International Conference on Applied Energy 2019
Aug 12-15, 2019, Västerås, Sweden
Paper ID: 371

A SELF-ADAPTIVE PRINCIPLE OF CURRENT DIFFERENTIAL PROTECTION FOR AC TRANSMISSION LINES IN AC-DC HYBRID POWER GRID

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ABSTRACT

This paper proposes a self-adaptive principle of current differential protection for AC transmission line in AC-DC hybrid power grid. By analyzing the post-fault transient characteristics of inverter-side AC current with commutation failure occurred, the principle is proposed by using the promoted instantaneous energy ratio of currents from line terminals. The principle eliminates the influence of commutation failure by constructing instantaneous energy of terminal currents using trigonometric method. Besides, based on the feature that zero-sequence network of inverter AC system is isolated from DC system, the principle promotes the sensibility in high resistance-ground fault situations by constructing self-adaptive criterion with promoted instantaneous energy of zero-sequence AC current. PSCAD/EMTDC simulations are provided to verify the reliability of proposed principle and the results show that the novel principle is unaffected from commutation failure and is suitable for AC transmission line protection in AC-DC hybrid grid.

Keywords: AC-DC hybrid grid, commutation failure, self-adaptive, current differential protection, promoted instantaneous energy

1. INTRODUCTION

With the rapid development of new energy power generation, high voltage power transmission technology has been widely used in long distance and large capacity power transmission [1-3]. The inverter AC system fault can easily lead to commutation failure in converter, which makes the transient procedure of AC system more complicated [4]. Several malfunction accidents of AC transmission lines protection in AC-DC hybrid grid in recent years show that existing protection is affected by DC commutation failure and new principles need to be proposed [5-6]. Therefore, it is necessary to study the transient procedure of post-fault AC system with commutation failure occurred and propose a new protection scheme to ensure the safety and stability of power grid.

In reference [7], an improved current differential protection method based on current amplitude ratio between terminals is proposed. The method can eliminate the influence of commutation failure, but it is insensitive to high resistance internal fault. Besides, the improved method still depends on full-wave Fourier algorithm, which is affected by rapid current change in post-fault AC current and is of low rapidity. Reference [8] proposes the concept of instantaneous energy, which can describe the transient variation of post-fault current with high accuracy and is suitable for AC-DC hybrid grid protection scheme. However, the calculation of instantaneous energy needs a quarter cycle and can hardly meet the rapidity of protection.

Post-fault transient characteristics of inverter side AC current with commutation failure occurred is analyzed in this paper. To adjust to these characteristics, a novel principle of current differential protection is proposed. By constructing instantaneous energy ratio of currents from line terminals through trigonometric method, the principle eliminates the influence of the commutation failure. The principle promotes sensibility by constructing self-adaptive criterion with promoted instantaneous energy ratio of zero-sequence current. PSCAD/EMTDC simulations are provided to verify the reliability of proposed principle and the results also prove that the principle is unaffected from commutation failures and is suitable for AC transmission line protection in AC-DC hybrid grid.

Selection and peer-review under responsibility of the scientific committee of the 11th Int. Conf. on Applied Energy (ICAE2019).

2. A SELF-ADAPTIVE PRINCIPLE OF CURRENT DIFFERENTIAL PROTECTION BASED ON PROMOTED INSTANTANEOUS ENERGY

2.1 Transient analysis of post-fault AC current

A bipolar AC-DC hybrid system is shown in Figure 1, where i_m is the equivalent AC current at inverter side provided by DC system.

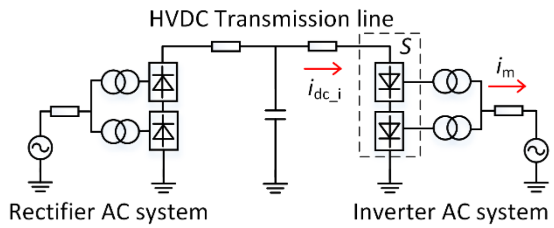


Fig 1 Bipolar AC-DC hybrid system

Based on switching function theory, i_m of each phase can be written as following:

$$i_{m(\Phi)}=S_{\Phi}\cdot i_{dc\_i} \quad \varphi=\text{A,B,C} \tag{1}$$

Where S_Φ is current switching functions of converter; i_{dc_i} is DC current flowing through HVDC transmission line.

