

Study of Distributed Grounding Line Selection Application Based on GOOSE

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SUMMARY

This paper introduces a distributed grounding line selection method based on GOOSE, which is also implemented in the protection device. In the small current grounding system, when single phase grounding fault happens, fault current is quite small due to the switching of arc-extinguish coil decreasing the capacitive current, which makes it difficult to recognize the fault line using steady-state determination method. By employing wavelets decomposition methodology, discriminating the high frequency component of transient current and recognizing the grounding line rapidly and accurately can be achieved. With exploiting GOOSE of station control layer to share information among several devices, wavelets method is utilized to judge grounding line locally. The algorithm is verified through MATLAB simulation and the microprocessor-based protection embedded in the algorithm is validated in RTDS test. The scheme presents great application prospects and is worth popularizing.

KEYWORDS

distributed; grounding line selection; wavelets analysis; GOOSE.

1. Introduction

In China, the low-medium voltage power system usually adopts small current grounding, which means the neutral point is not grounded or grounded through arc-extinguish coil. In this way, when single-phase grounding fault happens, zero-sequence current cannot complete the circuit and the fault current mainly consists of capacitive current which is quite small. The power system can keep operating for 1~2 hours because the three phase voltage is still symmetric. Especially for the arc-extinguish coil grounding system, the arc will be extinguished automatically, which is significant to reduce power failure frequency. The small current grounding system has high reliability, but single-phase grounding will lead to high over-voltage, which is dangerous in the long run. Hence a permanent single-phase grounding fault should be immediately recognized and the corresponding line must be cut off. When single phase is grounding in the small current system, the fault current is too small to discriminate the fault line, especially in the condition of arc-extinguish coil grounding the coil compensates the line capacity current resulting in the current of fault line approximating to that of normal line, which makes the fault feature less obvious. In recent years, there are several methods solving this problem including phase comparison, amplitude comparison, transient signal analysis etc. However, due to the minuteness of fault current and the sampling precision of protection device, the grounding line selection cannot be very accurate.

Wavelets analysis is a powerful tool to analyse compactly supported mutation waveforms, and is appropriate to decompose the transient fault current at initial stage accordingly being the research focus of grounding line selection. In addition, exclusive grounding line selection devices are generally implemented in substation, adopting distributed grounding line selection method can effectively exploit existing feeder protection, which can be only updated software to satisfy the demand for selecting grounding line, besides the cost is reduced.

This paper employs wavelets analysis methodology to decompose the transient fault current, and station-layer GOOSE communication technology is also utilized to achieve data sharing among several devices. Distributed grounding line selection algorithm finds the largest wavelets energy and judges the wavelets direction to determine the fault line and trip locally. MATLAB simulation and RTDS test reflect economic and practicality of the method, which is also worth marketing.

2. Fault Analysis of Small Current Grounding System

Fig.1 shows the typical structure of small current grounding system, three feeders adopts PI type equivalent model, switched arc-extinguish coil is installed at the low voltage side of transformer and feeder protection is installed at the bus side of feeder. In Fig.1, single-phase grounding fault happens at 'F' point in feeder 2, and dotted arrow denotes the direction of zero-sequence current namely the fault line is from line to bus and the non-fault line is opposite.

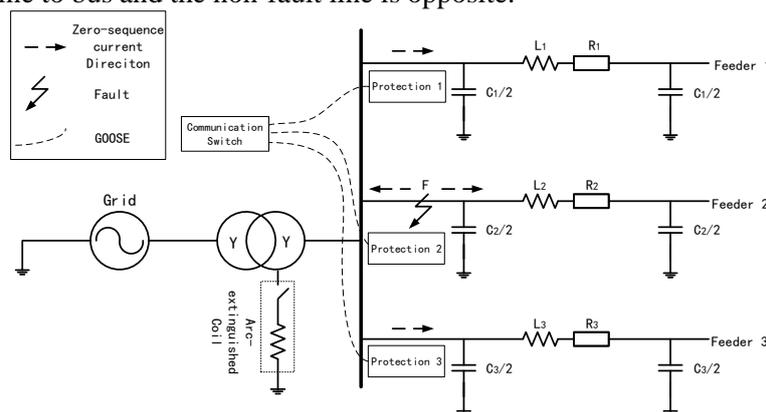


Fig.1 Typical structure of small current grounding system

In the condition of steady state, when single-phase grounding fault happened, the fault current is mainly comprised of capacity current. If the capacity current is over 10 A, arc-extinguish coil should be injected to compensate the capacity current, and the fault current becomes inductive which makes the grounding line selection difficult. Therefore the method to solve grounding line selection issue is chiefly focused on the recognition of transient current.

