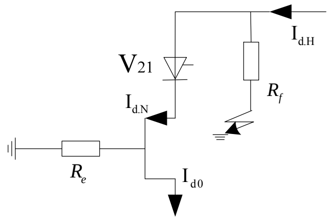
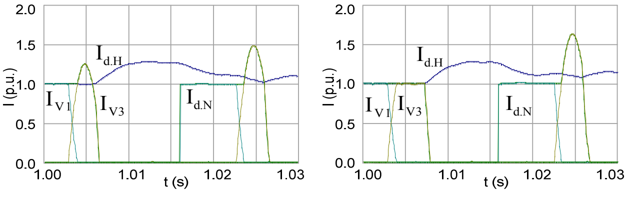


Fig.6. The fault circuit when IdN is built again

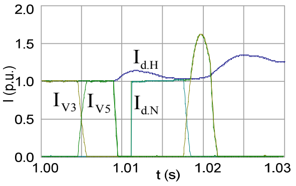
b) Fault time at the valve V_{21} off-state

When the fault occurs at the valve V_{21} off-state, it causes a two-phase short circuit in the low-voltage bridge. According to Fig.3, the winding voltage of the fault phase, i.e. e_a, is always bigger than the winding voltage of the phase connecting to the on-state valve V_{32} or V_{52}, i.e. e_b or e_c. As a result， the valve V_{32} or V_{52} will be fast turned off, and IdN is equal to zero. The period that IdN is equal to zero depends on the distance from the fault time to the beginning of the commutation from the valve V_{52} to the valve V_{12}. When the fault occurs at the end of the commutation from the valve V_{12} to the valve V_{32}, the period will be the longest, about 240°-(μ+2δ) electrical angle. For the fault at just the beginning of the commutation from the valve V_{52} to the valve V_{12}, the period will be the shortest, approaching to 0.

As the fault goes on, the valve V_{12} will turn on, and IdN will be established immediately and equal to I_{d0}. It means that the fault process will be the same as that in the situation of the fault occurring at the valve V_{12} on-state.



(a) Fault at the valve V_{12} on-state (b) Fault at the valve V_{32} on-state



(c) Fault at the valve V_{52} on-state

Fig.7. Simulations of No.2 Fault at different valves in on-state

Fig.7 shows the simulation results when the fault occurs at the valves V_{12}, V_{32} and V_{52} on-state, respectively. It can be seen from Fig.7 that, the fault process is typical when the fault occurs at the valve V_{12} on-state, if the fine distinction between the curves of IdH is ignored.

C) Other Ground Faults

The fault characteristics of No.3 Fault and No.4 Fault, are just similar to those in the situations of No.1 Fault (with the fault time at the V_{41} on-state) and No.2 Fault (with the fault time at the V_{12} on-state), respectively.

The fault characteristics of No.5 Fault, i.e. the fault of the neutral-voltage dc outlet line to ground, are fairly easy. It can be explained with the principle of parallel current division between the ground resistance and the ground electrode line resistance. Practically, the protection is hard to operation due to the quite small ground electrode line resistance.

Analysis of Influence of Ground Resistance

Since ground faults are nearly always with resistance in practice, and the ground resistance has important influence on fault characteristics, the paper will discuss the influence.

A) Influence on The Current IdH

The ground resistance suppress overshoot of the current IdH, and the suppression level depends on the resistance amount. For No.1 Fault, it is beneficial for the successful commutation of common-anode valves of the high-voltage bridge, which can enhance the suppression. With the same ground resistance value, IdH is still relative small in its entirety when the fault occurs at just the beginning of the commutation from the valve V_{61} to the valve V_{21}.

For No.2 Fault, the overshoot of IdH is small even without the ground resistance. With ground resistance, the overshoot of IdH will be mitigated more, and the distinction of IdH in the amount under various fault times will be quite slighter.

B) Influence on The Current IdN

a) Influence on IdN at No.1 Fault

The voltage drop of the ground resistance makes probably IdN not the same as that at the situation of metallic fault, in which IdN continues to be 0. The reasons are explained below.