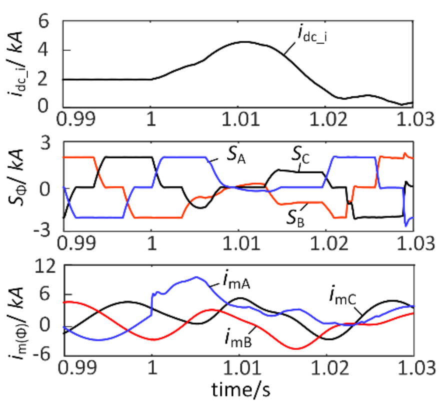


Fig 2 Transistent wave of i_{dc_i}, S_Φ and $i_{m(\Phi)}$ with phase A-ground fault occurred at inverter AC system

Figure 2 is the transient wave of i_{dc_i}, S_Φ and $i_{m(\Phi)}$ after a phase A-ground fault occurred at inverter AC system. During normal operation, i_{dc_i} is constant and valves in each phase commutate correctly, which makes $i_{m(\Phi)}$ vary in sinusoidal waveform. After faults occurred at inverter AC transmission line, AC voltage drop will make i_{dc_i} increase at first and then decrease because of the limitation from control system, which makes $i_{m(\Phi)}$ change in the same regularity according to equation (1). Besides, commutation failure caused by AC fault will change the form of S_Φ, which makes phase relation between $i_{m(\Phi)}$ of each phase disordered, as can be seen in Figure 2.

The invalidation of phase relation indicates that new protection method should base on magnitude relation between each phase, while the fast change of i_{dc_i} makes full-wave Fourier algorithm no more adaptive in extracting magnitude of $i_{m(\Phi)}$ with commutation failure occurred. Therefore, it is necessary to propose a new differential protection method which is based on current magnitude relation between each phase which is adaptive to the fast variation of $i_{m(\Phi)}$.

2.2 Introduction and promotion of instantaneous energy

To adjust to the transient characteristics of post-fault AC system, this paper adopts virtual instantaneous energy in time domain, which is equivalent to time-varying magnitude of a signal, to construct new criterion instead of traditional phasor theory. For a signal $x(t)$, the quadratic sum of two sampling points with a quarter cycle interval is the instantaneous energy of $x(t)$ [8], which can be denoted as $X(t)$:

$$X(t)=x^2(t)+x^2(t-\frac{T}{4}) \tag{2}$$

Where T is cycle of $x(t)$. If $x(t)$ is a sine signal:

$$x(t)=A\sin(\omega t+\varphi) \tag{3}$$

Where A, ω and φ are respectively the magnitude, radian frequency and initial phase of signal $x(t)$. Equation (2) can be expressed as below:

$$X(t)=[A\sin(\omega t+\varphi)]^2+\left[A\sin\left(\omega t+\varphi-\frac{\pi}{2}\right)\right]^2=A^2 \tag{4}$$

As can be seen from equation (4), the instantaneous energy of sine signal $x(t)$ is the square of magnitude.

Equation (4) also shows that the calculation of $X(t)$ needs at least a quarter cycle, which is still too long to adjust to the rapid change of post-fault AC current. Therefore, this paper adopts derivation of $x(t)$ and uses trigonometric method to construct a new signal $y(t)$:

$$y(t)=\frac{x'(t)}{\omega}=A\cos(\omega t+\varphi) \tag{5}$$

And the instantaneous energy $X(t)$ is derived as:

$$X(t)=x^2(t)+y^2(t)=[A\sin(\omega t+\varphi)]^2+[A\cos(\omega t+\varphi)]^2=A^2 \tag{6}$$

Contrasting with equation (4), the promoted instantaneous energy has the same result as original algorithm, while the window is shortened to two sampling points.

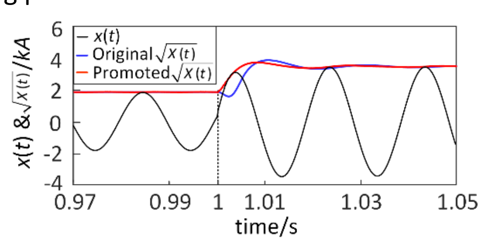


Fig 3 Comparison between promoted instantaneous energy algorithm and original algorithm

To verify the performance of promoted algorithm, the square root of promoted $X(t)$ and original $X(t)$ is contrasted in Figure 3, where sine signal $x(t)$ has a sudden change at 1s to simulate single phase fault.

As can be seen from Figure 3, the promoted algorithm responses at 1s immediately and can reflect the change of $x(t)$ more accurately than original algorithm, which is suitable for the protection of AC-DC hybrid grid with rapid transient process.

