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A Novel Current Differential Protection Scheme for Transmission Lines Using Fast Active Current Extraction

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Abstract

This paper presents a novel current differential protection scheme for UHV/EHV transmission lines. This method is based on active current component extraction using instantaneous power theory, which is also called ip-iq method, and it has been widely used in APF (active power filter). Adopt three digital PLL (phase-locked loop) to get the positive voltage's angle and active current containing DC and AC components can be obtained by using dq transformation. The average filter is employed to filter the AC active current component out. This algorithm can eliminate the influence of distributed capacity current fundamentally. Compared to compensation methods, it requires no heavy computation, line parameters and voltage information transmission. Compared to other differential protection methods, it has the advantages of clear physical meaning and simple operation. Simulation results show that the novel protection method is effective and robust, providing a new perspective on transmission lines' protection.

Keywords: *UHV/EHV transmission line, current differential protection, distributed capacity current, active current extraction, instantaneous power theory*

1. Introduction

Current differential protection has been widely adopted as the main protection in the UHV/EHV transmission lines due to its simple principle, inherent phase-selection ability and excellent applicability under complex operating status. However, sensitivity of current differential protection is susceptible to distributed capacitive current, especially in UHV long-distance transmission lines. And a lot of works have been done in order to solve this problem.

In the early time, shunt reactor is used in UHV/EHV transmission lines for compensating capacitive current and suppressing overvoltage. However, shunt reactor can only compensate the steady-state capacitive current; in addition, the compensation precision cannot be guaranteed because of the discrete regulating and various operation conditions. An accurate compensation method is mentioned based on Bergeron line model in paper [1, 2]. Although Bergeron method can eliminate the distributed current due to considering the distributed capacitances in its distributed parameter separately, it has some disadvantages in following aspects: high sampling rate and enormous computation. It's challenging to achieve acceptable results in practical device by using Bergeron model. In reference [3], transient impact of coupling capacitor voltage transformers (CCVT) was taken into consideration. By using the theory of equal transfer process transmission lines (ETPTL), the differential current without capacitive current can be got and the calculation can meet the requirements of current differential protection in long-distance transmission line. Reference [4, 5] has proposed an algorithm based on

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the differential equation of π or T equivalent circuit of the transmission line, which is known as time-domain compensation method. The time-domain compensation method can effectively compensate both transit and steady distributed capacitive current.

Instantaneous power theory (IPT) has been presented by Akagi.H and developed during these years, and it has many successful applications in various cases. IPT has been applied to shunt or series compensation device in reference [6-9]. Based on IPT (or p-q power theory), the active power component protection for power transformer has been proposed in reference [10]. Active power component can solve the inrush /fault discrimination problem in power transformers differential protection. In literature [11], IPT and artificial neural networks are adopted for fault location and classification in transmission line through phase-angles identification.

This paper proposes a novel differential protection method based on active current component for transmission lines. With this approach, the active current component extracted by using IPT can solve the distributed capacitive current dilemma. The differential active current represents the amount of inside active power consumption, so it has high sensitivity for detecting high resistance earth fault. The simulation platform is implemented by using PSCAD, and the test results show that differential active current protection is more advantageous than traditional differential current protection methods in sensitivity, selectivity and rapidity.

2. Fundamental

2.1. Power Transmission Line Model and Traditional Current Differential Protection

High voltage transmission lines normally use the PI equivalent model. A 500 kV transmission line MN and its system diagram and equivalent circuit diagram are illustrated in Figure 1, where Zπ is the line resistance, and Zc is the line-to-ground equivalent capacitive reactance.

