Wenhong LI, Xiuhua ZHANG, Xueguang QI, Shan ZHANG

Shan Dong University of Science and Technology

Online fractal identification of cable's ground fault traveling wave in mine

Abstract. *In order to capture the occurrence moment of traveling wave to accurately locate the ground fault of high voltage transmission electricity cable, we analyzed the transient process of the traveling wave produced by cable ground fault, finding it is a self-similar process on specific bandwidth in a strict sense, and further proposed a fractal identification algorithm based on quadratic spline orthogonal wavelet. Experiment denotes that the occurrence moment of traveling wave can be obtained from waveform on different scales by fractal identification of test signal.*

Streszczenie. *Opracowano system detekcji zwarć doziemnych w kablach wysokonapięciowych stosowanych w kopalniach. System bazuje na ortogonalnych splinowych falkach i realizuje identyfikację fraktalną. (**On-line fraktalna identyfikacja zwarć doziemnvch na podstawie analizy wędrującego udaru**).*

Keywords: Single-phase ground fault, Traveling wave, Wavelet fractal Identification
Słowa kluczowe: zwarcie doziemne, wędrujący udar, identyfikacja uszkodzeń.

Introduction

Underground power cable faults are mainly single phase ground faults with a little two-phase short-circuit or three-phase short-circuit faults in mine. Chinese electric power system requires that small current grounding system in which single-phase ground fault occurred is allowed to run within two hours, which means the time spent on fault localization should be as short as possible, but small single-phase current ground fault does not constitute an obvious short-circuit, and steady-state signal is not obvious, so to locate the spot of power cable fault accurately, rapidly and economically concerned the mining power supply engineers increasingly.

Power cable fault localization methods include traveling wave method and impedance method from principle point, online ranging method and offline ranging method from application point. Online ranging method is the most practical test methods[1], key technology of which is how to determine the time that traveling wave spent from the failure point to the test point. Most localization methods utilize the time difference that reflected traveling wave and initial traveling wave reached the measurement point. Localization method mentioned in document[2] is based on the theory that reflected wave and traveling wave have the similar waveform, use the correlation method to identify reflected wave produced in fault point and end point of cable, locate the fault location, but it exists the problem of how to select the appropriate signal length in the arithmetic. Document[3] proposed a method based on polarity of linear-mode traveling wave to identify the reflected wave of fault spot. Document[4] analyzed all methods that utilize the polarity of linear-mode current/voltage/direction traveling wave to identify the second reverse traveling wave. Document[5] pointed out that no matter what kind of traveling wave's polarity it is, none of them can identify the second reverse traveling wave in a full sense because of the affecttion of cable structure.

In this paper, we analyzed 10K~100KHz band traveling wave's signal on the base of a large number of actual online ground data, and proved theoretically that ground traveling wave has the quality of self-similarity, and its mathematical transmission model can be analyzed by Wavelet Fractal Method and its transmitting details can be obtained, which makes it easy to identify traveling wave, reflected wave and transmitted wave in test point.

Self-similarity analysis of cable ground current traveling wave

Any disturbance of the electricity transmission lines, such as short circuit, will spread to other parts of the system in the form of traveling wave and enter into a new steady state after multiple reflection and attenuation. This transient process can be described by a series of wavelet signal, and all these wavelet signals are self-similar.

1 Transient traveling wave produced by cable ground fault

In the system showed in Figure 1, e_M is the power transformers and e_N stands for other loads, where M、N are cables on both side, and signal monitoring devices are fixed in the switchgear box on M side. Current and electric potential exist in S-point which are produced by line capacitance distribution. Distribution electric potential do not produce current when cable insulation is normal, as showed in Figure 1(a). It can be considered that a virtual power e_s equal to the line voltage level apply on S-point in opposite direction when cable insulation fail and ground fault occur. The transient current or voltage traveling wave release when ground fault occur, as shown in Figure 1(b). Current or voltage signal monitored at test point is superposition of pre-fault current and fault transient traveling wave which contains information of the failure point.

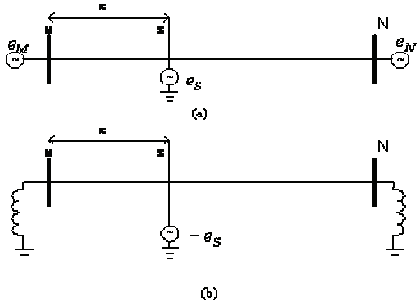

Fig 1 Transient traveling wave generated by ground fault

2 Fluctuation equation of transient grounding traveling wave

The fluctuation process of transient traveling wave can be described by differential equations, because this transient signal contains traveling wave signals of high frequency and its wavelength is very short compared to the length of cable, so it is reasonable to establish wave equation based on distribution parameter circuit model.

