Study and Solution of Current Differential Protection Disability for High Series Compensation Transmission Line

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Abstract

With the increasing day by day integration of large-size generators and tighter among the power systems, in internal fault, the fault current of Series Compensated (SC) lines could also be upturned. Therefore, the differential protection of SC transmission lines may stop working to operate because of less sensitivity. In this research article the causes for the current overturning in SC lines and its effects differential protection. The working characteristics of differential protection are analyzed by focusing on multiple-factors, for example, different series compensation degrees, types of fault, system operation mode, the difference of power angle, points of the fault, and transition resistance. An enhanced standard based on the current amplitudes and phases on both sides of the series compensated lines is proposed. Furthermore, to make stronger the operation characteristics of differential protection, the triple-fold line is chosen to get better sensitivity for internal faults in the article. The results are efficient to improve the protection sensitivity of SC lines during the internal fault. The PSCAD/EMTDC simulation and the power system dynamic physics simulation demonstrate that protection sensitivity is increased in the improved scheme.

Keywords: Differential Protection, Series compensation, EHV/ UHV, Current reverse, sensitivity analysis.

1. Introduction

The series compensated which is denoted by SC are largely used in today's power systems because of many advantages, likewise, good system stability, excellent power transmission, reduce transmission losses, improvement in voltage control, and high loading capacity of the transmission line[1-3]. On the other hand, the vector's balance in the transmission line is destroyed, which mostly causes problems such as current and voltage overturn when fault diagnosed on the compensated line. As a result, these capacitors influence the operational behavior of the power system, and also the performance of relay protection under short circuits [4, 5]. Using the SC in the transmission lines and their effect mainly large distance protection and short distance protection and many methods are proposed in [6-9].

However, the malfunction of differential protection on SC lines is generally ignored. in fact, with the interconnection of bulk power systems, the system impedance on the back of the line may be less than that of the traditional relay protection equipment when the power system operates in a certain way. So, the fault current may reverse during the line internal fault. This can have an unfavorable impact on transmission line protection. Mainly, the differential protection broadly used in SC lines cannot work properly due to the lack of sensitivity. This study is roughly divided into two categories to improve the sensitivity of the current differential protection. The algorithm based on the parameter model [10-12], and the improved braking principle [13, 14]. While the focal point of these research achievements is to minimize the effects of distributed capacitance and transition resistance, a few researchers worked about the effects of current overturn on differential protection have been discussed.

In the article [15], for SC lines different fault points and types of fault, conditions of the current reverse are investigated. However, it is a challenge to solve such kind of cases. In [16], the circuit mode effect on current differential protection capacity current compensation was analyzed and an appropriate capacity current compensation scheme of complex four-circuit lines on the same tower was put forward. The influence mechanism of the current reverse on zero sequence current differential protection is discussed in reference [17], and an improved algorithm is provided, aimed at limiting protection sensitivity when SC lines are found in high-resistance grounding failure. By analyzing the electrical characteristics of fault intercepted in multi-SC lines, the recording voltage and the remembering current are used in reference [18] to identify the current reverse, Thus it is proposed to block differential protection to protect SC lines, this technique does not solve the problem of failure of protection

operations.

In the above researches, it can be seen that many factors cause the current reverse. The current reverse influence on the current differential protection should be considered in combination with the SC degree of transition resistance, the power angle, the type of fault, the fault point, and so on. In addition, the use of SC in these lines was required to meet the present demands. In order to overcome these side effects, it is necessary to improve the sensitivity of SC lines during the internal fault. Hence in this paper, we study the effects of SC degree, the difference in power angle, transition resistance, type of fault, system operation mode, and fault point on differential protection operation characteristics.

2 Analysis of Current Reverse Reason

In transmission line compensation devices include TCSC and FSC. Both devices have a series capacitor and a spark gap ontology protection system (MOV+ Spark gap). Normally the level of protection is affected by the operation of the gap and bypass for external or internal faults. The large short-circuit current inside the capacitor will result in rapid protection action. Whereas high-resistance grounding failures limit the fault current to an amount may not result in a bypass where the capacitor is still functional. In terms of large system interconnection, the current reverse in the line will occur. When the current is reversed, a short circuit fault occurs in the line of series compensation. The working condition of relay protection will be in a more serious state. Failure to operate differential protection at this time will have adverse effects on the power system. Hence, the causes of the current reverse need to be analyzed in detail, in combination with the system characteristics. To exemplify the principle a simple two-terminal system is used. In figure 1 the equivalent model of the single-loop system is shown for high SC line under internal fault.
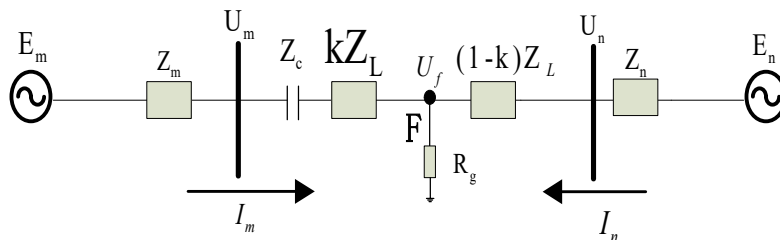

Figure 1. Schematic diagram of the internal fault of the transmission line system

The following parameters are considered while deducing the expressions of fault parameters.

Where E_m and E_n are voltages of the source at sending end and receiving the end of the transmission line respectively. U_m I_m U_n I_n are the voltage and current phases measured by the protection at two ends respectively. Uf is the fault voltage. Zm and Zn are used to denote equivalent impedance of power source at the sending end and receiving end.