3. Wavelets Analysis of Transient Fault Components

3.1 Analysis of transient fault current

At the early stage of fault, although arc-extinguish coil is implemented, only base frequency component of capacity current can be compensated thus there exists plenty of harmonics. So high frequency component of current can be utilized to select the fault line. Based on Fig.1, it is obtained that after the coil is put into the system the zero-sequence current i_0 flowing through fault line consists of capacity current i_C and inductive current i_L :

$$i_0 = i_C + i_L \quad (1)$$

$$i_C = I_{Cm} \left[\left(\frac{\omega_f}{\omega} \sin \varphi \sin \omega_f t - \cos \varphi \cos \omega_f t \right) e^{-t/\tau_C} + \cos(\omega t + \varphi) \right] \quad (2)$$

$$i_L = I_{Lm} [\cos \varphi e^{-t/\tau_L} - \cos(\omega t + \varphi)] \quad (3)$$

In equation (2) and (3), I_{Cm} is the amplitude of capacity current, ω_f is the angular velocity of transient free oscillation component, τ_C is the time constant of capacity loop, I_{Lm} is the amplitude of inductive current, ω and φ are the system angular velocity and voltage initial phase angle respectively, τ_L is the time constant of inductive loop.

Based on equation (2) and (3), i_C and i_L contain transient damping component and steady state AC component, whereas τ_C is smaller than τ_L thus i_C is damping more slowly than i_L . It can be concluded that at the early stage of fault zero-sequence current is the dominant component and the current of fault line is obviously larger than that of non-fault line. In addition, the current of fault line equals the sum current of other lines. Nevertheless the transient fault current is non-stationary signal, which is hard to be decomposed by conventional Fourier decomposition, wavelets analysis is appropriate for solving the issue.

3.2 Wavelets Energy Methodology

Wavelets transform is taken as excellent tool to analyse the signals with significant local characteristics. Through decomposing the waveforms with scale and wavelets function, transient component is analysed in multi-resolution. Taking dyadic wavelet as example, scale and wavelets function is presented as follow:

$$\varphi(t) = \sqrt{2} \sum_{n=-\infty}^{+\infty} h(n)\varphi(2t-n) \quad (4)$$

$$\psi(t) = \sqrt{2} \sum_{n=-\infty}^{+\infty} g(n)\varphi(2t-n) \quad (5)$$

In equation (4) and (5), $\varphi(t)$ is scale function and $\psi(t)$ is wavelets function, $h(n)$ and $g(n)$ are wavelets decomposition filter coefficient. Wavelets decomposition process is equal to use high-pass filter and low-pass filter to decompose the signal repeatedly afterwards multi subdivision frequency band is formed. The process of 3 levels wavelet packets is showed in Fig.2:

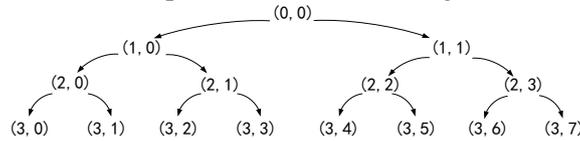


Fig.2 the process of wavelets packets decomposition

In Fig.1, the signal is decomposed into 3 levels namely 8 frequency bands from (3,0) to (3,7) which denotes frequency from low to high, and each frequency band includes wavelets energy. Following steps are proposed to determine the fault line:

- Compare sum of high-frequency wavelets energy of each feeder and find the largest one, in which the frequency band of the largest wavelets energy is chosen to be feature frequency band.
- Then compare the wavelets coefficient direction of feature frequency band with that of other feeders, namely one feeder can trip only if it possesses both the largest wavelets energy and reverse current direction.

