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A Novel Method to Discriminate Inrush Current from Internal Fault Based on Primary and Second Harmonic Energy

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Abstract: To discriminate inrush from an internal fault is a hot topic, as the inrush current may cause transformer differential protection to malfunction. Compared with Fourier algorithm, prony analysis can get amplitude and attenuation factor of one signal. Thus, prony analysis may have a better effect in discriminating inrush current. First, the energy concept of primary and second harmonic is first proposed based on prony analysis in this paper. Then, according to the study of attenuation characteristics of fundamental and second harmonic, it is found that the ratio of fundamental energy to second harmonic energy has a big difference in inrush current and internal fault. Thus, a novel method based on primary and second harmonic energy is presented. Simulation results of PSCAD prove the method to be correct.

1. INTRODUCTION

As an essential element of electric power systems, the transformer plays a key role in the safe operation of the power system. Many studies have been done on the transformer protection [1-2], but the correct operation rate is not very high. The inrush current is one of the primary factors leading to the mal-operation of differential protection. Therefore, how to distinguish inrush current from internal fault current is an important topic for relay protection.

Ref. [3] proposes a method to identify inrush current using pulse width modulation waveform. *Ref.*[4] presents a new method to identify inrush current based on error estimation. *Ref.* [5] detects transformer inrush based on the sine degree principle of current waveforms. Some other methods, such as correlation coefficient, time differential, and wavelet-based technique are all studied in [6-10].

In this paper, the characteristics of the fundamental and second harmonic in inrush current and internal fault current are analyzed first and an expression of energy for a certain frequency component is defined based on prony analysis. According to the energy, it is found that the ratio of fundamental energy to second harmonic energy in internal fault current is much larger than that in inrush current. So, a novel scheme is proposed to discriminate the inrush current from an internal fault, which is still applicable when the second harmonic is lower than 15% in inrush current or the second harmonic reaches 15% in internal fault current. At last, the proposed method is proved to be reasonable by a large number of simulation results.

2. Basic principle of the novel criterion

2.1 Characteristics of Inrush Currents and Internal Fault Currents

As we all know, there are great differences in amplitude and decay velocity between fundamental and second harmonic when the transformer is under different operating conditions. Compared with fundamental, the amplitude of second harmonic is relatively large in inrush current, and its decay velocity is almost the same as that of fundamental [10]. On the contrary, the amplitude of second harmonic is relatively small in internal fault current, and its decay velocity is much faster than that of fundamental.



According to above analysis, it is found that there are great differences in amplitude and decay velocity of the second harmonic between inrush current and internal fault current. So it facilitates us to discriminate the inrush current from internal fault current if an index involving both amplitude and decay velocity is introduced. In the following section, an expression of energy based on Prony analysis will be introduced, which can be used to identify the inrush current.

2.2 Prony Analysis

There are three main methods in signal processing, including Fourier algorithm, wavelet transform and Prony analysis. The Fourier algorithm is applicable to stationary signal, and it can not provide the local frequency domain information for transient signal. What is worse, the Fourier algorithm is limited by the uncertainty principle, so the signal must be long enough in order to achieve a good result. Although the local information of transient signal can be extracted by wavelet transform, it can not distinguish those components whose frequencies are similar.

Prony analysis is first put forward by Prony in 1795. It is an emerging methodology that extends Fourier analysis by directly estimating the frequency, damping, strength, and relative phase of modal components present in a given signal [11]. Prony analysis is suitable for the transient signal, which can still extract the components even when their frequencies are similar. In addition, the amplitude, phase and attenuation factor can be calculated by Prony analysis. But the computation complexity is small as there is no need to calculate these values in frequency domain.