ZL is the entire line impedance.

kZL is line impedance from sending end to point F.

(1-k)ZL is line impedance from receiving end to the fault point F.

Zc is the impedance offered by the series capacitor.

The current at M side is shown below when asymmetric short circuit occurs at point F.

$$\dot{I}_m = \frac{E_m}{Z_m + kZ_L - Z_c} \tag{1}$$

Under the interconnection of the bulk system, Zm will be smaller. At this point, if Zm+ k ZL is less than Zc, in addition, when point F closes to bus M, which means the value of K is relatively small, the denominator of the equation (1) is easy to satisfy the situation that Zm+ k ZL is much less than Zc.

In this case, the equivalent impedance at the left side of point F is capacitive. Namely, fault current Im is leading up to Em, or in other words, current reversed. The voltage at both ends of the SC device under the fault is shown

below.

$$\left|U_c\right| = \left|\frac{E_m}{Z_m + kZ_L - Z_c} Z_c\right| = \left|E_m \middle/ 1 - \frac{Z_m + kZ_L}{Z_c}\right| > \left|E_m\right| \tag{2}$$

In practical engineering, when |Uc| is greater than the fixed outlet value (65kV, less than), the self-protection of SC equipment will trigger the conduction of the spark gap so that the capacitor can be immediately bypassed. As a result, the current reverse appears only within 1 ms, and then recovers [19]. So, under symmetrical short-circuit, the SC device has little influence on the differential protection action characteristics.

Assume that if an asymmetric fault occurs at point F, the positive sequence impedance is equal to the negative sequence impedance in the system. The composite sequence network diagram of single-phase grounding after the fault is shown in Figure 2.
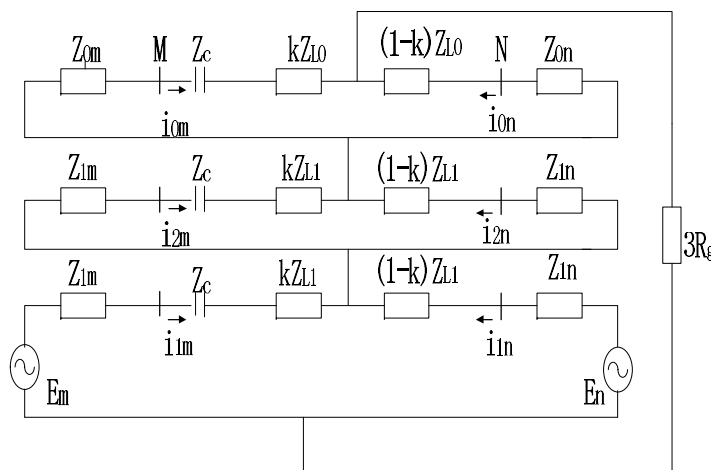

Figure 2. Composite single-phase grounding fault sequence network

The positive sequence fault currents of M and N sides can be obtained from Figure 2 via the same analytical method adopted in symmetric short circuits.

$$\dot{I}_{1m} = \frac{E_m - \dot{U}_{f(1)}}{Z_{1m} - Z_c + kZ_{L1}} \tag{3}$$

$$\dot{I}_{1n} = \frac{E_n - \dot{U}_{f(1)}}{Z_{1n} + (1-k)Z_{L1}} \tag{4}$$

$$\dot{U}_{f(1)} = (\dot{I}_{1m} + \dot{I}_{1n})\ R_g \tag{5}$$

In equation (3), when $Z_{1m} + kZ_L$ is much less than Z_c, fault current I_{1m} will lead voltage of E_m-$U_{f(1)}$ But whether that current is capacitive or not also depends on the opposite side fault current I_{1n} Supposing that the system potential amplitude values are equal on both ends, that is, $E_n = E_m e^{j\partial}$. Through equation (3), (4) and (5), the positive sequence fault current for M side can be acquired.

$$\dot{I}_{1m} = \frac{E_m(\ 1 + m - me^{j\partial}\ )}{(Z_{1m} + kZ_{L1} - Z_c) + R_g(1 + \frac{Z_{1m} + Z_{L1} - Z_c}{Z_{1n} + (1-k)Z_{L1}})} \tag{6}$$

Where, m= Rg/Z1n + (1-k)ZL1 From the above analysis study, If Zm+kZL is much less than Zc, the current

calculated in equation (6) could subsequently reverse. Additionally, the amplitude and phase angle of the positive sequence current is affected by the difference in power angle, system back impedance, and transition resistance. Specific analysis for the zero-sequence network is conducted in reference [17]. It is easy to find that if Zm+kZL is much smaller than Zc, the current would reverse.

The fault current of the M side is shown in equation (7) through calculating with positive sequence, negative sequence, and zero sequence fault current.

$$\dot{I}_m = \dot{I}_{1m} + \dot{I}_{2m} + \dot{I}_{0m} \tag{7}$$

It is observed from equation (7) that if the transition resistance Rg is too large, the fault current may be low, and then the system fails. In this case, SC equipment's ontology protection cannot operate and this equipment complies with the above mode of analysis, it will be equal as a capacitor. Therefore, a current reverse phenomenon occurs when an internal fault occurs in a high SC transmission line, which brings a risk of malfunction to the differential protection of the line current. Through the above analysis, the current reverse primary caused by a high SC degree during an asymmetric fault when the system meets that Zm+kZL is far less than Zc. In addition, transition resistance, power angle, and the equivalent impedance affect the amplitude and phase of fault current.