Moreover, in order to reduce the calculation burden in normal operation condition, zero-sequence voltage is also required to start algorithm.

4. Distributed Grounding Line Selection Based on GOOSE

From section 3, fault line can be discriminated rapidly based on wavelets decomposition, but centralized grounding line selection protection device is required, which costs much and needs laying cables. Distributed grounding line selection protection device based on GOOSE is proposed to replace the conventional one. Original feeder protection devices only need be updated software to run the algorithm, meanwhile GOOSE exploits existing station-layer MMS network to exchange information without laying new communication lines which reduces construction cost remarkably.

The wavelets analysis scheme is showed in Fig.3:

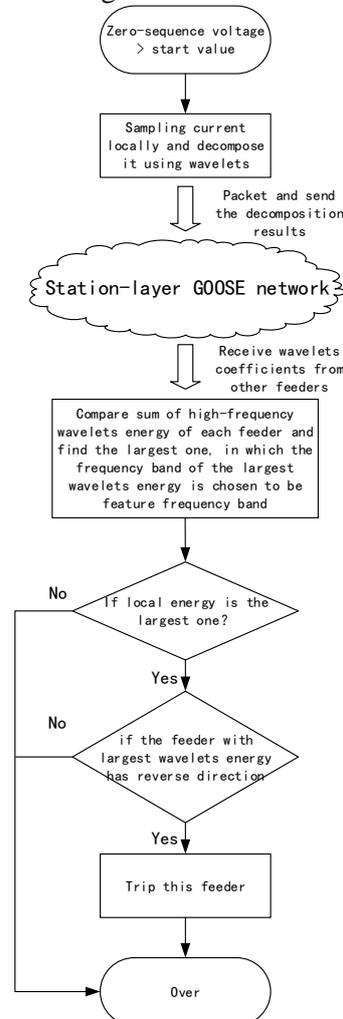


Fig.3 Grounding line selection method based on GOOSE

In Fig.3, distributed grounding line selection algorithm is based on section 3.2, after algorithm of any devices starts wavelets decomposition coefficients are calculated and packed transferring to station layer network through MMS network, any other devices can receive the coefficients. Acquiring the data of all feeders, protection devices can determine whether trip locally based on steps a) -b) in section 3.2.

Furthermore, data synchronization and network congestion are considered:

- a) Data synchronization: when there exists multiple feeders, transferred wavelets coefficients are likely to have time delay. Wavelets analysis decomposes the sampling values in a certain interval, GOOSE transfers data immediately after data changes and sends another frame in $T_1=2\text{ms}$. The presented algorithm in this paper can tolerate certain data transfer time delay, section 5 will investigate the issue.
- b) Network congestion: network flow generated by GOOSE is very small. According to transfer mechanism GOOSE only sends heartbeat packets whose interval T_0 is usually 5s in normal condition. After waveform mutation happens, GOOSE employs 2-2-4-8 mode to send information. Generally speaking, message flow generated by one device exceeds no more than 0.1 MB/s. If

there exists 30 devices, the message flow is less than 3MB/s which can be tolerated by most switches. Regarding the scenarios requiring more reliable protection, dual-network GOOSE can be used to enhance stability.

Fig.1 illustrates network structure of the proposed scheme, in which every feeder protection communicates through station-layer switch. Calculation of wavelets decomposition is equal to $O(N\log N)$ which is the same level to Fourier algorithm and most microprocessor-based protection devices can readily meet requirement. Besides every device packets and sends the wavelets coefficients rather than sampling values hence every device only computes its own wavelets coefficients considerably to reduce calculation burden. In the distributed system, all the program in the devices are identical and there is no central node, if any device quits others only needs turning off the GOOSE receiving soft plate and the algorithm will be not affected.