The Prony analysis uses the linear combination of exponential function to fit the original signal, as shown in (1).

$$x(n) = \sum_{i=1}^p b_i z_i^n, n = 0, 1, \dots, N-1 \quad (1)$$

Where b_i and z_i are complex numbers, which are shown by the following:

$$b_i = A_i \exp(j\theta_i) \quad (2)$$

$$z_i = \exp[(\alpha_i + j2\pi f_i)\Delta t] \quad (3)$$

Where f_i , A_i , θ_i and α_i represent the frequency, amplitude, phase and attenuation factor of the signal. It is worth noting that f_i may not be the integral multiple of the power frequency. From (3), it can be found that all the components in signal are considered to attenuate in Prony analysis. According to [11], f_i , A_i , θ_i and α_i can be calculated by a certain algorithm. For the damped signal, A_i , α_i can be used together to define a concept of energy, as shown in (4):

$$E_i = A_i^2 \sum_{n=0}^{N-1} \left| e^{\alpha_i n \Delta t} \right|^2 \quad (4)$$

Where E_i is the energy for a certain frequency component, Δt is the sampling cycle, N is the sampling number in one cycle.

3. A novel method to discriminate inrush current based on energy

3.1 Formulation of the Novel Criterion

(4) indicates that the energy for a certain frequency component is related to its amplitude and decay velocity. As for amplitude, the value of second harmonic in inrush current is large, while it is small in internal fault current. In terms of decay velocity, [10] points out that the decay velocity of fundamental and second harmonic is nearly identical in inrush current. Nevertheless, the decay velocity of second harmonic is much faster than that of fundamental in internal fault current.

Through the above analysis, it can be seen that the amplitude of second harmonic is large and its decay velocity is almost the same as that of fundamental for inrush current, so their energy have no great difference. However, for the internal fault current, the amplitude of second harmonic is small and its decay velocity is much faster than that of fundamental, so the energy of fundamental is far greater than

that of second harmonic. Thus, the ratio of fundamental energy to second harmonic energy in inrush current is much smaller than that in internal fault current. A new criterion to discriminate the inrush current from internal fault current is formed, as shown in(5).

$$\begin{cases} E_1 / E_2 > C & \text{internal fault} \\ E_1 / E_2 < C & \text{inrush current} \end{cases} \quad (5)$$

Where E_1 and E_2 represent the energy of fundamental and second harmonic respectively, C is the threshold value.

If $E_1/E_2 > C$, it means internal fault current; otherwise, it means inrush current. Considering the second harmonic may be small in inrush current or the second harmonic may be large in internal fault current, and combined with lots of simulation results, setting $C=150$ is reasonable.

3.2 Characteristic of the New Criterion

The second harmonic restraint and the dead-angle principle are widely used to avoid the mal-operation of the differential protection in engineering. Based on the practical experiences, the threshold for second harmonic restraint is often set to 15%. If the second harmonic is less than 15% in inrush current, the differential protection will mal-operate. For the internal fault current, if the second harmonic is larger than 15%, the differential protection will not operate until its amplitude decays below the threshold.

The novel criterion is not only related to amplitude, but also related to decay velocity, so it presents some new features. In some cases, the second harmonic may be small in inrush current, but it will not affect the decay velocity of the second harmonic. So the value of E_1/E_2 is still smaller than C . For the same reason, if the second harmonic is large in internal fault current, the relation $E_1/E_2 > C$ is still meet.

As for the dead-angle principle, the lock angle is difficult to choose and can only be set and modified by real-time tests. For instance, the dead angle may be small or even disappear in symmetry inrush current. However, this situation can not change the decay characteristic of the fundamental and second harmonic, so the novel criterion is not affected by the dead angle.

The logic diagram for the differential operation based on the new criterion is given in Fig.1.

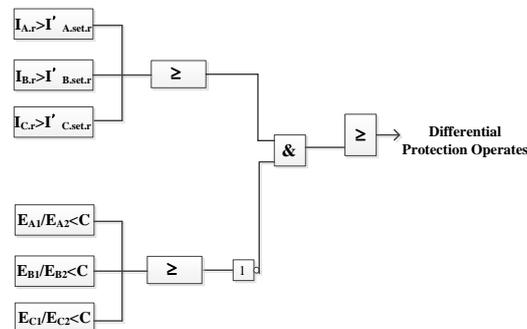


Figure1. Logic diagram of differential protection based on new criterion

$I_{\varphi,r} > I_{\varphi,set,r}$ and $E_{\varphi1}/E_{\varphi2} < C$ are used together to form the novel restraint scheme based on energy, as the dashed box shown in Fig.1. It is worth noting that the setting value of $I_{set,r}$ is very large, so the restraint components are not needed.