Firstly, the ground fault makes valve-side windings of the low-voltage birdge transformer (and the high-voltage bridge transformer, probably) be short circuit. Obviously, ground resistance damps the decay of IdN. Therefore, IdN will not decay fast to 0, and even probably makes the commutation of common-cathode valves of the high-voltage bridge and valves of the low-voltage bridge successful. Secondly, even if IdN decreases to 0 and causes these valves to be turned off, when the voltage drop of ground resistance is big enough, these valves can be turned on again at the presence of wide firing pulses, and IdN can be built again.

b) Influence on IdN at No.2 Fault

The analysis of influence on IdN at No.2 Fault is similar to the analysis above. In other words, IdN will not decrease fast to 0, or can be build again through the valve V_{32} or V_{52} turn-on.

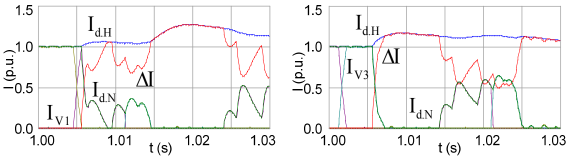
In addition, based on the characteristic analysis of the fault at the valve V_{12} on-state, the valve V_{12} can turn on to build IdN with or without ground resistance. The amount of IdN built can be calculated by the equation (2). Because the amount of the ground electrode line resistance is very small (about in the range from 1 to 4 ohm), IdN will approximate quickly to IdH with the increase of fault ground resistance R_f. When R_f reaches at the range from 4 to 16 ohm, the protection action value will be smaller than 0.05 p.u. and continue to the end of the commutation from the valve V_{12} to the valve V_{32}. The duration is about 120˚+μ electrical angle, converting into 7.8 ms. It means that for the low-value-stage protection with instantaneous return characteristic, the protection will not operate, if its setting value of delay time is larger than 12.2 ms.

C) Determining of Worst Fault Conditions

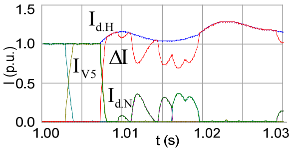
As can be seen from the analysis of the influence of ground resistance on the currents IdH and IdN, the ground resistance suppresses the overshoot of IdH and makes IdN not be 0 at all time, which ultimately reduces the protection action value.

When No.1 Fault occurs at the valve V_{11} on-state, the winding voltage in the short circuit of transformer valve-side windings is just from the low-voltage bridge. At any other time of the valve V_{31} or V_{51} on-state, the winding voltage will be added with an equidirectional winding voltage from the high-voltage bridge. Therefore, the decay of the current IdN will be slower at the former fault situation. Based on the analysis about IdH, the smallest protection action value may be available at just the beginning of the commutation from the valve V_{61} to the valve V_{21}, which corresponds to the worst fault condition of No.1 Fault.

When No.2 Fault occurs at the valve V_{12} on-state (including the commutation period of the valve V_{12} to the valve V_{32}), the winding voltage in the winding short circuit of the low-voltage bridge is the line voltage e_{ba}, which is just increasing from 0. For other fault times, the winding voltage will increase from a positive amount. Then, the decay of IdN will be slower at the former fault situation. Moreover, the presence of ground resistance makes ignoring the distinction between the amounts of the current IdH generated at various fault times much more adequate than that without ground resistance. Therefore, the smallest protection action value may be available at the valve V_{12} on-state, which corresponds to the worst fault condition of No.2 Fault.

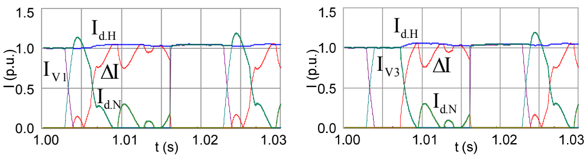


(a) Fault at the valve V_{11} on-state (b) Fault at the valve V_{31} on-state

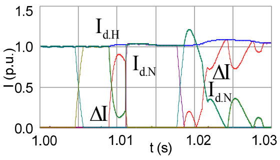


(c) Fault at the valve V_{51} on-state

Fig.8. Simulations of Fault No.1 with R_f of 75 Ω at different valves in on-state



(a) Fault at the valve V_{11} on-state (b) Fault at the valve V_{31} on-state



(c) Fault at the valve V_{51} on-state

Fig.9 The simulations of Fault No.2 with R_f of 75 Ω at different valves in on-state

Fig. 8 and Fig. 9 show the simulation results of No.1 Fault and No.2 Fault with R_f of 75 Ω at various valve-on-states. In these two figures, △I represents the difference between IdH and IdN, i.e. the protection action value. By the curves of △I, the influence of ground resistance can be verified, and the worst fault conditions determined above may be advisable.

