METHOD OF ZERO-CURRENT INCREMENTAL QUANTITY BASED ON WAVELET ANALYSIS OF SINGLE-PHASE-TO-GROUND FAULT LINE SELECTION IN RESONANT GROUNDED SYSTEM

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ABSTRACT

This paper puts forward and explains the application principle of the method of zero-sequence current incremental quantity, which is often used for single-phase-to-ground fault line selection in resonant grounded system. But, when some intermittent earth arc occurs, it could make mistake with that method used without any consideration. This paper induces the wavelet analysis into this method, in which the control system could identify the earth fault styles and self-adapt to different line selection methods such as the method of zero-sequence current incremental quantity or transient component methods. The fault line selection performance would be greatly improved with its introduction into the line selection equipment.

1. INTRODUCTION

In the resonant grounded system, because of the system capacitive current compensated by arc-suppression coil， when the single-phase-to-ground fault occurs, the zero-sequence current of all lines become weaker, and then no longer meet the characteristic of the method of group-comparing amplitude and phase. Thus the signal system is more sensitive to various disturbances, such as the three-phase imbalance of CT, which often makes the active component methods fail in the fault-line selection [1, 2]. Through the short-term adjustment of the coil current, people then put forward the method of zero-sequence current incremental quantity in which only the zero sequence current in the fault-line would get the incremental quantity, and then the fault-line would be selected out [1]. Since the method of zero-sequence current incremental quantity put forward, it has been widely applied in the resonant grounded system and greatly increased the accuracy of fault-line selecting in resonant grounded system. But the field test and field operation data show that the method of zero sequence current incremental quantity isn't a panacea. First, the amount of incremental quantitys generated would always take some time, which makes this method only apply to permanent earth faults, and is powerless to the instantaneous or short-time ground faults. Second, when some intermittent earth arc occurs, it could make mistake with that method used without any consideration; however, with a wealth of transient information in the intermittent arc fault [3, 4], the use of the transient method to select fault line would be satisfied. This paper induces wavelet analysis into the control system, with which it could identify the ground fault styles and self-adapt to different line selection methods such as the method of zero-sequence current incremental quantity or transient component methods.

2. PRINCIPLE OF ZERO-CURRENT INCREMENTAL QUANTITY

As shown in Fig.1, C_i $(i=1\sim4)$ indicate capacitance to earth of the lines. Supposed that the arc-suppression coil is respectively set at L_1 and $\left(L_1+L_2\right)$ before and after the adjustment, the zero-sequence voltage is respectively at $\dot{U}_{01}$ and $\dot{U}_{02}$, with the zero-sequence current of the lines respectively at $\dot{I}_{i1}$ $(i=1\sim4)$ and $\dot{I}_{i2}$ $(i=1\sim4)$.

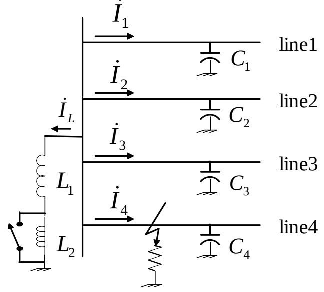


Fig1. Equivalent circuit before and after the adjustment of arc-suppression coil

When some single-phase-to-ground fault occurs in line4, and before the adjustment of the arc-suppression coil, the zero-sequence currents of the non-fault line and fault line are respectively as follows:

$$\begin{cases}\dot{I}_{i1}=j\omega C_i\dot{U}_{01}\\ \dot{I}_{41}=-\sum_{i=1}^{3}\dot{I}_{i1}+\dot{I}_{L1}\end{cases}\qquad(1)$$

And after the adjustment of the arc-suppression coil, they are respectively as follows:

$$\begin{cases}\dot{I}_{i2}=j\omega C_i\dot{U}_{02}\\ \dot{I}_{42}=-\sum_{i=1}^{3}\dot{I}_{i2}+\dot{I}_{L2}\end{cases}\qquad(2)$$

Then, it can be deduced that: $\dot{I}_{i1}=\dot{I}_{i2}\dot{U}_{01}/\dot{U}_{02}$ (3)