4. Simulation verification

4.1 Simulation Model

A simulation model is established based on MATLAB, as shown in Fig.2.

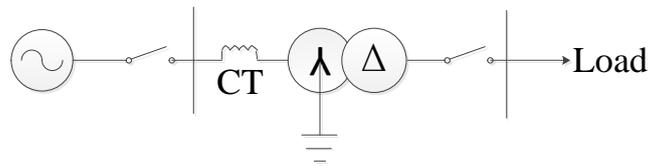


Figure 2. The simulation model based on MATLAB

The ratio of the current transformer (CT) is 1500/5. The sampling frequency is 4000Hz, the frequency of the system is 50Hz, and the fitting number for Prony analysis is 80 for every time computation.

4.2 The Simulation Analysis on Internal Fault Current

Given the following parameters: $A_1=1\text{kA}$, $A_2=0.17\text{kA}$, $\alpha_1=-0.6$, $\alpha_2=-60$ and $N=80$.

Where A_1 and A_2 represent the amplitudes of fundamental and second harmonic in the first data window, α_1 and α_2 are the attenuation factors for fundamental and second harmonic, N is the sampling number in one cycle. It should be noted that the values of α have been proved reasonable in [10].

The data window moves along with the sampling cycle and E_1 and E_2 can be calculated from (4) for each data window, as shown in Fig.3 (a). The blue solid line and the green one represent E_1 and E_2 respectively, the horizontal axis represents the sampling points, the vertical coordinates on the left side represents the value of E_1 , the right one is the value of E_2 . The curve of E_1/E_2 is given in Fig.3 (b). As shown in Fig.3 (b), although the second harmonic is large at the beginning, the criterion for internal fault is satisfied only 1.25ms later. It is worth noting that the second harmonic restraint will be met about 2ms later through calculation. Thus, the proposed criterion can operate faster. In addition, the value of E_1/E_2 is monotonically increasing, as shown in Fig.3 (b), which makes the novel criterion easier to meet with the data window moving forward.

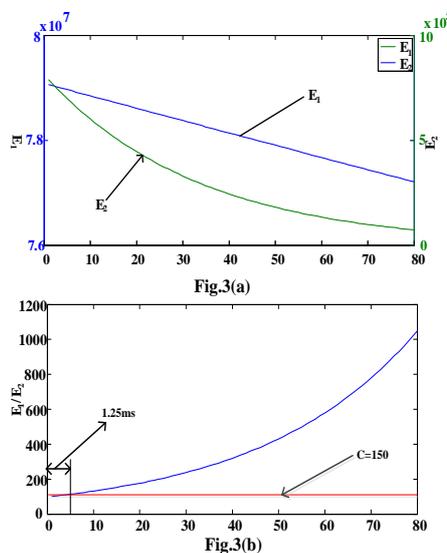


Figure 3. The application of new criterion in internal fault current

Considering the ratio of CT, Table 1 lists the simulation results in the first data window under different faults. From Table 1, it can be seen that the energy of second harmonic is much smaller than that of fundamental, so the value of E_1/E_2 is much larger than C . Through above analysis, it can be observed that if $E_1/E_2 > C$ is satisfied in the first data window, the $E_1/E_2 > C$ continues being met as the data window moves because of the monotonicity of E_1/E_2 . Thus, it can speed up the operation of differential protection.