3. The influenced factors and analysis of current differential protection

3.1 Current Differential Protection Factors Mis-tripping

SC lines are the potential to occur current reverse at an internal fault, according to the previous section. At the same time, the fault current is influenced by a number of factors, such as compensation degree, equal impedance, and device power angle, fault types, transfer resistance, etc. Current differential safety is the major protection of SC lines, and its differential current is measured at both ends of the protection network as the module value of the fault current vector number. Although one end's fault current reverses, due to lack of sensitivity the defense is very likely to fail to operate.

In order to analyze the new differential protection feature of misoperation when the new is reversed, this paper determines whether or not the differential protection is worked according to the shift in the sensitivity. The general criterion of the current differential defense is chosen for the convenience of the theoretical analysis, as shown in equation (8).

$$\begin{cases} I_d > I_{set} \\ I_d > K_1 I_r \end{cases} \tag{8}$$

Where $I_d = |I_m + I_n|$ is the line differential current axis and $I_r = |I_m - I_n|$ is the current of braking. I_{set} is the minimum threshold value for operating. The coefficient of the braking ratio is represented by K_1.

According to the calculation of sensitivity, coefficient $K_{sen} = Id/If$ is selected. As before, assuming the amplitude values of source voltage at two ends are equal, namely $E_n = E_m e^{j\partial}$, ∂ is power angles difference of system.

$I_d = |I_m + I_n|$ is the line differential current.

$I_r = |I_m - I_n|$ is the braking current.

I_{set} is the minimum operating threshold value.

K_1 is the braking ratio coefficient.

$K_{sen} = I_d/I_f$ is a coefficient selected according to the calculation of sensitivity.

$E_n = E_m e^{j\partial}$ While assuming the amplitude values of source voltage at two ends are equal.

∂ is the power angles difference of system.

The sensitivity coefficient of a positive sequence is obtained in (9) by taking asymmetric ground defect as an example and combining equation (3), (4), and (5).

$$K_{1sen} = \frac{[Z_{1n} + (1-k)Z_{L1}] + e^{j\partial}(Z_{1m} - Z_c + kZ_{L1})}{[Z_{1n} + (1-k)Z_{L1}] - e^{j\partial}(Z_{1m} - Z_c + kZ_{L1}) + 2R_g(1-e^{j\partial})} \tag{9}$$

The sensitivity coefficient was calculated for the zero-sequence circuit in reference [17]. It is shown in equation (10).

$$K_{0sen} = \frac{Z_{0n} + Z_{0m} + Z_{L0} - Z_c}{Z_{0n} - Z_{0m} + Z_c + Z_{L0} - 2kZ_{L0}} \tag{10}$$

It can be obtained from equation (10) that the sensitivity is diminished with increases in the degree of compensation and the value of K Moreover, equation (9) is more complex, and the sensitivity pattern cannot be solved directly, further study of the classification is as follows.

3.2 The Analysis and Effects of Series Compensated Degree

That the degree of compensation greater than 50 percent during internal circuit faults would lead to the current reverse [20]. In the first quarter of this article, the perspective was illustrated. As the degree of SC increases, coupled with the power system interconnection, the system impedance in the backside of the line becomes smaller, the fault point is relatively close to protection, and hence the current reverse probability will increase significantly. For equation (9), when the difference in the power angle and the transition resistance are constant, it can be simplified as equation (11).

$$K_{1sen} = \frac{Z_\alpha + m(Z_\beta - Z_c)}{Z_\alpha - m(Z_\beta - Z_c)} \tag{11}$$

Where, $Z_\alpha = [Z_{1n} + (1-k)Z_{L1}]$, $Z_\beta = Z_{1m} + kZ_{L1}$, $m = e^{j\partial}$ .The coefficient of m is constant. It also can be found from equation (11) that sensitivity decreases with the increase of SC degree.

However, a decline in sensitivity does not necessarily mean that there is going to be protection mis-trip. This must take into account system-equivalent impedance and short-circuit impedance. Taking equation (11) as an example, Z_β is generally greater than Zc in practical engineering.

And the coefficient of adaption is greater than one, which means that it doesn't make any difference to safe operating characteristics. However, with the introduction of large SC lines combined with the dorsal system's powerful interconnection, capability Zc will increase and device inductance will decrease in this sense.

Therefore Z_β is greater than Z_c is no longer necessary. It is the tipping point for the current reverse when Z_β equals to Z_c and the sensitivity of protection will be lower while Z_β is much less than Z_c. The variation relation between sensitivity and SC degree is reflected in Figure 3 when the system occurs a fault close to the capacitor under a certain fixed operation. If SC degree is more than 50%, the sensitivity of protection will be lower than 0.45. Under these circumstances, differential protection is unable to trip due to a lack of sensitivity during the internal fault.
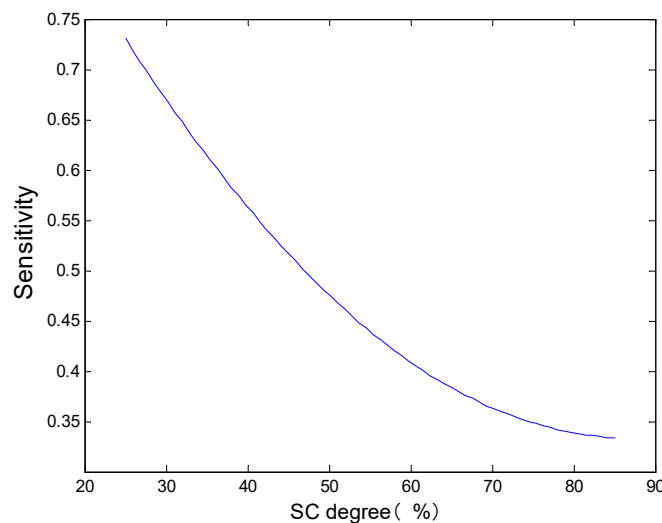