2.3 The self-adaptive criterion of current differential protection for AC transmission lines in hybrid grid

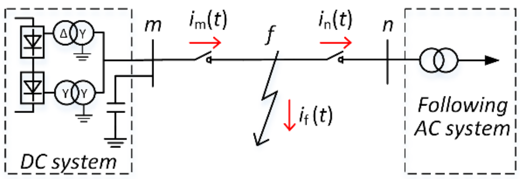


Fig 4 The inverter AC system after fault

Figure 4 is post-fault inverter AC system in AC-DC hybrid grid. $i_m(t)$ and $i_n(t)$ are terminal currents. $i_f(t)$ is fault current. The instantaneous energy of $i_m(t)$ and $i_n(t)$ are respectively $I_m(t)$ and $I_n(t)$. Define the instantaneous energy ratio $R(t)$ as below:

$$R(t)=\frac{\max\{I_m(t),I_n(t)\}}{\mathrm{avg}\{I_m(t),I_n(t)\}} \tag{7}$$

Where the numerator and denominator of $R(t)$ in equation (7) are respectively the bigger one and the average value of $I_m(t)$ and $I_n(t)$. $i_m(t)$ equals to $i_n(t)$ when system is in normal operation or occurs an external fault. Therefore, $R(t)$ equals to 1 for non-fault phases and greater than 1 for phases where internal faults occurred. Based on this, $R(t)$ can be used in new criterion of current differential protection.

However, for high resistance internal faults especially occurred in weak AC system, the difference between $i_m(t)$ and $i_n(t)$ is small, which may decrease the sensibility of new criterion. High resistance faults usually occur as single phase-ground faults and generate zero sequence current $i_{m0}(t)$ and $i_{n0}(t)$ [7]. As can be seen from Figure 4, the transformer connection for bipolar 12-pluse converter are YN/y and YN/d respectively, which guarantees the zero-sequence current in inverter AC system is unaffected by DC system. Therefore, $i_{m0}(t)$ and $i_{n0}(t)$ are effective in promoting the sensitivity of new criterion when high resistance-ground fault occurred. $i_{m0}(t)$ and $i_{n0}(t)$ can be calculated by Clark transform in time domain:

$$i_{p0}(t)=\frac{1}{3}(i_{pa}(t)+i_{pb}(t)+i_{pc}(t)) \quad p=m,n \tag{8}$$

The promoted instantaneous energy of $i_{m0}(t)$ and $i_{n0}(t)$ can be derived from simultaneous equations (6)-(8), which are denoted as $I_{m0}(t)$ and $I_{n0}(t)$ respectively. The instantaneous energy ratio of zero sequence current can be defined as below:

$$R_0(t)=\frac{\max\{I_{m0}(t),I_{n0}(t)\}}{\mathrm{avg}\{I_{m0}(t),I_{n0}(t)\}} \tag{9}$$

Denote $P_0(t)$ as the reciprocal of $R_0(t)$, which equals to 1 when system is in normal status and approximates to zero when severe asymmetrical phase-ground faults occurred. To promote the sensibility of new protection criterion, $P_0(t)$ is used to make a self-adaptive criterion:

$$\begin{cases} R(t)\geq\varepsilon_1 & ,I_0(t)<I_{set} \\ R(t)\geq\varepsilon_2+k(1-P_0(t)) & ,I_0(t)\geq I_{set} \end{cases} \tag{10}$$

Where ε_1 and ε_2 are fixed thresholds, ε_1 should be greater than ε_2 for ε_2 has an additional self-adaptive threshold $k(1\text{-}P_0(t))$; k is the coefficient. I_{set} is the minimum instantaneous energy value of zero sequence current.

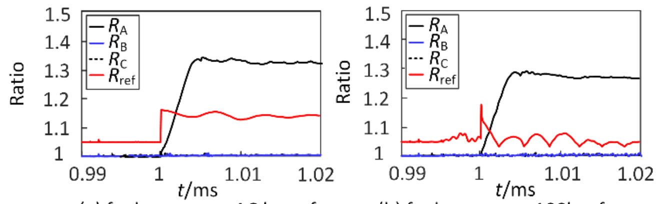
Referring to normal value of $R(t)$, the range of ε_1 and ε_2 should be greater than 1. For symmetrical or ungrounded faults, $I_0(t)$ approximates to zero and I_{set} can be set just above zero. $k(1\text{-}P_0(t))$ approximates to k for severe ground faults and approximates to zero for high resistance-ground faults, which can adjust the threshold of criterion and promote the sensibility of protection. The value of k should range from zero to $(\varepsilon_1\text{-}\varepsilon_2)$.