From the above formula, it is found out that when the zero-sequence currents of all lines are converted into the same zero-sequence voltage level such as $\dot{U}_{02}$, the incremental quantity of non-fault lines and fault line can be deduced as follows:

$$\begin{cases} \Delta \dot{I}_i = 0 \qquad (i = 1,2,3) \\ \Delta \dot{I}_4 = \dot{I}_{L1} - \dot{I}_{L2} = \dfrac{\dot{U}_{01}}{j\omega L_1} - \dfrac{\dot{U}_{02}}{j\omega (L_1 + L_2)} \end{cases} \qquad (4)$$

Considering the zero-sequence voltage converted to the same level, it can be seen from the above equation that the adjustment of arc-suppression coil would only lead to the change in the zero-sequence current of the fault line. On this basis, the following criterion is constructed:

$$\left|\Delta \dot{I}_i\right| = \left|\dot{I}_{i2} - \dot{I}_{i1} * \dot{U}_{02} / \dot{U}_{01}\right|, \text{ i=1}\cdots\text{n} \qquad (5)$$

The line which makes $\left|\Delta \dot{I}_i\right| \neq 0$ is selected as the fault line; and if all the lines make $\left|\Delta \dot{I}_i\right| = 0$, some bus fault may be selected out. This is the principle of the method of zero-sequence current incremental quantity [1].

3. METHOD OF ZERO-SEQUENCE CURRENT INCREMENTAL QUANTITY BASED ON WAVELET ANALYSIS

The proposal of zero-sequence current incremental quantity method makes the earth fault line selection of permanent stable fault no longer a problem, which greatly improves the fault line selection accuracy in resonant grounded system. But the field test and data show that the method of zero-sequence current incremental quantity isn't a panacea, for example, when the development of the fault is unstable, it may bring significant affect to the implementation of current incremental quantity method. When the earth fault is a strongly intermittent arc fault, the zero-sequence current variation is very likely to be submerged by the arc-current, due to its large energy, which may also lead to wrong selection. When the fault is some weak intermittent arc, in which the fault may be seen as disappeared during the arc extinguished; then the zero-sequence current in all the lines may show a decline in the process of decay, in pace with the zero-sequence voltage [4], which show some characteristic of bus-ground fault. So in this case, if method of zero-sequence current incremental quantity is still in use, some bus-ground fault is most likely to be selected out, which is unacceptable. So that, the fault-line selection algorithm should be able to identify the characteristics of all these faults, avoiding the indiscriminate use of zero-sequence current incremental quantity method in these cases, thus avoiding the alignment failed.

3.1 Characteristics Recognition of Intermittent Arc Fault

The intermittent arc earth fault, whether it is strong or weak intermittent arc, is generally caused by damage to the insulation, which is a repeated process of breakdown, recovery, re-breakdown, and recovery again, which caused a large transient component with the frequency ranged between 300Hz and 2500Hz [3]. These high frequency components exist in the ongoing process of failure, which is located in the region traditionally regarded as the "steady state" signals, which make difficulties for fault line selection on the one hand, but make it possible for the implementation of transient signal line selection criterion in "steady-state" on the other hand. It should be noted that, the "steady state" signal pointed out in this paper does not mean a stable sine wave signal, but all signals from the time 2 cycles after the failure occurs till the end of the failure. If we can identify such a phenomenon of intermittent arc earth in the continuous process of the failure, then we can not only use transient criterion for continuous line selection, but avoid the mistakes in the blind implementation of method of the zero sequence current incremental quantity.

To solve this problem, it is the key to extract the fault signal characteristics of intermittent arc earth fault. Based on wavelet analysis theory, this paper constructs the line selection criterion, with db6 wavelet function applied as the analysis tool for the characteristics extraction.

On the moment that the intermittent arc fault occurs, zero-sequence voltage and current will get an incremental quantity, in which high-frequency oscillatory component will appear some incremental quantity at the corresponding point on each wavelet scale. In phase-to-ground fault, zero-sequence voltage generated is relatively larger, with a rather high signal to noise ratio. So, the zero-sequence voltage signal is selected as the base to find out the incremental quantity of wavelet coefficients, in which the appropriate wavelet scale should be selected. For an application, it is important not only to separate the useful signal as wide as possible from a given original signal with a limited bandwidth, but also no low frequency components of the load released into the details of the components. And it also requires less decomposition levels to reduce computation. So, the second scale wavelet coefficient is adopted in this paper. With the sampling frequency f_s at 5kHz, the bandwidth of sampling is 0 ~ 2500Hz. After 2 levels of wavelet decomposition, we can obtain wavelet detail coefficients in different frequency bands. The frequency band division of the wavelet coefficient is shown in Figure 2.