Figure 3. Relation of sensitivity and series compensation

3.3 The Effects of Compositing Series Compensation and Fault Location

In some cases, especially at the outlet of the capacitor and with high compensation rates, the capacitive impedance can be higher than the inductive source impedance. So, the resulting fault current reversal may occur. However, the performance of relaying should be decided by the MOVs and gaps operation. In this case, if the short circuit is too small to trigger MOVs and gaps. The differential protection will not work properly. Given that power angle difference and transition resistance are fixed, equation (9) can be simplified to equation (12).

$$K_{1sen} = 1 - \frac{2}{1 - \left[Z_{1n} + (1-k)Z_{L1} \right] / m(Z_{1m} + Z_{L1} - Z_c)}$$
(12)

Seen from equation (12), the sensitivity will increase as the value of K ($m = e^{j\partial}$) increase. In integrating SC's function, the output of security for SC lines after short-circuit start can be an action failure.
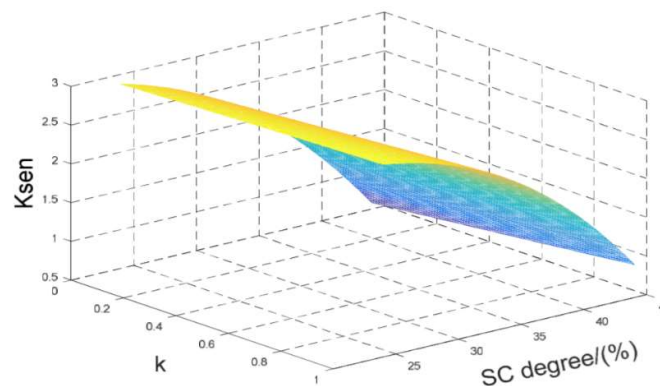

Figure 4. Relation between degree of sensitivity and compensation to series, fault points ($\vartheta=30°$)

3.4 Effects of Compensated Series Degrees and Grounding Resistance

Based on the above review, the defense will work correctly only when the fault current reaches the MOV thermal limit and bypasses the activity. However, due to the small fault current the fault with high transition resistance does not affect bypass operation. Even if the degree of compensation isn't too high, due to the adverse effects of capacity and resistance, the sensitivity will be greatly reduced. Assuming that the amplitude values of the source voltage are equal at two ends, and the power angle difference is a constant, that is $E_n = E_m e^{j\partial}$

Equation (9) can be simplified further, as Equation (13).

$$K_{1sen} = \frac{Z_\alpha + e^{j\partial}(Z_\beta - Z_c)}{Z_\alpha - e^{j\partial}(Z_\beta - Z_c) + 2R_g(1 - e^{j\partial})}$$
(13)

Figure 5 shows the susceptibility to defense under varying degrees of SC and Rg. In figure 5, SC plays a major role in reducing the sensitivity of differential protection when the transition resistance is small, and only large series compensation will have lower sensitivities. If the degree of series compensation is between 25 percent and 45 percent, then there will be differential protection. Nevertheless, transition resistance plays a major role in raising the vulnerability of differential safety when the transfer resistance reaches 200Ω. The sensitivity of the protection shown in Figure 5 is less than 0.5, and the differential protection does not work due to the lack of sensitivity of the series compensation lines within the internal fault.
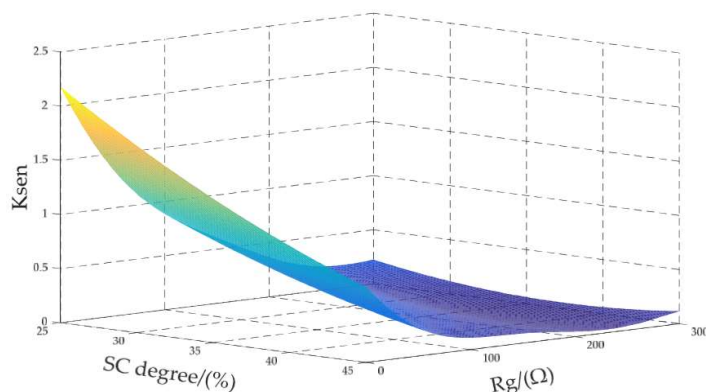
Figure 5. Relationship between degree of sensitivity and series compensation, resistance to grounding

3.5 Impact of Composite Series Compensated Grades and Disparity in Power Angle

Analysis previously is under the assumption of the disparity in the invariable power angle. In addition, with system operation the power angle is variable. Equation (9) may also conclude that the difference in angle has an effect on the sensitivity of differential protection. If the SC lines contain a metallic grounding fault, Equation (9) can be converted into Equation (14).

$$K_{1sen} = \frac{Z_\alpha + e^{j\partial}(Z_\beta - Z_c)}{Z_\alpha - e^{j\partial}(Z_\beta - Z_c)} \tag{14}$$

