Research on Ultra-High-Speed Directional Relay of EHV/UHV Transmission Lines Using Wavelet Transform

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Abstract: - This paper proposes a novel ultra-high-speed directional relay using the wavelet transform. Two relay signals indicating traveling direction are composed of fault-induced voltage and current waves propagating along EHV/UHV transmission lines. Wavelet transform technique is employed to extract transient components from the relaying signals, and represent the transient component magnitude with wavelet transform spectrum energy (WTSE). Fault direction is determined by comparing the transient component WTSE of the two relaying signals during a post-fault period. A large number of various fault scenarios have been simulated with EMTP to evaluate the validity and reliability of the proposed scheme.

Key Words: - Directional, EMTP simulation, Relay, Traveling wave, Ultra-high-speed, Wavelet transform

1 Introduction

The rapid fault clearance has been recognized as an effective way to improve transient stability of modern EHV/UHV power systems. A great amount of effort has been dedicated to the research on ultra-high-speed (UHS) protection, including directional relays.

During the 1970s and 1980s, various UHS directional protection schemes [1]-[3] were proposed due to the development of traveling wave-based technique. This technique has the advantages of fast response and immunity to power swing, CT saturation, and series compensation capacitor, compared with the conventional protection techniques based on fundamental components. But the correctness of these methods is limited with the initial traveling wave since the following traveling wave is affected by the reflected and transmitted wave. Also, the sensitivity greatly depends on the fault inception angle. In the 1990s, other principles of UHS directional protection were developed, which are based on transient-based protection technique [4]-[5]. The technique utilizes fault-generated high frequency components and concomitant arcing noises to overcome a drawback caused at a low fault inception angle.

However, the application of these principles above suffers relatively low reliability and feasibility by its limitations such as lack of effective signal processing tools. In recent years, the advent of the mathematical morphology (MM) and the wavelet transform (WT) give a great impetus to investigating the possibility of improving the UHS protection. Q H Wu, et al, proposed a MM-based directional protection by comparing the sudden-change magnitude of the fault-induced signals [6]. W Chen, et al, presented a WT-based directional protection by comparing the sudden-change polarity between the fault-induced voltage and current wave [7]. X Z Dong, et al, studied another WT-based directional protection (called surge impedance relay) by computing the ratio of voltage to current traveling-wave [8]. These previous schemes all extract the fault feature from the initial traveling waves, so the reliability may be influenced by low inception angle and the reflected traveling-waves.

In this paper, a different approach to UHS directional protection based on the wavelet transform spectrum energy (WTSE) is proposed. Firstly, a process of deriving the direction discriminants of a fault occurring on transmission lines is given, based on traveling wave analysis. Then, the wavelet analysis theory is described, and the WTSE concept is defined to extract the transient features directly from fault-induced transient signals. Finally, the proposed UHS directional relay is verified by EMTP simulation transient data from a typical 500kV transmission model under various fault conditions.

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2 Fault Analyses and Principle of UHS Directional Relay

The underlying principle of the studied directional relay scheme is addressed with reference to a 500-kV transmission lines system as shown in Fig. 1. A directional relay （DR） is situated near busbar M at the end of the protected section II. The positive direction at the relaying point is defined as current flowing from busbar M into section II.

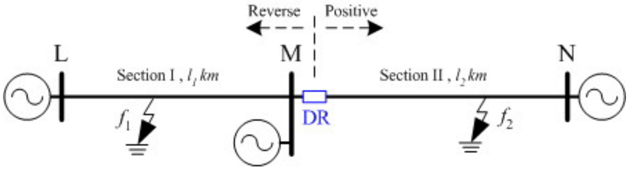


Fig.1 Single-line diagram 500-kV transmission system

The relaying signals adopted in this scheme, introduced in [6], [9], are given as

$$S_R = \Delta u_M(t) - Z\,\Delta i_M(t) \quad (1)$$

$$S_P = \Delta u_M(t) + Z\,\Delta i_M(t) \quad (2)$$

where S_R and S_P are called the reverse and positive traveling wave, $\Delta u_M(t)$ and $\Delta i_M(t)$ observed at DR are the transient voltage and current signals generated by a fault, and Z is a line surge impedance.