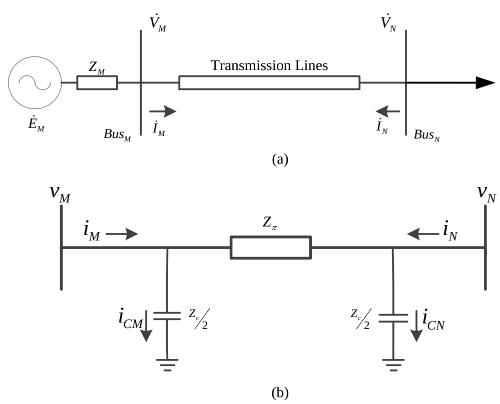

Figure 1. 500kV Transmission System and it's Equivalent Circuit. (a) 500kV Transmission System (b) Equivalent Circuit

The principle of current differential protection is based on Kirchhoff's current law. It is used as the major protection method for high-voltage transmission lines because it is highly selective, sensitive, and reliable. Currently used operating criteria for digital split-phase protection are

$$\left|\dot{I}_M + \dot{I}_N\right| > I_{set} \tag{1}$$

$$\left|\dot{I}_M + \dot{I}_N\right| > K\left|\dot{I}_M - \dot{I}_N\right| \tag{2}$$

where $\dot{I}_M$ and $\dot{I}_N$ represent the bus bar and the current vector on Side M and N, respectively, I_{set} represents the operating threshold, and K represents the restrained coefficient (0< K <1), $\left|\dot{I}_M + \dot{I}_N\right|$ and $\left|\dot{I}_M - \dot{I}_N\right|$ are the operating quantities and the restrained quantities, respectively. Equation (1) is the auxiliary tripping criterion that mainly prevents the line from incorrect operation under no-load switching conditions. Equation (2) represents the main criterion. The protection will be effective only when both equations (1) and (2) are satisfied. With the existence of the distributed capacitance current, the current measured at both terminals of the line no longer satisfies Kirchhoff's current law, thereby affecting the sensitivity and reliability of traditional current differential protection.

2.2. Power Transmission Line Model and Traditional Current Differential Protection

As indicated by the basic circuit principle, the phase of resistive current is in the same direction with the voltage phase, the phase of the capacitive current is 90° ahead of the voltage phase, and the phase of inductive current is 90° behind the voltage phase. The resistive current is defined as the active current and the capacitive (inductive) current as the idle current. Figure 1 shows that the phases of the line-distributed capacitive current (I_M and I_N) are 90° ahead of the bus voltage (V_M and V_N). The influence of the distributed capacitive current on differential protection can be prevented by splitting the reactive current. This paper proposes a method in which the phase information of power positive-sequence fundamental voltage is obtained through three-phase digital PLL and then the active component of the three-phase current is extracted through *dq* transformation. The extraction frame of the active current is illustrated in Figure 2.

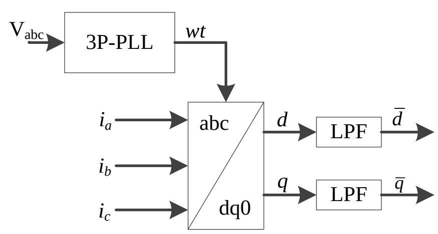

Figure 2. Active Current Component Extraction

2.2.1 Three-phase Digital PLL

Literature [12, 13] proposes the three-phase digital PLL, which is the characteristic of qPLL based on instantaneous reactive power theory. The locked loop has excellent dynamic response and robustness, and it can effectively follow the phase angles of the positive-sequence voltage components of fundamental waves, particularly when the voltage waveform is distorted and asymmetrical. The principle of the PLL is illustrated in Figure 3.

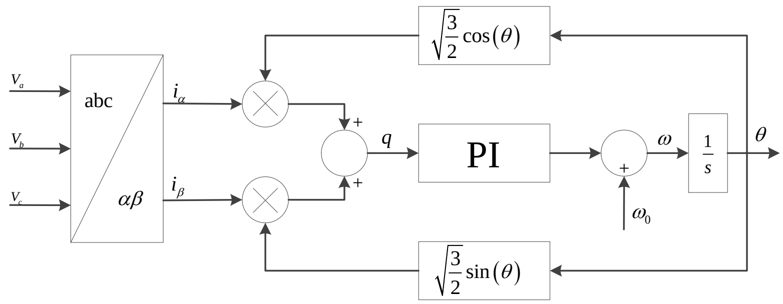

Figure 3. qPLL System

In case of short-circuit fault, the line voltage will generate a large amount of positive-sequence, negative-sequence and harmonic components. Suppose that the positive-sequence and negative-sequence three-phase voltage signals are