Figure 6 shows the susceptibility to protection under different degrees of SC and difference in power angle. As seen from Figure 6, the sensitivity to protection is high when the difference in the power angle is low. However, with the increase in power angle and SC degree, the sensitivity of the protection decreases, and due to lack of sensitivity the protection can also fail to work.
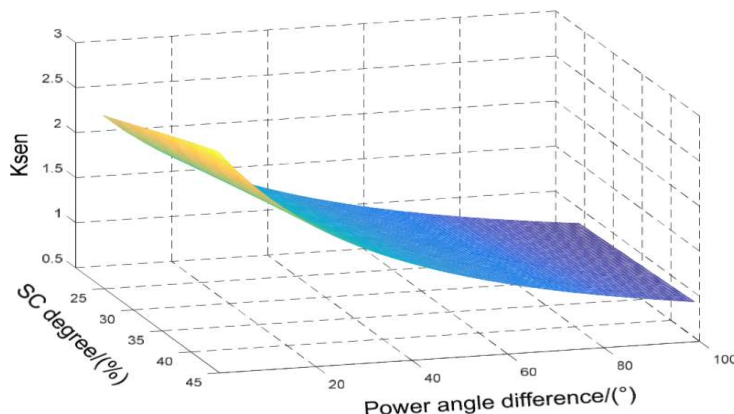
Figure 6. Relationship between degree of sensitivity and series compensation, (Rg = 0).

4   The Improved System

In an internal fault, the possibility of the current reverse exists in the SC lines which can lead to a reduction in sensitivity or even a breakdown of the differential safety. In addition, differential security operations are a compromise between the differential current (operation) and the current (restraint) biases. As a result, because of different selection of operation or restraint current, the sensitivity coefficient will have a bigger difference. The traditional differential protection principle of braking is based o n the sum of phasor or amplitude. Unlike traditional differential protection, in this article a new nonlinear braking protection criterion is constructed by

studying the scalar product constraint characteristics and using the current amplitude-phase relation on both sides of the SC lines.

Differential protection based on scalar product braking characteristics has improved the sensitivity for internal fault and the reliability of external fault braking characteristics. This is however restricted as the current reverse occurs during an internal failure on SC axes, and this technique is also not checked for SC with capacitor export fault, far-end fault, and high resistance fault. Therefore more appropriate differential security systems should be put forward, taking into account the reverse current characteristics. Therefore given the bus voltage and the current at both ends of SC lines are Um, Im and Un In respectively and the differential current calculation is unchanged, the value of Id=|Im+In| is still taken. The amplitude of the typical braking properties is combined with the circuit's phase characteristics when measuring the braking current. The features, like the fault current period, appear to be the same, and the internal fault, which is contrary to normal activity or external fault, does not pose a current reverse similar to the principle of scalar product braking in this article, multiplying the conventional brake amount by the value of $\left|\sin\dfrac{\theta}{2}\right|$, then $\dot{I}_r = \dfrac{\left|\dot{I}_m - \dot{I}_n\right|}{0.5}\left|\sin\dfrac{\theta}{2}\right|$, θ is the angle between I_m and I_n. In these blocking characteristics, the original braking effect during external faults is kept, while restriction is sharply reduced to improve the sensitivity of the protection at internal faults. Moreover, even the reversal of fault current, the angle of the phase is not around 180° but actually around 235°. During that point the bias current by using new algorithm is comparatively small, thus improving the sensitivity of protection to internal faults. In addition, in order to reinforce the operational characteristics of differential protection, the Cartesian Plan is chosen to improve the sensitivity for internal faults in this paper, particularly in the case of high resistance failure. The Cartesian Plan Operating Criteria are as follows.

In addition, in order to reinforce the operation of differential protection, the Cartesian Plan is chosen to improve the sensitivity for internal faults in this article, particularly in the case of high resistance failure. The operation criteria of the Cartesian Plan are as follows.

$$\begin{cases} I_d > I_{set} & 0 \le \dot{I}_r \le \dot{I}_{r1} \\ I_d > k_1 \dot{I}_r & \dot{I}_{r1} < \dot{I}_r \le \dot{I}_{r2} \\ I_d > k_1(\dot{I}_{r1}\text{-}\dot{I}_{r2})\text{+}k_1\dot{I}_{r2} & \dot{I}_{r2} < \dot{I}_r \\ k_1 = 0.3 \\ k_2 = 0.65 \end{cases} \quad (15)$$

k, k_1 and k_2 are the coefficients of restraint and set on the basis of general engineering experience. k_1 varies from 0.2 to 0.5, k_2 varies from 0.6 to 0.9. In this analysis, k_1 takes 0.3 to ensure the sensitivity of security for internal fault, k_2 takes 0.65 to prevent external defect safety maloperation. I_{r1} is the controlling current of the triple line differential safety first inflection point; I_{r2} is the controlling current of the triple line differential protection second inflection point.
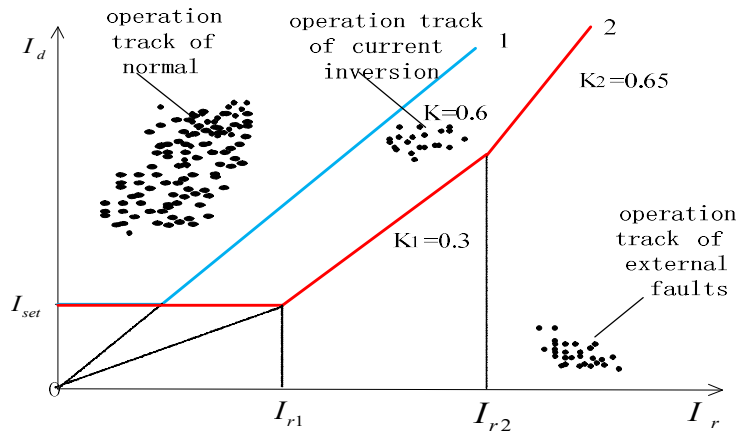

Figure 7. Protection characteristics under system fault

As shown in Figure 7 the resulting point is below the characteristic curve, either external fault or normal conditions. In this case, as in the case of the current reverse, a trip signal will be given. This means that the improved criteria will not be influenced by the low sensitivity of internal faults; hence the defense will not be miss-tripping.