5. Simulation

The typical distributed grid structure with arc-extinguished coil in Fig.1 is taken to validate the proposed algorithm. Feeder protection injected in distributed grounding line selection algorithm are installed at the top of three feeders and connected by a switch through which wavelets coefficients are transferred. The voltage level of transformer is 110/10kV and the arc-extinguished coil inductor L and resistor R are calculated as follow:

$$L = \frac{1}{3(1+p)(2\pi f_N)^2 l C_0} \quad (6)$$

$$R = 0.03 \cdot (2\pi f_N) \cdot L \quad (7)$$

In equation (6) and (7), f_N is system frequency 50Hz, p is compensation ratio which is usually between 5% to 10%, l is the line length, C_0 is the zero-sequence capacity of unit length line. Three feeders are all 15km and the line parameters are displayed in Tab.1:

Tab.1 Line parameters

Sequence	Resistance Ω/km	Inductance mH/km	Capacitance $\mu\text{F}/\text{km}$
positive, negative	0.17	0.38	0.10
zero	0.23	1.72	0.06

The zero-sequence voltage start value (primary value) of the algorithm is 1kV, arc-extinguished coil is always put in. Considering that actual line fault is usually grounding through resistor, grounding resistor $R_f=200\Omega$ is set in the simulation. The sample frequency of devices is 4.8kHz, wavelets decomposition adopts db10 and is decomposed to 4 layers which generates 16 frequency bands denoted as (4,0)~ (4,15) from low to high.

5.1 Simulink Validation

Simulink is firstly employed to verify the proposed algorithm and the impact of different communication delay is investigated. Delay module of Simulink is applied to simulate the time delay caused by GOOSE and communication delay is denoted as t_{delay} . Simulation time is 0.6s.

5.1.1 No time delay

In Fig.1, B phase grounding fault happens at 100ms in F point with no time delay namely $t_{\text{delay}}=0\text{ms}$. Simulation result is that the algorithm determines that feeder 2 is the fault line at time 103.44ms. The proposed algorithm in this algorithm transfers wavelets coefficients not zero-sequence current. However in order to directly demonstrate the communication delay impact on algorithm, the zero-sequence current of corresponding delay is depicted in the Fig.4:

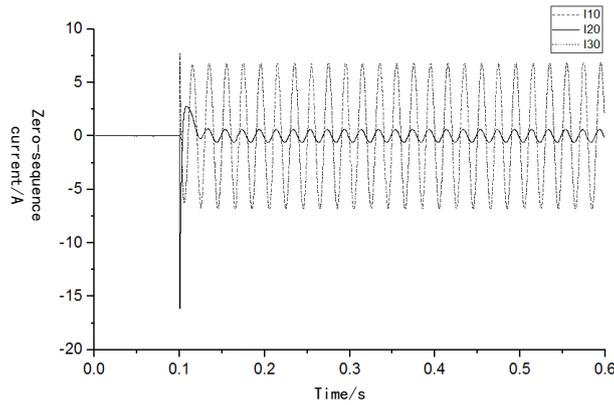


Fig.4 zero sequence current waveforms sampled by feeder 2 protection device
 From Fig.4, after grounding fault happens at 0.1s there is obviously transient process. Due to the over compensation of arc-extinguished coil zero-sequence current is quite small and inductive, but by analysing transient process wavelets decomposition methodology can still discriminate the fault line. The wavelets energy of all three feeders are depicted in Fig.5:

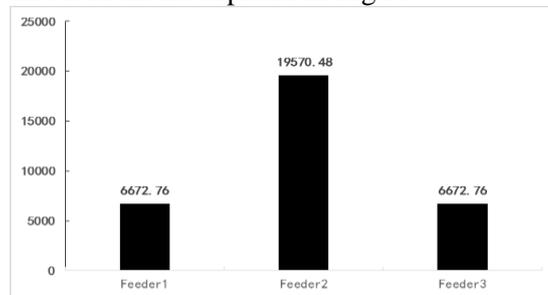


Fig.5 Wavelets energy of all 3 feeders

From Fig.5, it is concluded that the energy of feeder 2 is far larger than other feeders. And energy percentage of each frequency band is showed in Fig.6:

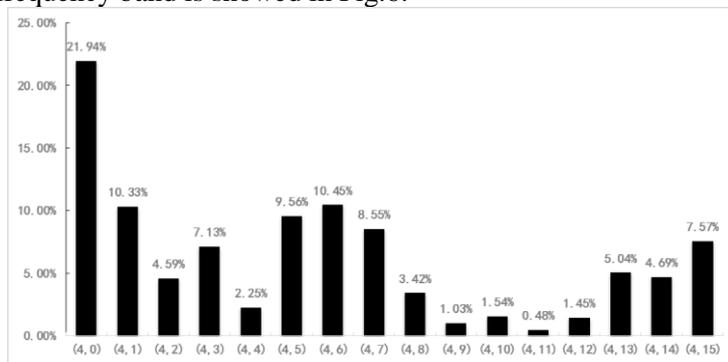


Fig.6 Energy percentage of each frequency band in feeder 2

From Fig.6 energy percentage of frequency band (4,0) is largest therefore it is chosen to be the feature frequency band and those of other feeders are in opposite direction thus feeder 2 is fault feeder.

5.1.2 Small time delay

In this section the impact of communication delay on wavelets algorithm caused by GOOSE is investigated, and the transmission time delay between feeders is set to $t_{\text{delay}}=3\text{ms}$ with the other conditions remaining unchanged. The simulation result is that proposed algorithm can still discriminate the fault feeder accurately and zero-sequence current waveform of three feeders sampled by feeder 2 is showed as follow:

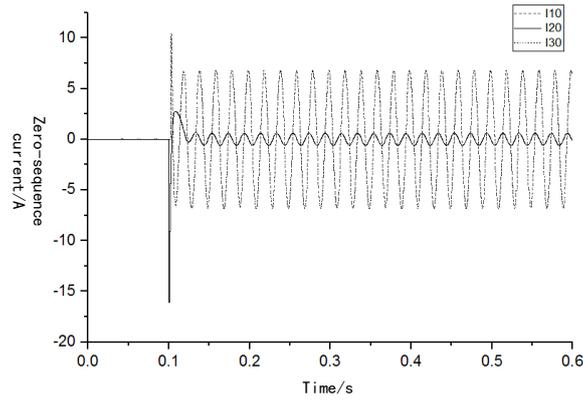


Fig.7 Zero-sequence current waveform of three feeders sampled by feeder 2 with 3ms delay
 In Fig.7, transmission delay results in phase delay of zero-sequence current between feeders 1, 3 and feeder 2, the discrete sampling waveform of zero-sequence current between 100 to 110 ms is depicted in Fig.8:

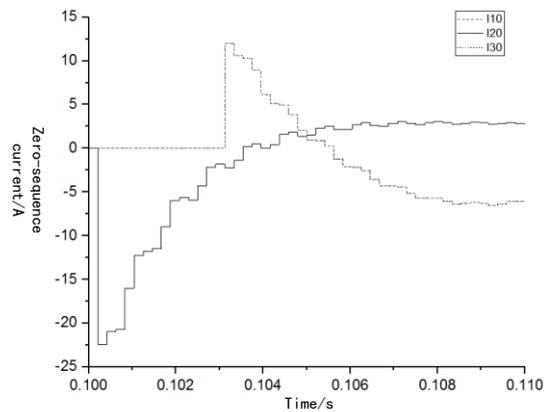


Fig.8 Discrete sampling locally enlarged of zero-sequence current

From Fig.8 it is illustrated that although there exists nearly 3ms peak shifting wavelets algorithm can still determine fault feeder accurately. The zero-sequence current peak of feeder 1 and 3 in Fig. 7 is different from that in Fig. 4 because transient zero-sequence current waveform is so steep that different sampling time leads to different current value. This can be overcome by enlarging sampling frequency. In this simulation, sampling frequency is 4.8kHz which is enough for wavelets algorithm.

5.1.3 Large time delay

Continuing enlarging transmission delay t_{delay} and other conditions remaining the same, if $t_{\text{delay}} > 4.7\text{ms}$ wavelets algorithm can no more discriminate the fault feeder. The reason is that due to larger peak shifting the judgment of wavelets coefficients direction fails.