$$\begin{cases} v_a = V_p \sin(\theta_p) + V_n \sin(\theta_n) \\ v_b = V_p \sin(\theta_p - 2\pi/3) + V_n \sin(\theta_n + 2\pi/3) \\ v_c = V_p \sin(\theta_p + 2\pi/3) + V_n \sin(\theta_n - 2\pi/3) \end{cases} \tag{3}$$

where V_m represents the amplitude of the positive-sequence voltage component, and V_n represents the amplitude of the negative-sequence voltage component. Through Clarke transforms, the voltage signal is transformed from *abc* coordinate system to $\alpha\beta$ coordinate system, and the transformation matrix is

$$T_c = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \tag{4}$$

Given a unit virtual current, in accordance with instantaneous reactive power theory, the instantaneous reactive power $q(t)$ will be

$$\begin{aligned} q(t) &= v_\beta i_\alpha - v_\alpha i_\beta \\ &= \underbrace{\frac{3}{2} V_p \sin(\theta_p - \theta_{d\cdot q})}_{\bar{q}(t)} + \underbrace{\frac{3}{2} V_n \sin(\theta_n + \theta_{d\cdot q})}_{\tilde{q}(t)} \end{aligned} \tag{5}$$

where $\bar{q}(t)$ is the average component, and $\tilde{q}(t)$ is the oscillating component. The PI controller has a low-pass feature. Therefore, the oscillating component will be filtered. Thus, when the PLL has successfully locked the phase, it only outputs the phase information of the positive-sequence voltage for the fundamental wave.

2.2.2. Extraction of Active Current

The composite vector of the three-phase voltage on the $\alpha\beta$ plane coordinate system is given as $\dot{V}$, and the angle between the voltage vector $\dot{V}$ and the axis α at any time is

θ . Suppose that the composite vector of the three-phase current is $\dot{I}$. The vector diagram of the voltage and current is illustrated in Figure 4.

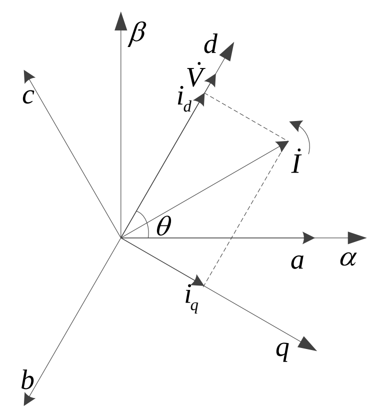

Figure 4. Phase Diagram of Voltage and Current

Suppose that the d-axis component of the current vector $\dot{I}$ is i_d , and the *q*-axis component is i_q , the values of i_d and i_q can be obtained by using *dq* transformation. The *dq* transformation equation is

$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\left(\theta_{d\cdot q}\right) & \cos(\theta_{d\cdot q} - \frac{2}{3}\pi) & \cos\left(\theta_{d\cdot q} + \frac{2}{3}\pi\right) \\ \sin\left(\theta_{d\cdot q}\right) & \sin\left(\theta_{d\cdot q} - \frac{2}{3}\pi\right) & \sin\left(\theta_{d\cdot q} + \frac{2}{3}\pi\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (6)$$

Figure 4 shows that i_d and $\dot{V}$ are in the same direction, and i_q is 90° behind $\dot{V}$. Therefore, i_d is the active current component, and i_q is the reactive current component. A large amount of harmonic waves and negative-sequence fundamental current will be generated when the system has a short-circuit fault at one instance. Suppose that the positive-sequence and negative-sequence currents during a fault are

$$\begin{cases} i_a = I_p \sin\left(\omega t\right) + I_n \sin\left(\omega t\right) \\ i_b = I_p \sin\left(\omega t - 2\pi/3\right) + I_n \sin\left(\omega t + 2\pi/3\right) \\ i_c = I_p \sin\left(\omega t + 2\pi/3\right) + I_n \sin\left(\omega t - 2\pi/3\right) \end{cases} \quad (7)$$