5   Results and Simulations of PSCAD

The two-terminal device (500kV,50Hz) is shown in Figure 8 to check the behavior of the new current differential security algorithms developed for this article. It is simulated in EMTDC / PSCAD software to achieve responsive data which is used to evaluate protection performance. Under such circumstances, to contrast the sensitivity of the modified algorithm with the conventional algorithm, these influential factors concentrate on specific SC, type of fault, the difference in power angles, the position of faults, and grounding resistance.

Fault points are located on the left side of the capacitor c respectively, the outlet of K_2 the right side of the area of K_3, right side out of the area K_4. Compensation equipment is placed near bus M.

K_1 is the fault point set on the left side of the capacitor.

K_2 is the fault points set on the outlet of the capacitor.

K_3 is the fault point set on the right side of K_2.

K_4 is the fault point set on the right side out of the area.

X_{m1}=7.8 Ω，X_{n1}= 35 Ω are the positive sequence impedance of each source.

$X_{m0} = 15\Omega$, $X_{n0} = 79\Omega$ are the zero-sequence impedance of each source.

$0.0242 + j0.294\Omega/\text{km}$ is equal to the positive sequence impedance of the basic circuit.

$0.299 + j1.33\Omega/\text{km}$ is equal to the zero-sequence impedance of the basic circuit.
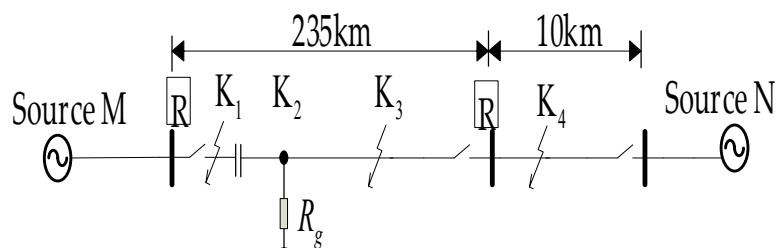
Figure 8. Simulation System

5.1 Transition Resistance and its Effect

From Table 1 it can be concluded that the sensitivity of the two algorithms decreases as the transition resistance increases and the SC degree. Whereas with the increase of the SC degree, the sensitivity of the conventional algorithm decreases considerably, even less than 0.4, when the resistance to the transformation is low (no more than 50 Ohm). The sensitivity as for the improved algorithm is higher than 1If the transfer resistance is high (more than 150 Ω), the sensitivity of the two algorithms decreases marginally as the SC degree increases, both of which are below 1. At this time the resulting point is put above the characteristic curve whose ratio is 0.3 for high resistance fault. It means that suffices for the sensitivity given by the improved algorithm. The conventional protection failed to function in comparison but the improved one operated reliably.

Table 1. Protection sensitivity under different SC and grounding resistances

| SC degree | $R_g = 0$ | | | | | | $R_g = 50$ | | | | |
| | I_d | Conventional algorithm | | enhanced algorithm | | I_d | Conventional algorithm | | enhanced algorithm | |
		I_r	k_{sen}	I_r	k_{sen}		I_r	k_{sen}	I_r	k_{sen}
26%	13.89	9.07	1.70	3.59	5.97	6.55	7.76	0.93	3.67	3.07
36%	13.29	9.56	1.53	3.89	5.25	6.02	8.23	0.89	3.98	2.68
46%	12.88	9.04	1.42	4.12	4.80	5.76	8.63	0.88	4.16	2.50
66%	12.29	9.59	1.28	4.35	4.37	5.31	8.94	0.43	4.57	2.21
76%	11.94	10.13	1.18	4.67	3.99	4.84	9.14	0.56	4.35	2.12
86%	11.52	11.48	1.11	4.92	3.68	4.28	9.72	0.46	4.05	2.05

| SC degree | $R_g = 150$ | | | | | | $R_g = 300$ | | | | |
| | I_d | Conventional algorithm | | enhanced algorithm | | I_d | Conventional algorithm | | enhanced algorithm | |
		I_r	k_{sen}	I_r	k_{sen}		I_r	k_{sen}	I_r	k_{sen}
25%	2.01	4.59	0.44	2.03	0.99	1.41	4.36	0.32	1.88	0.75
35%	1.89	4.92	0.38	2.45	0.77	1.17	4.72	0.25	1.99	0.59
45%	1.75	5.17	0.34	2.52	0.69	1.03	4.55	0.23	2.01	0.51
65%	1.45	5.23	0.28	2.12	0.68	0.98	4.42	0.22	1.98	0.49
75%	1.15	5.12	0.22	1.83	0.63	0.83	4.04	0.21	1.88	0.44
85%	1.01	4.98	0.20	1.74	0.58	0.67	3.77	0.18	1.68	0.40

5.2 Power Angle and The Effect

Table 2 shows the sensitivity of the protection under different compensation series and angle of control. When the difference in the power angle is small (less than 50 °), the sensitivity of the enhanced system is greater than 1 despite of the SC degree, whereas the conventional system 's sensitivity is even less than 1. For example, with the increase in power angle and SC degree, when the power angle difference is higher than 70 °, the standard sensitivity to protection will be lower than 0.6. Thus maloperation due to lack of sensitivity will occur. The resulting points are put above the characteristic curve which has a ratio of 0.65 for the improved scheme. The ratio is much smaller that the effect, so the differential defense will work accurately.