2.1 Fault in positive direction

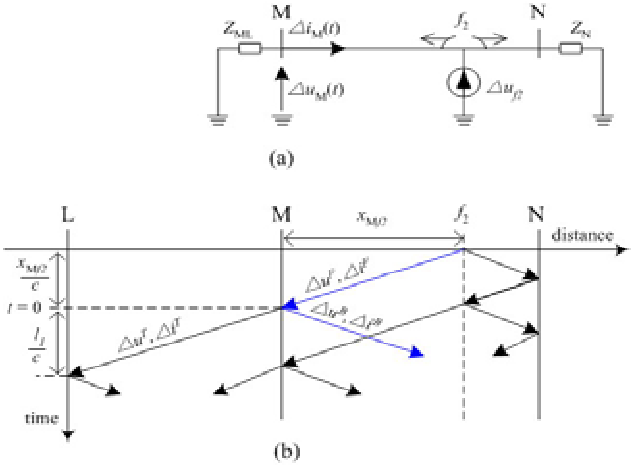


Fig.2 Equivalent superimposed circuit under a fault in positive direction (a) and its Bewley-lattice diagram (b)

Fig. 2 depicts an equivalent superimposed circuit with a fault occurring in positive direction at a distance of x_{Mf2} from busbar M and with the propagation of the fault-generated transient waves along a single-phase lossless transmission line. The superimposed voltage Δu_{f2} and associated current Δi_{f2} at the fault point f_2, caused by the injection of an equivalent fictitious source, travel at a speed c toward the line terminals, and $\Delta i_{f2} = -u_{f2}/Z_{II}$, where Z_{II} is the line surge impedance of section II.

The relaying signals S_R and S_P observed at the relaying point DR can be derived by applying the traveling-wave equations, described in [3], as follows:

$$\begin{aligned}\Delta u_M(t) &= \Delta u_M^F(t) + \Delta u_M^B(t)\\ &= \Delta u_{f2}(t-\frac{x_{Mf2}}{c}) + k_r \Delta u_{f2}(t-\frac{x_{Mf2}}{c})\\ &= (1+k_r)\Delta u_{f2}(t-\frac{x_{Mf2}}{c}) \quad (3)\end{aligned}$$

$$\begin{aligned}\Delta i_M(t) &= [-\Delta u_M^F(t) + \Delta u_M^B(t)]/Z_{II}\\ &= [(-1+k_r)\Delta u_{f2}(t-\frac{x_{Mf2}}{c})]/Z_{II} \quad (4)\end{aligned}$$

$$S_R = 2\Delta u_{f2}(t-\frac{x_{Mf2}}{c}) \quad (5)$$

$$S_P = 2k_r \Delta u_{f2}(t-\frac{x_{Mf2}}{c}) \quad (6)$$

where the superscripts F and B indicate a incident (forward) and a reflected (backward) wave respectively. In this case, the reflection coefficient

$$k_r = \frac{Z_{ML} - Z_{II}}{Z_{ML} + Z_{II}} \quad (7)$$

where Z_{ML} is the equivalent surge impedance viewed from point M outwards.

2.2 Fault in reverse direction

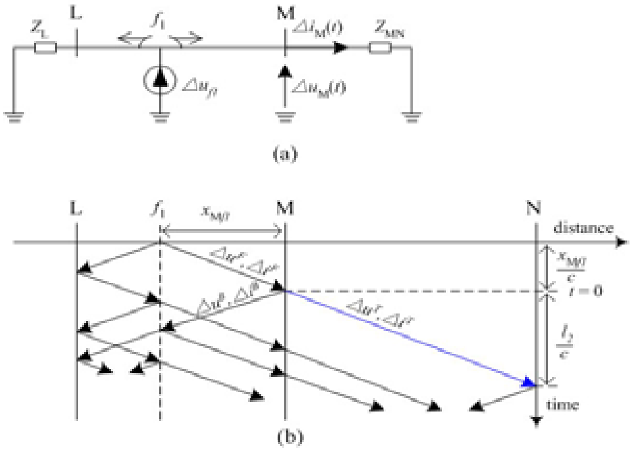


Fig.3 Equivalent superimposed circuit under a fault in reverse direction (a) and its Bewley-lattice diagram (b)