In this equation, ω is the angle velocity of the system. For easier analysis, the voltage phase angle θ at this moment is

$$\theta = \omega \text{t} + \varphi \quad (8)$$

Where φ is the initial phase angle of the voltage, as shown in equations (7), (8), and (9).

$$i_d = \underbrace{I_p \sin(\varphi)}_{\bar{i}_d} + \underbrace{I_n \sin(2\omega t + \varphi)}_{\tilde{i}_d} \tag{9}$$

Thus, the positive-sequence current of the fundamental wave is transformed into DC component, and the negative-sequence current of the fundamental wave is transformed into a 100 Hz AC signal. When low-pass filter is used to filter AC component $\tilde{i}_d$, the DC component $\bar{i}_d$ will be obtained, which is the fundamental wave active current component.

3. Protection Scheme Using Active Current

3.1. Extraction of Active Differential Current

M side is used as an example. Suppose that the voltage phase angle of the three-phase voltage digital PLL output at the t_0 moment is θ_m, and the sampling values of the three-phase current are i_a, i_b and i_c. After *dq* transformation, the *d*-axis component is

$$\begin{aligned} i_{md} &= \bar{i}_{md} + \tilde{i}_{md} \\ &= 2/3\left[\cos(\theta_m)i_a + \cos(\theta_m - 2\pi/3)i_b + \cos(\theta_m + 2\pi/3)i_c\right] \end{aligned} \tag{10}$$

where $\bar{i}_{md}$ is the d-axis DC component, and $\tilde{i}_{md}$ is the d-axis AC component. The DC component $\bar{i}_{md}$ can be obtained after i_{md} having been filtered by mean filter. For the three-phase instantaneous current value sampled at each sampling moment, the amplitude of the *d*-axis DC component obtained by using *dq* transformation is the amplitude of the three-phase positive-sequence active current.

$$I_{m\bar{d}} = \bar{i}_{md} \tag{11}$$

$I_{n\bar{d}}$ at N side can be obtained using the same computation method.

$$I_{n\bar{d}} = \bar{i}_{nd} \tag{12}$$

3.2. Criteria of Protection

The above analysis indicates that the active current component is orthogonal to the current component generated by the capacitive current and compensation devices. Theoretically, capacitive current does not affect the active current. The difference of active current components at both terminals reflects the internal active loss. When the line is in normal operation or has an outside fault, the differential current of the active current is small. When the line has an internal short-circuit fault, the short-circuit current of the short-circuit point will consume a large amount of active power, which will increase the differential current of the active current. According to equation (4), the main criterion based on the protection of the differential current of the active current proposed by this paper is provided below.

$$\left|I_{m\bar{d}} + I_{n\bar{d}}\right| > I_{setd} \tag{13}$$

$I_{m\bar{d}}$ and $I_{n\bar{d}}$ are the active current DC components on the M and N sides, respectively, $\left|I_{m\bar{d}} + I_{n\bar{d}}\right|$ is the operating quantity, and I_{setd} is the threshold. Since *dq* transformation is used for three-phase transformation, split-phase protection cannot be achieved by merely depending on equation(13). To increase the selectivity of the protection algorithm, the traditional differential protection criteria with restrained coefficient, namely equation(2), is introduced as the auxiliary criteria. The output executive organs will not operate unless both the main criterion and auxiliary criterion have been satisfied.

3.3. Setting Principle for Criteria

The role of the main criterion is to increase the sensitivity for internal faults. The differential current of active current is not zero when the line is under normal operation because of the difference between the voltage phases on both sides and the transmission velocity of current traveling waves. Therefore, the operating threshold of the differential current of the active current should avoid the maximum value of the differential current of the active current that is under maximum operation. The setting equation is provided below.

$$I_{setd} = K_{reld} I_{\max d} \tag{14}$$

where $I_{\max d}$ is the differential current of active current when the system is under maximum operation mode, and K_{reld} is the reliability coefficient.

The auxiliary criterion is mainly responsible for enhancing the selectivity for external and internal faults so that it will not operate in case of external faults. The restrained coefficient K of the auxiliary criterion can be set according to the following principles:

1) By avoiding the maximum differential current of external faults without considering the influence of capacitance current.