Table 2. Sensitivity to protection under the various SC and power angles

SC degree	$\partial = 90°$									$\partial = 70°$				
	I_d	Conventional algorithm		Improved algorithm		I_d	Conventional algorithm		Improved algorithm	
		I_r	k_{sen}	I_r	k_{sen}		I_r	k_{sen}	I_r	k_{sen}
25%	5.85	12.02	0.49	5.86	1.00	6.12	10.84	0.56	5.01	1.22
35%	5.56	12.22	0.45	6.10	0.91	5.90	10.99	0.54	5.25	1.12
45%	5.01	11.45	0.44	5.74	0.87	5.76	11.05	0.52	5.52	1.04
65%	4.85	11.15	0.43	5.66	0.86	5.01	10.63	0.47	5.12	0.98
75%	4.64	10.95	0.42	5.44	0.85	4.88	10.50	0.46	5.01	0.97
85%	4.01	10.43	0.38	5.12	0.78	4.65	10.23	0.45	4.88	0.95

SC degree	$\partial = 50°$									$\partial = 40°$				
	I_d	Conventional algorithm		Improved algorithm		I_d	Conventional algorithm		Improved algorithm	
		I_r	k_{sen}	I_r	k_{sen}		I_r	k_{sen}	I_r	k_{sen}
25%	6.33	9.73	0.65	4.75	1.33	6.54	8.79	0.74	4.24	1.54
35%	6.19	9.78	0.63	4.85	1.28	6.33	8.99	0.70	4.44	1.43
45%	6.17	9.89	0.62	4.96	1.24	6.31	9.08	0.69	4.57	1.38
65%	5.23	9.01	0.58	4.31	1.21	6.16	9.12	0.68	4.59	1.34
75%	4.98	8.68	0.57	4.22	1.18	5.54	8.76	0.63	4.16	1.33
85%	4.61	8.38	0.55	4.13	1.12	4.95	8.17	0.61	3.78	1.31

SC degree	$\partial = 30°$									$\partial = 20°$				
	I_d	Conventional algorithm		Improved algorithm		I_d	Conventional algorithm		Improved algorithm	
		I_r	k_{sen}	I_r	k_{sen}		I_r	k_{sen}	I_r	k_{sen}
25%	6.79	8.15	0.83	3.56	1.91	6.94	7.65	0.91	3.18	2.18
35%	6.47	8.27	0.78	3.98	1.63	6.61	7.79	0.85	3.39	1.95
45%	6.34	8.32	0.76	4.02	1.58	6.43	7.88	0.82	3.54	1.81
65%	6.20	8.41	0.74	4.22	1.47	6.21	7.63	0.81	3.72	1.67
75%	5.88	8.01	0.73	4.10	1.43	6.10	7.58	0.80	3.68	1.66
85%	5.47	7.78	0.70	3.87	1.41	5.92	7.49	0.79	3.58	1.65

5.3 impacts of fault types

Table below shows the sensitivity of the protection under various compensation series and grounding resistances. The sensitivity is somewhat different when different faults on SC lines occur under the same conditions. The sensitivity of inter-phase fault, in particular, is obviously higher than that of grounding fault. Integrating the negative effect of high SC degree and high grounding resistance, in situations such as this, SC degree exceeds 50 percent and transition resistance exceeds 150 percent, traditional safety does not move because the sensitivity is too small when there is a two-phase or single-phase grounding failure. While the improved system's sensitivity isn't too high, it's still larger than 0.3. The resulting points are set above the characteristic curve which has a ratio of 0.3. There for different protection will also can cut off the fault.

Table 3. Protection sensitivity under different SC and fault types

| fault type | $R_g = 0$, SC degree =30% | | | | | $R_g = 50$, SC degree =45% | | | | |
| | I_d | Conventional algorithm | | Improved algorithm | | I_d | Conventional algorithm | | Improved algorithm | |
		I_r	k_{sen}	I_r	k_{sen}		I_r	k_{sen}	I_r	k_{sen}
ABCG	20.10	16.24	1.24	3.28	6.12	5.04	7.49	0.67	3.74	1.35
AG	11.27	10.53	1.07	3.32	3.39	4.61	7.80	0.59	3.56	1.29
AB	17.91	15.73	1.14	3.52	5.09	7.72	9.02	0.86	4.43	1.74
ABG	17.77	15.29	1.16	3.49	5.09	4.18	6.79	0.62	3.39	1.23

| fault type | $R_g = 150$, SC degree =60% | | | | | $R_g = 300$, SC degree =80% | | | | |
| | I_d | Conventional algorithm | | Improved algorithm | | I_d | Conventional algorithm | | Improved algorithm | |
		I_r	k_{sen}	I_r	k_{sen}		I_r	k_{sen}	I_r	k_{sen}
ABCG	1.79	5.26	0.34	2.62	0.68	0.94	4.63	0.20	2.30	0.41
AG	1.75	5.28	0.33	2.63	0.67	0.92	4.63	0.20	2.31	0.40
AB	3.06	5.80	0.53	2.82	1.09	1.61	4.83	0.33	2.38	0.68
ABG	1.66	5.17	0.32	2.57	0.65	0.90	4.59	0.20	2.27	0.40

5.4 Fault Point Effects

Table 4 demonstrates the sensitivity of the defense at various compensation and fault points of the array. According to Table 4 the K_{sen} of the two security systems is less than 0.15 when the system has an external fault (K_4). The sensitivities in figure 7 are all under the characteristic slop of the curve 0.65. Therefore no trip for this condition will be given. The K_{sen} measured by the enhanced protection scheme is twice as high as that of the traditional protection system when the device has internal fault. If there is a serious short circuit at the SC outlet (K_2), K_{sen} is not less than 0.8, calculated by the enhanced system.