Setting Calculation of DC Differential Protection Improved

Traditional experience about the setting calculation of two-stage differential protection can be explained below. For low-value stage, its action value is used to ensure the protection sensitivity, which should avoid the measurement error under the steaty-state overload, and its delay time to ensure the protection reliability of non-mal-operation, which should avoid system transient process. For high-value stage, its action value is used to ensure the protection reliability of operation, which should avoid the measurement error at the most severe external fault, and its delay time to ensure the protection speedy.

However, under the rapid adjustment of dc controllers, the fault through current is just not large in HVDC system. Then, by the setting experience above, the action value of high-value stage will not large enough for satisfying the protection reliability of non-mal-operation. According to the analysis of fault characteristics, the paper will set the setting values of high-value stage, by the influence levels of faults on the system operation and device security.

A) Setting Calculation of Low-value Stage

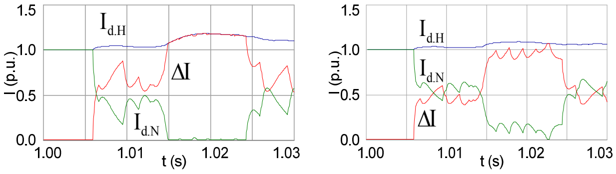
According to the operation characteristics divided, the low-value stage is used to protect those inverter ground faults which may result in minor effect, and its setting value needs to satisfy the requirement of the protection sensitivity and reliability. It is recommended to adopt the original action value of the one-stage dc differential protection, 0.05 p.u.. The delay time of the low-value stage can be setting by the system transient process and dc control characteristics. It should be noted that for instantaneous protection return characteristic, the delay should be no longer than 12.2 ms. The paper sets arbitrarily the delay time at 10 ms .

B) Setting Calculation of High-value Stage

According to the operation characteristics divided, the high-value stage is used to protect those inverter ground faults which can result in transformer dc biasing, and its setting value needs to satisfy the requirement of protection speedy. It implies that the high-value stage should operate before the dc control system reduces the fault current. Since the increase of setting value of the high-value stage will delay the start of protection action timing, the paper sets the delay time at 4ms, which was 5 ms in the one-stage protection in some HVDC projects in China.

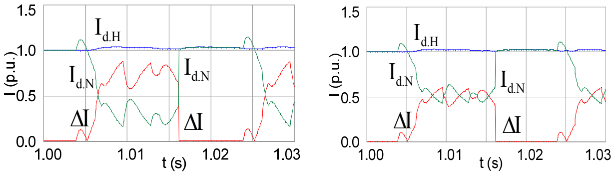
In practice, ground resistance is almost always at presence and its amount may change with the development of fault. Therefore, in order to raise the operation speedy of the high-value stage, the setting value needs to cover an adequate range of ground resistance. According to analysis results of fault characteristics, the paper selects the worst fault conditions for No.1 Fault and No.2 Fault, and obtains curves of the differential current △I, shown in Fig.10 and Fig.11. Fig.10 is for No.1 Fault with R_f of 100 Ω and 150 Ω, respectively, and the same to Fig.11 for No.2 Fault. By comparing these curves of △I, it can be seen that the effect of faults will be fairly small when R_f reaches to 150 Ω. Hence, the paper choosed 150 Ω as the superior limit of the cover range of ground resistance.