TABLE 1. Simulation Results for Internal Fault Currents

Operation state			E_1	E_2	E_1/E_2
Faults at Y side	Turn ratio	A0.05	4.8	7.72e-4	6.22e3
		A0.10	12.8	2.00e-4	6.40e4
	Phase to ground	A	1.46	1.38e-4	1.06e4
		B	1.48	1.27e-4	1.17e4
Faults at Δ -side	Turn ratio	A0.1	7.66	4.56e-4	1.58e4

4.3 The Simulation Analysis on Inrush Current

Given the following parameters: $A_1=1\text{kA}$, $A_2=0.12\text{kA}$, $\alpha_1=\alpha_2=-10$ and $N=80$. The data window moves with the sampling cycle and E_1 and E_2 can be calculated from (4), as shown in Fig.4 (a). The values of α is also proved to be reasonable in [10]. It is obvious that the differential protection will mal-operate by using second harmonic restraint. While from Fig.4 (b), it is found that the value of E_1/E_2 is about 70, which is far less than the threshold. So the novel criterion can discriminate the inrush current correctly. Through calculation, the new criterion can still discriminate the inrush current correctly when the second harmonic is reduced to about 8%.

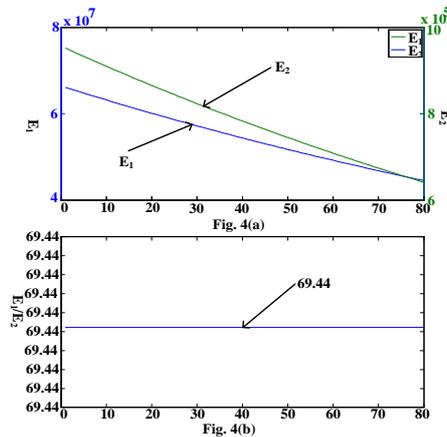


Figure 4. The application of new criterion in inrush currents

Table 2 lists the simulation results for inrush currents at different closing time considering the ratio of CT. In Table 2, “8.62e2/6.27e2” represents that the value of E_1 is 8.62e2 in the first data window, and the value of E_1 becomes 6.27e2 one cycle later. The rest have the same meaning. From Table 2, it is found that the value of E_1/E_2 tends to be stable for each differential current over time and satisfies the new criterion. It is worth noting that i_{db} at No.1 and i_{db} at No.3 are the symmetrical inrush currents.

TABLE 2. Simulation Results for Inrush Current

No.	differential currents	t/s	$E_1(\text{J})$	$E_2(\text{J})$	E_1/E_2
1	i_{da}	0.1	8.62e2/6.27e2	1.18e2/1.09e2	7.31/5.75
	i_{db}		1.37e3/1.20e3	2.97e1/1.56e1	46.13/76.92
	i_{dc}		8.52e2/6.48e2	1.23e2/1.17e2	6.93/5.54
2	i_{da}	0.105	8.62e2/6.26e2	1.19e2/1.09e2	7.24/5.74
	i_{db}		1.37e3/1.19e3	2.97e1/1.87e1	46.13/63.64
	i_{dc}		8.51e2/6.48e2	1.22e2/1.16e2	6.98/5.59
3	i_{da}	0.11	8.61e2/6.28e2	1.19e2/1.08e2	7.24/5.81
	i_{db}		1.36e3/1.21e3	2.96e1/1.55e1	45.94/78.06
	i_{dc}		8.53e2/6.49e2	1.24e2/1.18e2	6.88/5.50
4	i_{da}	0.115	8.63e2/6.26e2	1.19e2/1.09e2	7.25/5.74
	i_{db}		1.36e3/1.19e3	2.97e1/1.87e1	45.79/63.64
	i_{dc}		8.51e2/6.48e2	1.22e2/1.16e2	6.98/5.59

Through the simulation results, it is found that the proposed criterion can distinguish inrush current from the internal fault current correctly. Particularly, when the second harmonic is relatively large in fault current or relatively small in inrush current, the novel criterion can be still applicable.

5. Conclusion

A novel criterion based on energy is put forward in this paper in order to discriminate the inrush current from the internal fault faster and more reliably. The new method has many advantages:

- (1) The Prony analysis is less affected by the transient component compared with Fourier algorithm, so it has more accuracy in the transient process.
- (2) The energy is a function of amplitude and decay velocity, so it has higher operation speed compared with the second harmonic restraint when the second harmonic is large in internal fault. In addition, the new criterion can still identify the inrush current even when the second harmonic is small.
- (3) The novel criterion is not affected by the dead angle, so it can discriminate the symmetric inrush current.
- (4) Overall, the proposed criterion is superior to the conventional restraint schemes.

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