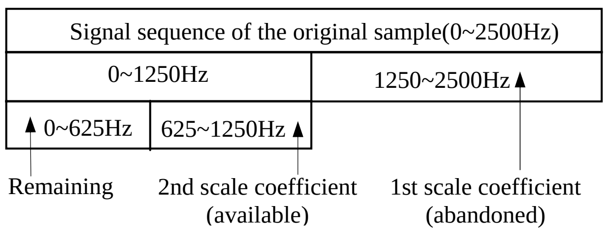


Fig. 2 Frequency division after wavelet decomposition

The transition resistance of the intermittent arc earth fault is generally small, in which the wavelet scale coefficient of the zero-sequence voltage will have significant changes. So, in this paper the second scale wavelet coefficient is selected to get some determined threshold d_{ft} for the fault characteristic recognition. After the wavelet decomposition of the fault signal, and when the wavelet coefficient on the second scale appears bigger than the threshold d_{ft} , it means that this signal is no longer stable one, but some of intermittent arc earth fault. It is worth mentioning that, due to the non-incremental quantity of line voltage during the single-phase earth fault, some defects of data acquisition card could be captured through wavelet decomposition to line voltage at the same time, with which interference from defects of data acquisition card could be excluded and the performance of fault line selection would be greatly improved.

3.2 Transient Method of Fault-line Selection for Intermittent Arc Earth Fault

As pointed out before, according to the recorded field fault data analysis, transient or steady fault process is not strictly distinguished by time, but distinguished by the fault style. Some transient process may often occur in the "steady state". For intermittent arc earth fault, we can capture transient process several times during continuous process of the fault. The wavelet analysis is a time-domain and frequency-domain analysis, which has good localization properties not only in the time domain but in frequency domain, and is particularly suitable for the detection of the occurrence and its time of transient incremental quantitys. Accordingly, a variety of transient line selection criterion could be used in this signal when intermittent arc earth fault occurs, with which the adaptive line selection can be implemented. The transient line selection criterion includes wavelet-analysis method [5] and the first-half wave method [6], etc. And the method of zero sequence current incremental quantity could be used for the relatively stable signals.

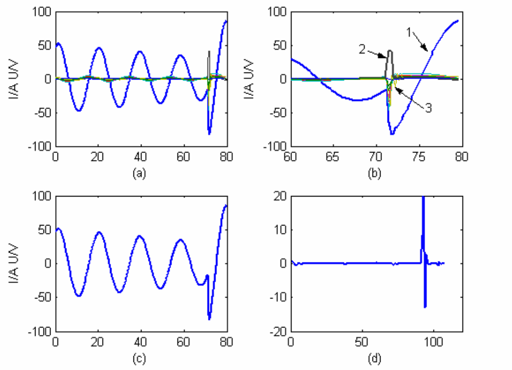
3.2 Algorithm Flow

This paper has discussed how to determine whether there is an intermittent arcing earth fault by the wavelet coefficient decomposed at the second scale by wavelet db6, and whether the method of zero-sequence current incremental quantity is suitable. By lots of comparison, this paper proposes that the wavelet coefficient threshold d_{ft} should be selected as 10. That is to say that when wavelet coefficient at the second scale of zero-sequence voltage, appears to be bigger than the threshold, it shows that there is some characteristic of the intermittent arc, in which the method of zero sequence current incremental quantity should not be suitable, but the transient method such as transient wavelet method or first-half wave method could bring us good results; Otherwise, if the wavelet coefficients is less than the threshold, it means that some stable fault occurs(dead earth or stable arc earth), and it is suitable for zero sequence current incremental quantity method, which gives line selection system good adaptive capability.

4. FIELD TEST VERIFICATION

Various types of ground fault tests have been carried out in the 10kV power grid, including intermittent arc earth fault, and results of which show that indiscriminate application of zero-sequence current incremental quantity method in intermittent arc earth fault, without any fault type identification, would bring great probability to the wrong choice. The method of zero-sequence current incremental quantity based on wavelet analysis described in this paper possess good adaptive performance, which further increases the success rate of fault line selection in the resonant grounded system.

Experimental verification 1: a field test in 10kV power grid, with the fault type as metal intermittent arc earth fault, in which the intermittent arc was set up by the insulation breakdown between two metal electrodes on the insulators.