Fig.12 shows two curves, $\triangle I_1$ and $\triangle I_2$, which corresponds to the curves of △I in Fig.10(b) and Fig.11(b), respectively. In Fig.12, $\triangle I_{max}$ represents such a curve value of △I, which should satisfy simultaneously two conditions below. One condition is that the curve values following $\triangle I_{max}$ at the range of 4 ms can make the protection continue timing, and the other is that such a curve value of △I is the maximum value which can match the former condition. According to Fig.12, $\triangle I_{max}$ is defined as 0.39 p.u.



(a) With R_f of 100 Ω (b) With R_f of 150 Ω

Fig. 10 The simulations of No.1 Fault with R_f of 100 and 150 Ω



(a) With R_f of 100 Ω (b) With R_f of 150 Ω

Fig.11 The simulations of No.2 Fault with R_f of 100 and 150 Ω

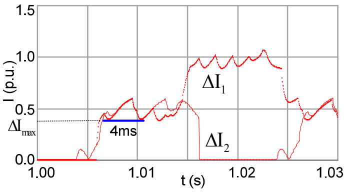


Fig.12 Setting of the high-value stage

A sensitive factor k_{sen} in the setting calculation of the high-value stage is introduced and valued as 1.5. Then, the setting value of the high-value stage, named I_{set}^{II} , can be obtained by the equation (3).

$$I_{set}^{II} = \Delta I_{max} / k_{sen} \tag{3}$$

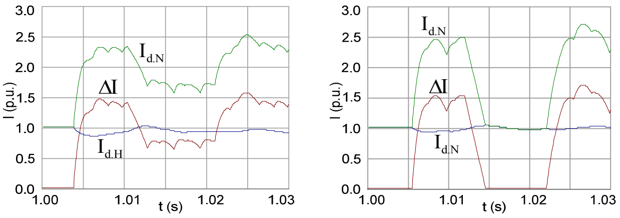
Therefore, I_{set}^{II} is calculated at 0.26 p.u.. The value can avoid the imbalance current from measurement devices at the most severe external fault.

Simulation Verification

In the previous sections, the paper uses simulations to analyze the fault characteristics of inverter ground faults and to set the setting value of two-stage dc differential protection improved. The process of the characteristics analysis and setting calculation can in nature ensure that the requirement of protection speedy, sensitivity, and reliability is satisfied for the two-stage protection under various fault conditions. In the next, the paper devotes to verify operation characteristics of the two-stage protection and cover range of ground resistance for rectifier ground faults by simulation.

The simulation results show that the two-stage protection cannot operate under metallic ground fault of the rectifier, although they have started to time. However, the high-value stage of converter short circuit operates. These operation results accord with the required operation characteristic. When the fault is with ground resistance R_f lager than 103 Ω (for No.1 Fault) or 52 Ω (for No.2 Fault), the high-value stage of the converter short circuit protection can not operate any more, and the high-value stage of the protection improved can operate. It can be seen from Fig.13

that the protection operation results. Moreover, when the ground resistance value is at some range, fault ground current, i.e. △I, is fairly big (slight slower than 1.5 p.u.), and so to IdN (slight slower than 2.5 p.u.). Consequently, the fault will cause the second highest stage of the ac overcurrent protection to time, whose action value is set at 2.1 p.u. Obviously, the fault above should be cleared rapidly, and the two-stage protection improved can match this requirement.



(a) No. 1 Fault with R_f of 103 Ω (b) No. 2 Fault with R_f of 52 Ω
Fig.13 Rectifier ground faults under the bipolar rating power mode

Conclusion

For some HVDC projects in China, the one-stage dc differential protection needs to respond to all inverter ground faults under various fault conditions. Consequently, the protection is subject to mal-operation. This paper divides the operation characteristics of main protection for converter ground faults into three parts by effect levels of faults. Then, it improves the protection stage from one to two. Based on the analysis about fault characteristics of inverter ground faults and influence of ground resistance, the paper obtains the worst fault conditions and used it for setting calculation of the two-stage protection. The operation performance of the two-stage protection is verified by the PSCAD-EMTDC simulation results of Guiguang II HVDC project. Hence, the research in this paper is helpful to resolve the contradiction among the speedy, sensitivity and reliability of protection.

Acknowledgments

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