2) By avoiding the maximum differential current of normal operation without considering the influence of capacitance current

4. Case Study

4.1. Model Construction

PSCAD is used to construct the simulation model. The system parameters are described below. System parameters on Side M: $\dot{E}_M = 1.05\angle 0$, R_{M1}=1.0515 Ω, L_{M1}=0.13743 H, R_{M0}=0.6 Ω and L_{M0}=0.0926 H; Line parameters: r_1=0.02083 Ω/km, l_1=0.8948 mH/km, c_1=0.0129 uF/km, r_0=0.1148Ω/km, l_0=2.2886 mH/km and c_0=0.00523 uF/km. The line length is 100 km, BRK_M is the breaker on Side M, and BRK_N is the breaker on Side N.

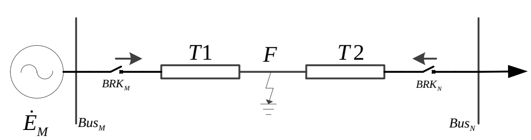

Figure 5. Simulation Model

4.2. Testing of Voltage PLL

When short-circuit fault occurs on a power transmission line, the system voltage waves will exhibit distortions of various degrees. Fast and accurate locking of the positive-sequence voltage phase by PLL is very important to the extraction of the active current. For a metallic three-phase short-circuit fault at the center of Line MN, the phase information of its system voltage waves and the three-phase digital PLL output are described in Figure 6.

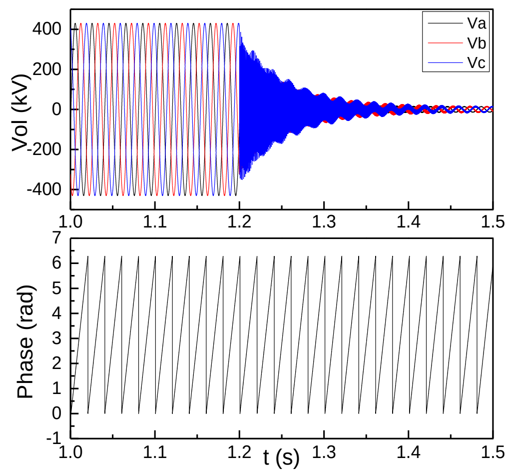

Figure 6. Three Phase Voltage and PLL Output

Figure 7 describes the error signals of the three-phase digital PLL when three-phase metallic grounding faults occur at the exterior of Side M and Side N, and at the interior MN.

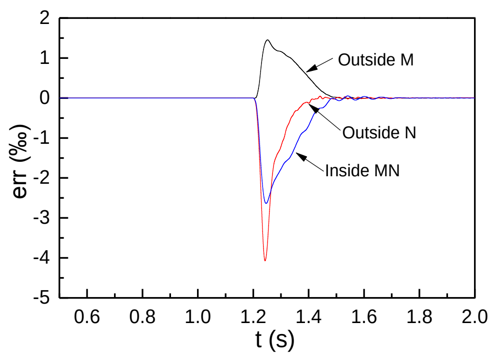

Figure 7. Error of qPLL in Different Situations

Figure 6 and Figure 7 show that when the system has been seriously disrupted, the system voltage will change significantly, which generates a large amount of harmonic wave, asymmetrical, negative-sequence, and zero-sequence components. The three-phase digital PLL can still quickly and accurately lock the positive-sequence fundamental voltage phase. The maximum deviation is only 4%, which satisfies the phase-locking requirement of the algorithm under various poor conditions.

4.3. No-load Switch-on

Figure 8 shows the voltage and current waves when the breaker BRK_N on Side N is switched off and the breaker on Side M is switched on at 1.2 s. Current under no-load closing condition is mainly capacitance current, and the wave peak of the transient capacitance current can be as high as 1.5 kA. After 0.3 s, the current on the line is mainly stable zero-sequence current, and its effective value can reach 120 A.