As showed in Figure 1, monitoring device, current transformers and high-speed signal sampling equipments are fixed on M-point, and data are sampled when ground faults occur, where x- distance between M-point and S-point, t -time, R_0 -resistance/m, L_0 -inductance/m, G_0 -shunt conductance/m, C_0 -shunt capacitance/m. Figure 2 shows cable's distribution parameters circuit model. When faults occur, there will be ground current traveling waves transmitting in cable. According to Kirchhoff's law, we can acquire transient voltage $u(x, t)$ and transient current $i(x, t)$ wave equation of any point of this cable:

$$\frac{\partial u(x,t)}{\partial x} + L_0 \frac{\partial i(x,t)}{\partial t} + R_0 i = 0$$
$$\frac{\partial i(x,t)}{\partial x} + C_0 \frac{\partial u(x,t)}{\partial t} + G_0 u = 0$$

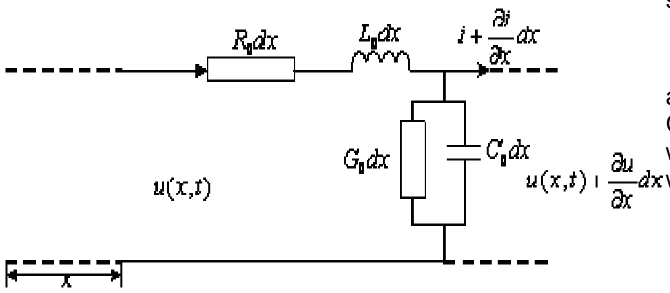

Fig 2 Cable's mathematical model of distribution parameters

These are linear singularity equations. Theoretically partial differential equations are solvable if boundary conditions and initial conditions are determined. Signal on test point was zero before occurrence of single-phase ground fault ($t=0^-$) and became the actual monitored current signal after $t=\Delta t$, then we can get current/voltage traveling wave equation. But due to various uncertainties under actual environment, cable's parameters can not be determined certainly, thus equation of traveling wave can not be obtained, not mention to initial traveling wave and reflected wave.

3 Analysis of ground traveling wave's self-similarity

Assuming that capacitance, inductance, conductance and resistance of unit length are constants, equation(1) can be transformed into linear odd ordinary differential equation, and solution is:

$$u(x,t) = A_1(x,t)e^{-rx} + A_2(x,t)e^{rx}$$
$$i(x,t) = \frac{1}{Z_c}(A_1(x,t)e^{-rx} + A_2(x,t)e^{rx})$$

Where r=α+jβ -line propagation constant, α -attenuation constant, β-phase constant. So instantaneous voltage and current of any point of this cable is superposition of forward-traveling wave $A_1(x, t)^{-rx}$ and reverse traveling wave $A_2(x, t)^{rx}$, then we can acquire:

$$\alpha = \sqrt{\frac{1}{2}[-\omega^2 L_0 C_0 + R_0 G_0 + \sqrt{(R_0^2 + \omega^2 L_0^2)(G_0^2 + \omega^2 C_0^2)}]}$$

$$\beta = \sqrt{\frac{1}{2}[\omega^2 L_0 C_0 - R_0 G_0 + \sqrt{(R_0^2 + \omega^2 L_0^2)(G_0^2 + \omega^2 C_0^2)}\,]}$$

The propagation velocity of the traveling wave is

$$v = \lim_{\Delta t \to 0} \frac{\Delta x}{\Delta t} = \frac{\omega}{\beta}$$

From the equation, we can see that cable's attenuation constant, phase constant and phase velocity are all related to signal's angular frequency. For signals of particular frequency-band, their propagation velocities are close to speed of light, phase and phase velocity almost unchangeable, their waveforms have quality of self-similarity.

So transmission process of ground current traveling wave is a self-similar waveform moving process along timeline.

The wavelet fractal of ground transient process

For deterministic self-similar process $u(x, t)$, its waveform measured on any test point can be described as $u(t)$, and $u(t)= \alpha^{-H}u(\alpha t)$, if α>0, where *α* -scale, *H* -constant.