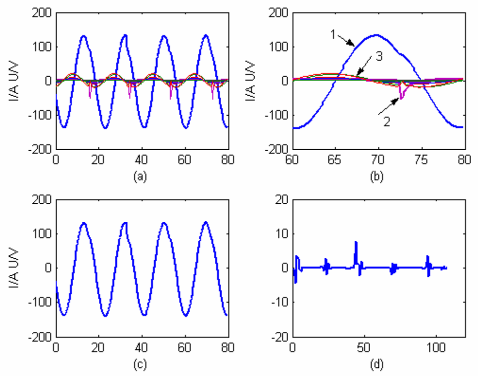


$1 \rightarrow U_0$; $2 \rightarrow I_0$ *of fault line;* $3 \rightarrow I_0$ *of non-fault line*

Fig 3 Waveform of fault zero-sequence voltage, current and wavelet coefficient of fault voltage in case 1

Figure 3(a) indicates the steady waveform of fault zero-sequence voltage and zero-sequence current of the lines, in which the transient waveform of the previous failure is not shown in the diagram. It can be seen that the zero-sequence fault voltage has been declining before t = 71ms, which is in the recovery process after the last insulation breakdown. Here, the steady state line selection criterion does not suitable, with the zero sequence current of all the lines reflecting no characteristics of the ground fault. The re-breakdown of insulation at t = 71ms around makes the fault re-establish, but soon the insulation resumed and the earth arc extinguished again, in which the zero sequence voltage will repeat the attenuation process after its rising till the next insulation breakdown. Figure 3(b) shows the enlargement of the re-breakdown of fault, while figure 3(c) shows the waveform of zero sequence voltage. Figure 3(d) shows the detail component of the zero-sequence voltage at the second scale wavelet-decomposed with the algorithm proposed in this paper, in which a strong incremental quantity can be detected. And this is what we need to extract from the fault signal of the intermittent arc, which indicates that some intermittent arc earth fault took place at that moment, and method of zero-sequence current incremental quantity is not suitable in the fault line selection. The result showed that, the wavelet methods and first-half wave method select the correct fault line, but method of zero sequence current incremental quantity had chosen bus-ground fault, which is discarded by the system. And the adaptive fault line selection result is correct.

Experimental verification 2: a field test in 10kV power grid, with the fault type as metal continuously stable arc earth fault, in which the compensation of the arc-suppression coil was not very good.



$1 \rightarrow U_0$; $2 \rightarrow I_0$ *of fault line;* $3 \rightarrow I_0$ *of non-fault line*

Fig 4 Waveform of fault zero-sequence voltage, current and wavelet coefficient of fault voltage in case 2

Figure 4(a) indicates the steady waveform of fault zero-sequence voltage and zero-sequence current of the lines, in which the transient waveform at the failure occurred is not shown in the diagram. It can see that this is an arc earth fault and the insulation breakdown happened each cycle, which is some relatively stable metal arc earth fault. Figure 4(b) shows the enlargement of the re-breakdown of fault, while figure 4(c) shows the waveform of zero sequence voltage. Figure 4(d) shows the detail component of the zero-sequence voltage at the second scale wavelet-decomposed with the algorithm proposed in this paper, in which no strong incremental quantity can be detected, despite the rapidly changing in the zero-sequence current, which indicates that some continuously stable arc earth fault took place at that moment, and method of zero sequence current in fault line selection select the correct fault line. And the adaptive fault line selection result is correct.

5. CONCLUSIONS

This paper analyzes the problem of line selection of single-phase-to-ground fault in resonant grounded system, describing the application principle of the widely adopted method of zero sequence current incremental quantity. It is pointed out that this method isn't a panacea, which would lead to failure when the intermittent arc earth fault occurred. Based on the wealth of transient information generated by this fault, this paper proposed the method of zero sequence current incremental quantity based on wavelet analysis, in which wavelet coefficient of zero-sequence voltage is utilizing to recognize the steady ground fault, continuously steady arc earth fault and intermittent arc earth fault. In this algorithm the method of zero-sequence current incremental quantity is suitable for the former two faults, but the intermittent arc earth fault is appropriate to adopt the transient method. The field tests show that the adaptive algorithm could greatly improve the accuracy rate of fault line selection in the resonant grounded system.

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BIOGRAPHIES

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