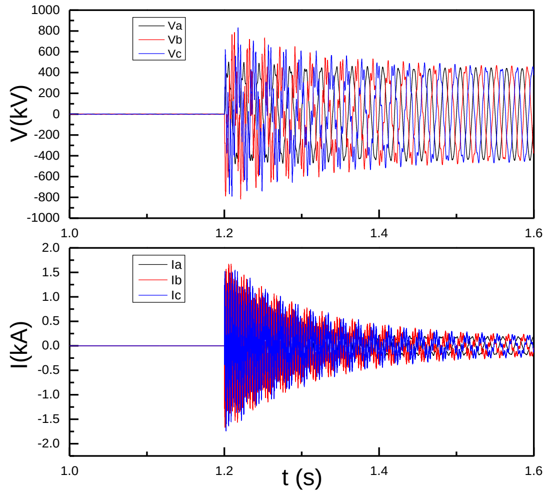

Figure 8. Voltage and Current Waveform Under No-load Closing Condition

As a result of the effect of auxiliary criteria, the differential protection algorithm will not experience false operation under no-load closing condition. However, no-load closing operation is the best way to test the abilities of various compensation methods in curbing the capacitance current. The line differential currents of the original line current's effective value, phase compensation method, time-domain compensation method, and active current method are described in the Figure 9. The figure shows that the phase compensation method cannot compensate transient capacitance current and that its compensation effect for a stable capacitance current is also poor. Time-domain compensation method can effectively curb the transient capacitance current and is more capable of compensating for a stable capacitance current than the phase compensation method. On the other hand, the active current compensation method curbs the transient capacitance current as efficiently as the time-domain compensation method, and it can completely curb the stable capacitance current. A comparison between the active current compensation method and the time-domain compensation method indicates that the active current method does not need the line parameters.

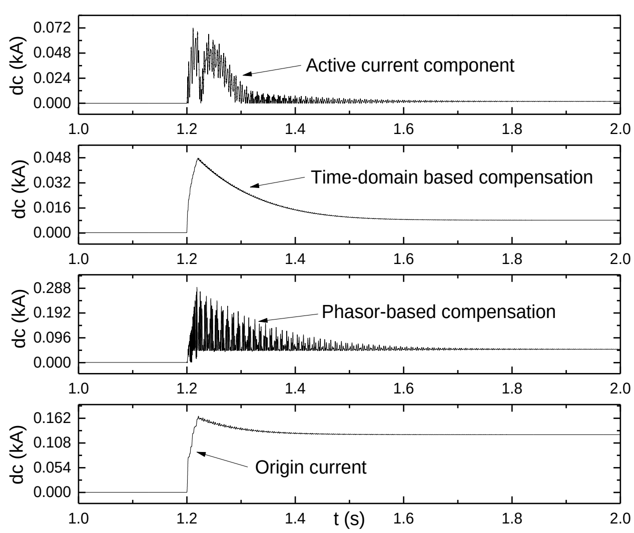

Figure 9. Differential Current Waveforms of Various Methods

4.4. Setting of Protection Threshold

Suppose the maximum operation mode of the system is $\dot{E}_M = 1.05\angle 0$, $\dot{E}_N = 1\angle -45^{\circ}$. A simulation shows that the differential current of the active current reaches 0.062 kA. Set the reliability coefficient as 1.2 and the threshold of the active current differential protection's criteria as 0.074kA based on equation (14).

4.5. Internal Fault

Suppose that the fault point F is at the center of line MN and fault occurs at 1.2 s. Such faults include single-phase grounding fault of metallic Phase A, phase-A-to-B short-circuit fault, phase-A-to-B-to-ground short-circuit fault and phase-A-to-B-to-C-to-ground short-circuit fault. The differential current of the active current is illustrated in Figure. **10**. The analysis shows that when the fault occurs, the differential current of the active current will be transient for a short time before stabilizing. If the transition resistances are the same, the single-phase grounding short-circuit fault has the minimum differential current of the transient and stable active current, while the differential currents of the transient active currents that correspond to the two-phase short-circuit fault, two-phase grounding short-circuit fault, and three-phase grounding short-circuit fault are basically the same. However, the differential currents of the stable active currents are presented in increasing sequence as follows: three-phase grounding short-circuit fault, phase-to-phase short-circuit fault, and phase-to-phase grounding short-circuit fault.