To eliminate the influence of harmonics, both $R(t)$ and $I_0(t)$ should use the average value of m sampling points. m usually equals to 10 to guarantee the rapidity and filtering effect simultaneously [8].

2.4 Simulation results and analysis

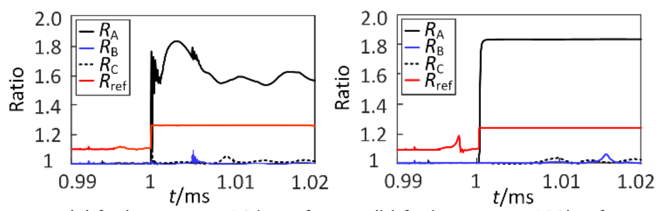
Based on PSCAD/EMTDC simulation software, AC-DC hybrid grid of Figure 1 is built. The length of inverter side AC transmission line is 100km with distribution model. The transmission line parameters refer to actual operation parameters of Huizhou 220kV overhead line in three Gorges-Changzhou DC transmission project [9]. The fault occurs at 1s and lasts for 50ms. The sampling frequency is set as 2.4kHz. ε_1 and ε_2 are set as 1.35 and 1.05 respectively, while I_{set} and k equal to 0.1 and 0.2.

Figure 5 shows phase A-ground fault with 200Ω transition resistance. Faults respectively occur at the inverter AC bus and 100km away from the AC bus, in order to testify the sensitivity of new criterion in high resistance-ground fault. Figure 6 is phase A-mental-ground fault which has the same fault position as Figure 5. Figure 7(a) shows three phase symmetrical fault type with 10Ω resistance, and Figure 7(b) shows phase B-C unground fault type with 20Ω resistance, both of them occur at the midpoint of transmission line. AC faults in Figure 6-7 are severe enough to cause commutation failure in DC converter and are proved by simulations that existing AC transmission line protection tends to malfunction in these situations [7]. $R_{\Phi}(\varphi$=A,B,C) is the promoted instantaneous energy ratio of phase A, B and C. R_{ref} is the right side of equation (10), which represents ε_1 in symmetrical faults and $\varepsilon_2+k(1-P_0(t))$ in asymmetrical ground faults.



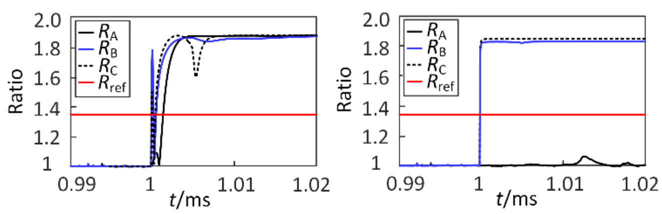
(a) fault occurs at AC bus of inverter side (b) fault occurs at 100km from AC bus

Fig 5 A-ground fault with 200Ω resistance at different position



(a) fault occurs at AC bus of inverter side (b) fault occurs at 100km from AC bus

Fig 6 A-mental-ground fault at different position



(a) FABC fault with 10Ω resistance occurred at line midpoint (b) FBC fault with 20Ω resistance occurred at line midpoint

Fig 7 Three-phase fault and B-C fault at line midpoint

Figure 5-7 show that the self-adaptive principle of current differential protection based on promoted instantaneous energy can operate correctly in various situations. The new method is unaffected by fault position by contrasting group (a) with (b) in Figure 5-6, and it is with high sensitivity with a high resistance-ground fault occurred, which is shown by Figure 5. Fault type and commutation failures have little influence on the new criterion, as can be seen from Figure 6-7.

2.5 Conclusions

Post-fault transient characteristics of inverter side AC current with commutation failure occurred is analyzed and a self-adaptive current differential protection principle based on promoted instantaneous energy is proposed in this paper. Following conclusions are drawn from the research: (1) Commutation failure caused by inverter side AC faults will lead to current change in both fault phases and non-fault phases, and it will make AC current increase at first and then rapidly decrease. These features can lead to malfunction of existing AC transmission line protection. (2) Promoted instantaneous energy algorithm is unaffected from problems in (1) and can reflect transient variation of post-fault signal with higher accuracy and rapidity than original algorithm. (3) Self-adaptive current differential protection principle based on promoted instantaneous energy is unaffected by fault type, transient resistance and commutation failure, which is suitable for main protection of AC transmission line in AC-DC hybrid grid.

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