1 Wavelet analysis of self-similar waveform

For deterministic self-similar process, there exist a set of specifications orthogonal wavelet bases

$$\{\varphi_{j,l}(t) = 2^{1/2}\varphi(2^j t - l)\}_{j,l \in Z},$$

and wavelet basis' regular degree is greater than 1. Conduct wavelet transform based on these orthogonal wavelet bases, $u(t)$ can be described as the sum of multiple wavelet:

$$u(t) = \sum_j \sum_l d_l^{(j)} \varphi_{j,l}(t),$$

where $d_l^{(j)} = 2^{\frac{j}{2}} \int u(t)\varphi(2^j t - l)dt$ -wavelet coefficients.

Test equipments can capture the transient process $u(x, t)$, it's a squiggle, *x* -unknown constant.

In order to facilitate analysis, transform $u(x, t)$ to $u(X, t)=u(t)=2^{-nH}u(2^n t)$, we can use orthogonal wavelet basis $\varphi_{j,l}(t)$ to expand $u(t)$ under any scale:

$$D_j\{u(t)\} = \sum_l d_l^j \varphi_{j,l}(t)$$

Approximate signal:

$$A_j\{u(t)\} = \sum_l a_l^{(j)} \varphi_{j,l}(t), \text{ where } \beta = 2^{2H+1}$$

Scaling function: $\varphi_{j,l}(t) = 2^{\frac{j}{2}} \varphi(2^j t - l)$

Scale coefficient: $\alpha_l^j = \int u(t)\varphi_{j,l}(t)dt$

Let $p[l]$ stands for sale coefficient when scale is 0, that is $p[l] = a_l^0$,

Then

$$a_l^{(j)} = \beta^{-\frac{j}{2}} a_l^{(0)} = \beta^{-\frac{j}{2}} p[l]$$

$$A_j\{u(t)\} = \beta^{-\frac{j}{2}} \sum_l p[l]\varphi_{j,l}(t)$$

What indicate that $p[l]$ can be close to $u(t)$ under any arbitrary precision. $p[l]$ can be considered as $u(t)$'s characteristic sequence.

2 Ground transient traveling wave's wavelet fractal identification

If $p[l]$ and ground traveling wave can be identified from test sequence $u(x, t)$, then $u(x, t)$ tested on *x*- point is the combination of traveling wave under different scale. Find the approximate signal $p[l]$ combined by orthogonal wavelet bases under different scales until traveling wave can be distinguished, we can get the time difference by dividing the time between those two traveling wave by 2^j.

According to the formula:

$$p[l] = \beta^{\frac{j}{2}} \int x(t)\varphi_{j,l}(t)dt$$

Actual sampled values were sample sequence, formula used to construct waveform based on those sample sequence is:

$$p(i) = 2^{H+\frac{1}{2}} \sum_{m=0}^{n} u(i)\varphi_{j,l}(m)$$

Extract approximate signal *p*[*l*] sequence and get ground traveling wave (Timeline elongation) under specific scales (time stretching). According to the waveform of the traveling wave, time information of the first ground fault wave, reflected wave, projected wave could be obtained. The time information will help us localize the cable fault point.

3 Experiment

Experiments to localize fault location of power cable were did in 10kV central substation of Dongtan coal mine. Cable is XLPE insulation and PVC three-core power cable. L=2.25km -total length, R_1=0.193ohm/km -resistance, L_1=0.2573H/km, L_2=6.6904*10^{-3}H/km – inductance, C_1=C_2=0.2390*10^{-6}F/km -capacitance.

Four Hall current sensors which would pass through 100KHz and lower signals were fixed on the outlet side of the 10 kV high voltage switchboard. Automatic sampling system of 40Msap, 512MB cache was adopted to capture signals 5ms before and after the pulse caused by ground fault. We did experiments under the following two conditions.

Condition 1 Experiment on new cable.

A switch signal was generated when power transmission switch was turned on in substation of coal mine, the actual waveform of this signal was showed in the following Fig.3.