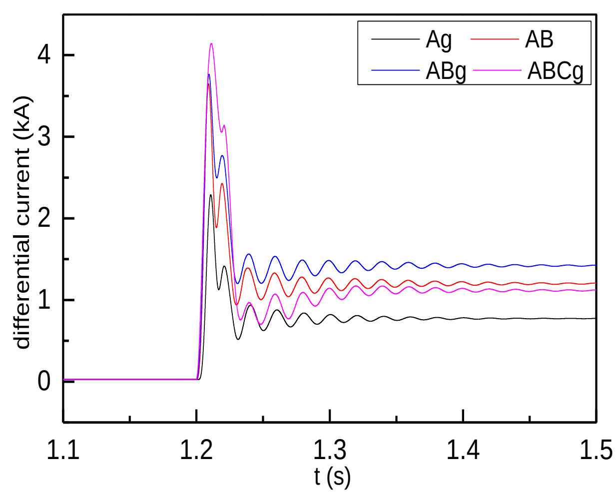

Figure. 10. Active Differential Current in Different Kind of Fault Types

Suppose that the metallic Phase-A grounding short-circuit fault point F is located at the center of Line MN and occurs at 1.2 s. when the initial phase angles θ are 0°, 30°, 60°, and 90°, respectively, the differential current of the active current is described in the Figure 11. The figure shows that current components of stable active current that correspond to different fault initial phase angles are the same: a smaller initial phase angle indicates a larger peak value of the transient active current component and a longer time for the transient process.

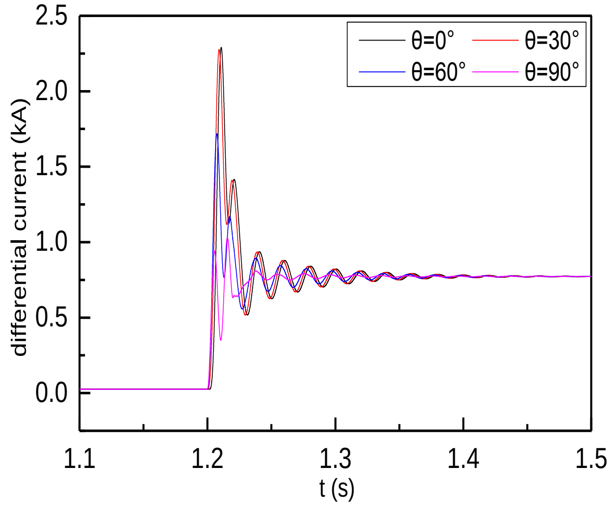

Figure 11. Active Differential Current in Different Fault Angles

The above analysis indicates that the differential value of the active current for the single-phase short-circuit grounding fault is the smallest, thus different transition resistance values can be set to analyze the sensitivity of the criteria for active current differential protection. The grounding resistances of Phase A at the fault point are assumed to be 0.1, 50, 100, 300, 600, 750, and 1000 Ω. According to the following equation:

$$S = \frac{\left| I_{df} \right|}{I_{set}} \tag{15}$$

the differential protection sensitivity is calculated separately by using the active current and the time-domain compensation methods. In this equation, I_{df} is the operating quantity, and I_{set} is the operating threshold. The sensitivity of the active current, the time-domain compensation and uncompensated methods under different transition resistances is illustrated in Figure 12. If the transition currents are the same, the sensitivity of the active current compensation method is obviously better than that of the time-domain compensation method, and time-domain-based method is better than that of uncompensated method. When the transition resistance is larger than 300Ω, the uncompensated method loses the fault detection ability. When the transition resistance is larger than 600 Ω, the time-domain compensation method is unable to determine if a fault has occurred (the sensitivity is smaller than 1). However, the active current compensation method is still sufficiently sensitive, which means that it can identify faults when the transition resistance is as high as 1000 Ω.