Actually with smaller grounding resistance, high frequency component increases and low frequency component decreases thus the transmission delay tolerance of the proposed algorithm declines. With grounding resistance $R_f = 10\Omega$, simulation result demonstrates that no more than 0.45ms time delay is allowed for the algorithm to determine the fault feeder. Energy percentage of each frequency band in feeder 2 is compared in Fig.9:

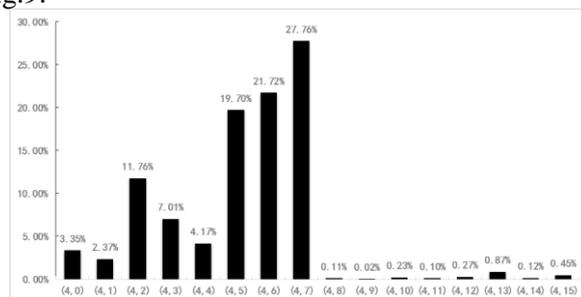


Fig.9 Energy percentage of each frequency band with grounding resistance 10Ω

Comparing wavelets energy of higher frequency band in Fig.9 with that in Fig.6, it can be concluded that wavelets energy with $R_f=10\Omega$ is obviously larger than that with $R_f=200\Omega$. This is because higher frequency signal is more sensitive to time delay than lower one.

Aiming at large transmission delay condition, the device can line up timescale according to timestamp in GOOSE frame.

5.2 RTDS Test

The proposed distributed grounding line selection algorithm is injected into the protection device which is based on low-voltage line protection PCS-9611 produced by NR, and the example in 4.1 is validated through RTDS. The RTDS test environment is showed in Fig.10:

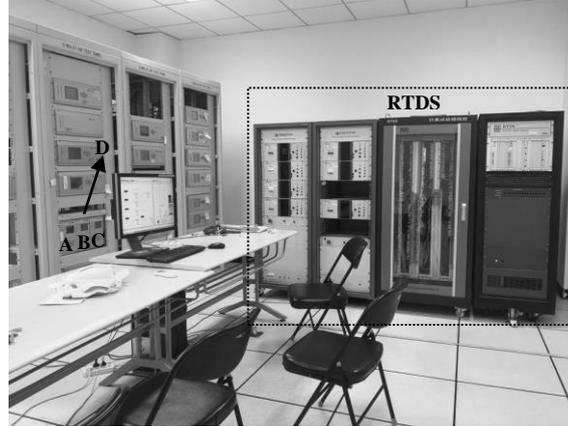


Fig.10 RTDS experimental platform construction

In Fig.10, A, B, C are the protection devices of feeders 1, 2, 3. D is the network switch. The dotted line frame denotes the RTDS test system, simulation model is constructed as Fig.1 and parameters are identical with section 4.1. The test results are showed in Tab.2:

Tab.2 Test results of RTDS

Grounding resistance / Ω	Trip
50	Yes
100	Yes
200	Yes
400	Yes
600	Yes
800	Yes
1000	Yes
1500	Yes
2000	Yes
2500	Yes
3000	Yes
3500	No

All the tripping time is less than 30ms, and protection device cannot discriminate the fault feeder with grounding resistance larger than $3k\Omega$. Based on equation (2), larger grounding resistance leads to smaller τ_c so that i_c attenuates rapidly and transient component becomes too small, which make it difficult for wavelets algorithm to discriminate obvious high-frequency component. But for most cases, $3k\Omega$ grounding resistance is quite enough. RTDS test further validates the effectiveness of the proposed algorithm in this paper, which is worth greatly popularizing.

6. Conclusion

This paper presents the transient model of grounding fault in small current grounding system, and wavelets algorithm is employed to analyze the fault transient zero-sequence current. In order to avoid installing centralized grounding line selection device, distributed grounding line selection device based on GOOSE is proposed and calculated wavelets coefficients are transferred through station-layer MMS network. After comparing wavelets energies, the feature frequency band is selected and directions are compared to determine the fault feeder. MATLAB and RTDS simulation verify the

effectiveness and practicability of proposed algorithm, which is also economic and worth greatly popularizing.

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