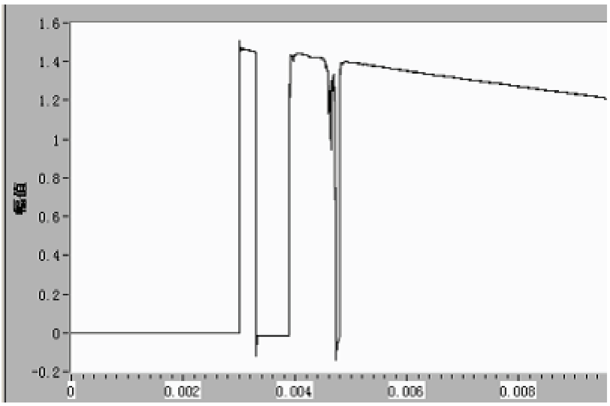

Fig 3 Actual test waveform

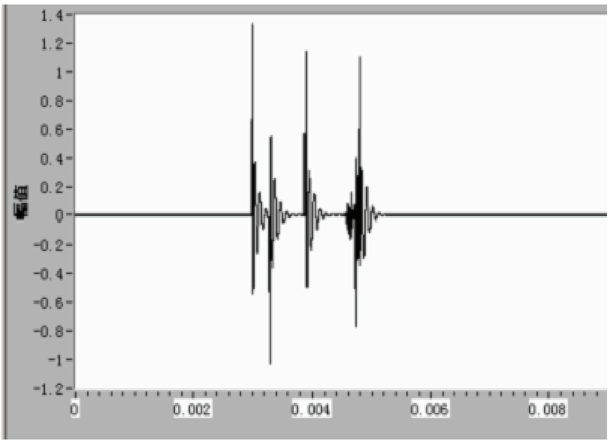

Fig 4 Traveling wave signals through bandpass filter

Apply a 20K-100KHz band-pass filter on the signal, extract signal of specific frequency, make sure that the signal's propagation speed and phase did not change, as showed in Fig 4.

Use orthogonal spline as the orthogonal wavelet basis to decompose the signal and only keep the approximate signal, waveform decomposed under one-scale was showed in the following Figure 5:

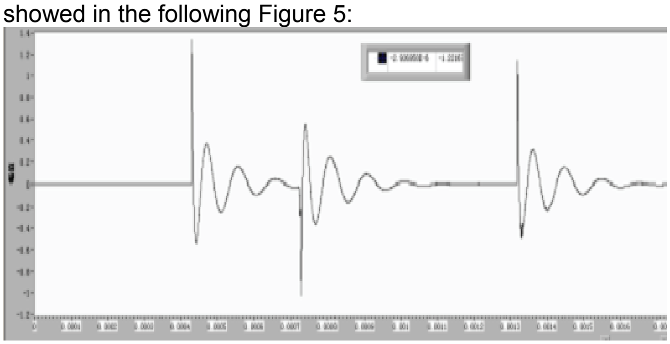

Fig 5 Fractal waveform under 1-scale

Extracted approximate waveform under three-scale as showed in figure 6:

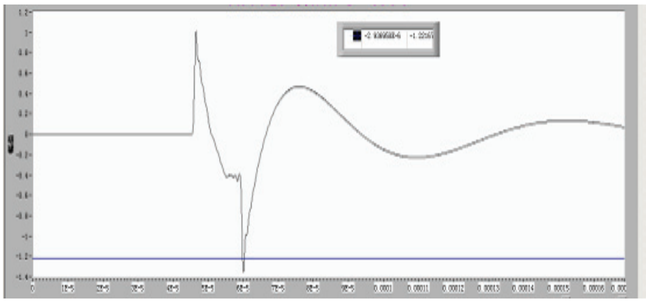

Fig 6 Fractal waveform under 3-scale

All that above means using Wavelet Fractal method to identify current transient traveling wave from sampled signal is feasible.

Condition 2 Experiment on cable used for some time.

Deliberately created a ground fault on one joint, we could obtain time difference between the two traveling waves as showed in Fig. 7. Signals passed through 20K - 100KHz band-pass filter were showed in the following Fig. 8.

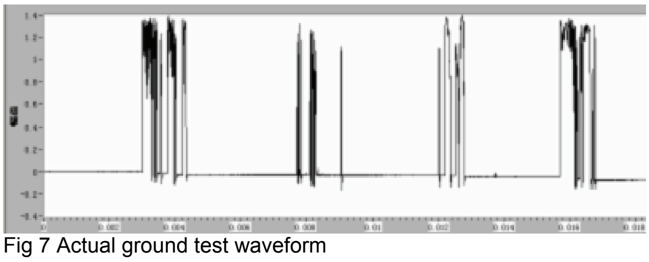

Fig 7 Actual ground test waveform

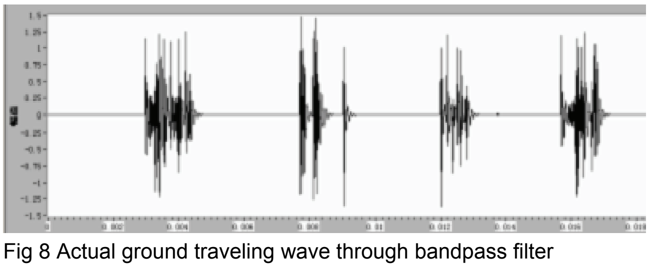

Fig 8 Actual ground traveling wave through bandpass filter

Due to the relatively short distance, those traveling-wave signals superposed on test point, which make it difficult to separately identify traveling waveform. Waveform decomposed under one-scale was showed in the following figure 9:

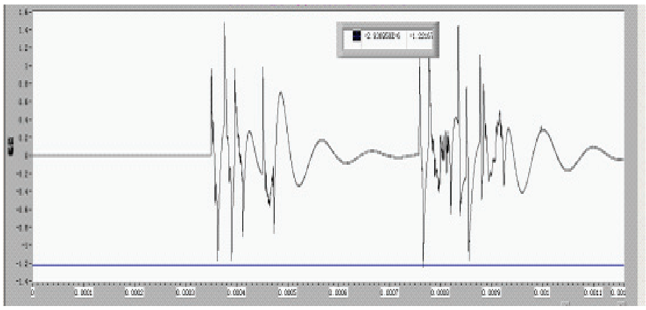

Fig 9 Fractal ground traveling wave under 1-scale

Waveform decomposed under three-scale was showed in the following figure 10, the time interval of traveling wave can be distinguished.

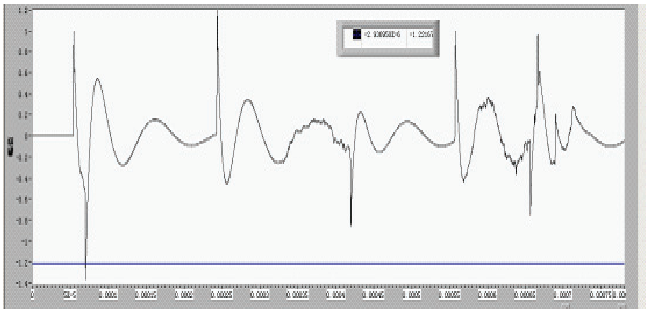

Fig 10 Fractal ground traveling wave under 3-scale

Conclusion

Theoretical analysis proves that cable ground transient process is an odd process which can be analyzed by odd differential equation, and traveling wave signals' mobile process whose energy is limited can be obtained in cable-time coordinates. For those 20K -100KHz traveling wave signals, whose velocity and phase change little, and have the quality of deterministic self-similarity, they can be fractionalized under different scales by wavelet fractal approach which can use quadratic spline as orthogonal wavelet bases. Then we can get the tip of transient traveling wave which can further be used for cable fault localization and fault protection.

REFERENCES

[1] Ge Yaozhong, New types of protective relaying and fault location theory and techniques[M], Xi’an: Xi’an Jiaotong University Press, 1996: 217-314

[2] Shehab-Eldin E. H., Mclaren P. G.,Travelling W ave Distance Protection Problem Areas and Solutions, IEEE Trans on Power Delivery, 1988, 393): 894-902

[3] Ge Yao-zhong, Dong Xin-zhou, Dong Xing-li, Traveling Wave Based Distance Protection with Fault Location Part One—Theory and Technology, Automation of Electric Power Systems, 2002, 26(6): 34-40

[4] ShiShen-xing, Dong Xin-zhou, ZHou Shuan-xi, Analysis of Singale-phase-to-ground Fault Generated Traveling Waves, Automation of Electric Power Systems, 2005, 29(23): 29-32,53

[5] SHi Shen-xing, Dong Xin-zhou, ZHou Shuang-xi, A New Method of Wave Identification of Second One-phase-ground-fault Reverse Wave.

[6] Li Bi-cheng, Luo Jian-shu, Wavelet Analysis and It’s Application[M], BEIJING Publishing House of Electronics Industry, 2003, 5: 145-161

[7] L Keen, Time-Frequency analysis[M], U.S Prentice Hall 1995

[8] ZHan Fan, etc, Transmission Line Fault Location and Protection Based on Gap Between Zero Mode and Aerial Mode Traveling Wave Propagation Time, Proceedings of CSEE. 2009 29(10): 78-83

Authors: *Prof. Dr Li Wenghong. Shan Dong University of Science and Technology, 17 Shenglizhuang Road Tianqiao Zone, Jinan Shandong Province, 250031 P.R.China, E-mail:liwenhong6849 @ sina.com*