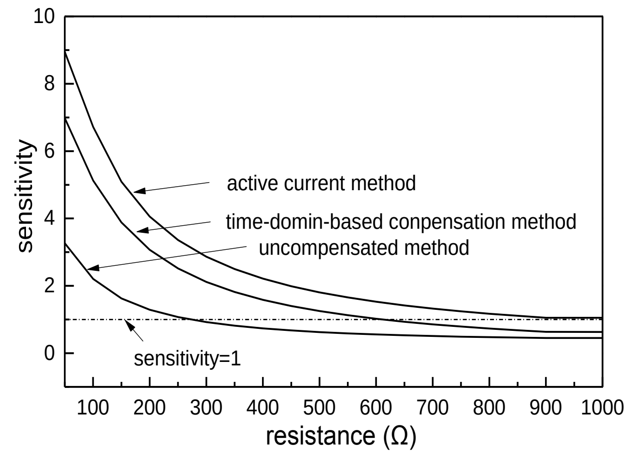

Figure 12. Sensitivity Curves of Different Methods

Suppose that the fault points are set as follows:

1) The distances of the fault point F from the bus bar are 10, 30, 60 and 90 km, respectively;

2) The fault types are single-phase short-circuit grounding fault (AG), phase-to-phase short-circuit fault (AB), phase-to-phase short-circuit grounding fault (ABG), and three-phase short-circuit grounding fault (ABCG).

3) The fault resistance is 0.1 and 1000 Ω.

4) The fault angle is 0, 30, 60, and 90°.

The operating time of criteria for the active current compensation method is illustrated in Table 1. Table 1 shows that when the transition resistance reaches 1000 Ω, the active current compensation method performs quickly, with a less-than-8ms operating time.

Table 1. Criterion Operating Time under Different Fault Conditions

Fault position	Fault type	Fault resistance /ohm							
		0.1				1000			
		Fault phase /degree							
		0	30	60	90	0	30	60	90
		Operation time /ms							
10	AG	3.16	1.6	1.03	0.86	6.68	5.06	3.93	7.77
	AB	1.36	0.82	0.63	0.73	2.75	1.65	1.39	1.79
	ABG	1.03	0.78	0.63	0.71	3.41	2.63	2.43	3.84
	ABCG	0.62	0.62	0.62	0.62	2.3	2.3	2.3	2.3
30	AG	3.27	1.67	1.06	0.88	6.72	5.1	3.95	7.7
	AB	1.42	0.82	0.68	0.73	2.79	1.68	1.39	1.77
	ABG	1.06	0.78	0.67	0.71	3.44	2.64	2.4	3.79
	ABCG	0.67	0.67	0.67	0.67	2.29	2.29	2.29	2.29
60	AG	3.38	1.71	1.05	0.86	6.86	5.25	4.06	7.85
	AB	1.47	0.84	0.68	0.72	2.89	1.72	1.4	1.76
	ABG	1.05	0.79	0.68	0.71	3.52	2.74	2.53	3.79
	ABCG	0.67	0.67	0.67	0.67	2.39	2.39	2.39	2.39
90	AG	3.44	1.71	1.03	0.83	6.85	5.22	4.0	7.43
	AB	1.51	0.86	0.66	0.72	2.91	1.73	1.4	1.7
	ABG	1.02	0.8	0.65	0.7	3.51	2.7	2.42	3.62
	ABCG	0.64	0.64	0.64	0.64	2.32	2.32	2.32	2.32

5. Conclusion

This paper proposed and analyzed a method of extracting active current components from a power transmission line. The proposed method uses three-phase digital PLL and dq transformation, which transformed the traditional protection problem into the automation control problem. In addition, this paper presented the new scheme of differential protection, namely the active current differential protection, which is based on the proposed method and traditional current differential protection. The protection criteria inherited the phase selection function of traditional current differential protection and construct the differential protection criteria by utilizing the active current component, thus theoretically eliminating the influence of capacitive current. Compared with the time-domain method, the proposed method has lower computational cost, does not need to use line parameters, and effectively curbs the capacitive current. Hence, unlike traditional current differential protection, the proposed method cannot be easily influenced by the distributed capacitive current. The simulation experiment shows that the proposed method can quickly and accurately identify faults under various conditions and will not be affected by system operating conditions, transition resistance, fault positions and fault types. Furthermore, the application of the differential active current protection on the protection of power equipment such as parallel multi-circuit transmission lines, transformer and generator is worth further research.

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