Table 4. Sensitivity to cover under various penalties and fault points of the sequence

| SC degree | k_1 | | | | | k_2 | | | | |
| | I_d | Conventional algorithm | | Improved algorithm | | I_d | Conventional algorithm | | Improved algorithm | |
		I_r	k_{sen}	I_r	k_{sen}		I_r	k_{sen}	I_r	k_{sen}
25%	2.72	5.00	0.54	2.41	1.13	2.73	5.50	0.50	2.75	0.99
35%	2.71	5.12	0.53	2.56	1.06	2.66	5.85	0.45	2.92	0.91
45%	2.70	5.43	0.50	2.61	1.03	2.63	5.87	0.45	2.94	0.89
65%	2.74	6.13	0.45	2.98	0.92	2.49	5.90	0.42	2.95	0.84
75%	2.72	6.03	0.45	2.95	0.92	2.44	5.84	0.42	2.92	0.84
85%	2.45	5.56	0.44	2.71	0.90	2.17	5.42	0.40	2.70	0.80

| SC degree | k_3 | | | | | k_4 | | | | |
| | I_d | Conventional algorithm | | Improved algorithm | | I_d | Conventional algorithm | | Improved algorithm | |
		I_r	k_{sen}	I_r	k_{sen}		I_r	k_{sen}	I_r	k_{sen}
25%	2.27	3.10	0.73	1.73	1.31	0.23	3.01	0.08	1.50	0.15
35%	2.26	3.72	0.61	1.76	1.28	0.23	3.37	0.07	1.68	0.14
45%	2.25	3.90	0.58	1.86	1.21	0.22	3.54	0.06	1.76	0.13
65%	2.22	4.11	0.54	1.96	1.13	0.21	4.16	0.05	2.18	0.10
75%	2.12	4.12	0.51	1.95	1.09	0.20	4.12	0.05	2.12	0.09
85%	1.95	3.90	0.50	1.81	1.07	0.18	3.69	0.05	1.92	0.09

5.5. Contrast Before and after Enhancement

Figure 9 is a simulation based diagram drawn by I_d-I_r. The red dots are the traditional system, and the blue dots are the modified system. As external fault occurs in the system, both the traditional system and the enhanced system are in the restraining region, and the security is not working. The traditional protection system may fail to work due to the reverse current when an internal fault occurs in the device. With the improved protection scheme, the improved restraining current makes the resulting points (Id, Ir) The enhanced protection system makes the resulting points (I_d, I_r) on the I_d-I_r coordinate plane closer to the Y-axis, that is the sensitivity is greatly improved with the improved restraining current. Therefore the arrangement of the enhanced restraining current and the triple-fold line will ensure the safety device's reliability.
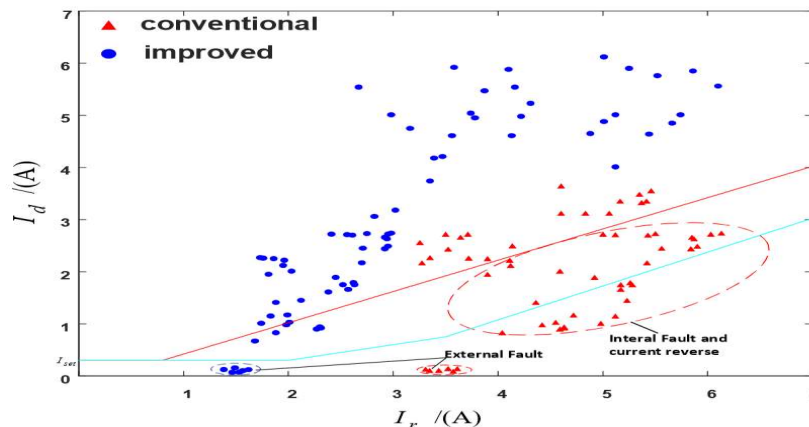

Figure 9. Id-Ir Diagram of contrast, before and after improvement.

6 Conclusion

The characteristics of the current reverse in internal fault lines of SC are studied in this research. The presence is determined by several factors such as degree of SC, fault forms, difference in the power angle, fault points and resistance to change. The current reverse disappears in 1ms when the internal symmetric fault occurs on the SC lines, which has no effect on differential safety. Where the asymmetric fault exists, a number of variables may influence how the current is reversed. Besides, the closer the fault point is to the SC system, the more likely it is to reverse the current.

In response to the current reverse-caused failure of differential protection, an improved scheme based on the current amplitudes and phases on both sides of SC lines is being put forward. At about the same time, the standard double-fold line restraining features of relays are modified to triple-fold line restraining features. The sensitivity of the improved scheme is relatively enhanced compared with the conventional scheme, both for the current reverse and high transition resistance fault. The PSCAD / EMTDC simulation and dynamic physics simulation of the power system show that safety sensitivity in the improved scheme is obviously increased.

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