For a fault occurring at point f_1 on section I in a distance of x_{Mf1} from busbar M in reverse direction as indicated in Fig. 3, only the transmitted transient waves can be observed at the relaying point DR and their traveling direction is positive. The relaying signals are derived similarly as follows:

$$\Delta u_{\mathrm{M}}(t) = \Delta u_{\mathrm{M}}^{T}(t) = k_t \Delta u_{f1}(t - \frac{x_{\mathrm{M}f1}}{c}) \qquad (8)$$

$$\Delta i_{\mathrm{M}}(t) = \Delta u_{\mathrm{M}}^{T}(t)/Z_{\mathrm{II}} = k_t \Delta u_{f1}(t - \frac{x_{\mathrm{M}f1}}{c})/Z_{\mathrm{II}} \qquad (9)$$

$$S_R = 0 \qquad (10)$$

$$S_P = 2k_t \Delta u_{f1}(t - \frac{x_{\mathrm{M}f1}}{c}) \qquad (11)$$

where the superscripts T indicates a transmitted wave, and the refraction coefficient

$$k_t = \frac{2\mathrm{Z}_{\mathrm{MN}}}{\mathrm{Z}_{\mathrm{MN}} + Z_{\mathrm{I}}} \qquad (12)$$

Similarly Z_{I} is the line surge impedance of section I and Z_{MN} is the equivalent terminating surge impedance.

2.3 Features about fault direction

From the foregoing analysis, the following summarization can be given.

(1) The fault direction relative to the relaying point can be determined by comparing the magnitudes of the transient relaying signals S_R and S_P.

(2) Equations (5) and (6) for a positive direction fault and (10) and (11) for a reverse fault will be satisfied during a period which is twice that of the line transit time, i.e., $2l_1/c$ or $2l_2/c$, as illustrated in Fig. 2 and 3, where l_1 and l_2 are line lengths of section I and II, respectively.

(3) Considering the stray busbar capacitance, the equivalent terminating surge impedance is not equal to the line surge impedance, i.e., $0<|k_r|, |k_t|<1$.

2.4 Principle of UHS directional relay

According to the summarized fault features, during a period of time Δt after the fault is detected, the ratio (13) of relay signals S_P to S_R will discriminate the fault direction,

$$\lambda = S_P / S_R \qquad (13)$$

- If $\lambda \le \lambda_0$, the fault direction is identified to be positive. The ratio λ is equal to the reflection coefficient $|k_r|$ at the busbar viewed from the relay installation point, thus $0<\lambda<1$.
- If $\lambda > \lambda_0$, the fault direction is reverse. At this time, in theory, the ratio λ tends to be infinite.

Inside the directional criteria above,

(a) The time period Δt <min { $2l_1/c$, $2l_2/c$ }. Generally Δt is no more than 1ms in EHV/UHV transmission systems.

(b) The λ value is calculated with the S_P, S_R magnitude, or their energy during Δt. In fact, the latter is more reliable.

(c) The threshold λ_0, in theory, is between the reflection coefficient k_r and the infinite. In the circumstance of application, λ_0 will be set to be a proper value more than 1.

(d) With extension to three-phase transmission system, the phase variations of currents and voltages are decomposed into modal components using the Karrenbauer modal transformation [9]. The aerial mode is utilized in this scheme.

3 Wavelet-based Directional Relay

In order to convert the above principle of directional protection into the applicable UHS relay algorithm, it is necessary to use the fast analysis tool to extract and represent the fault transient signals. As a novel time-frequency analysis method, the wavelet transform has been proved to be fairly suitable to process the power system transients.

3.1 Wavelet analysis

In this section, a concise description of the wavelet theory and its application in signal analysis [10]-[11] is provided. The wavelet transform (WT) of a continuous signal $y(t)$ is defined as

$$CWT(a,b) = \int_{-\infty}^{+\infty} y(t)\psi_{a,b}^{*} dt \qquad (14)$$

where $\psi_{a,b}^{*} = \frac{1}{\sqrt{2}}\psi^{*}(\frac{t-b}{a})$, $\psi(t)$ is the mother wavelet, the asterisk * denotes a complex conjugate, and $a, b \in R$, $a \neq 0$, are the dilation and translation parameters respectively. The WT processes data at different scales or resolutions by dilating and translating $\psi(t)$ continuously.

The WT expressed in (14) has a digitally applicable counterpart, the discrete wavelet transform (DWT), which is defined as

$$DWT(m,n) = 2^{-\frac{m}{2}} \sum_{m}\sum_{n} y(n)\psi^{*}(\frac{t-n2^m}{2^m}) \qquad (15)$$

where the discretized mother wavelet becomes $\psi_{m,n}(t) = \psi(\frac{t-nb_0a_0^m}{a_0^m}) \Big/ \sqrt{a_0^m}$. With $m \ n \in Z$, a_0 =2 and b_0 =1, WT is converted into dyadic wavelet transform. The latter is implemented using the multi-resolution signal decomposition (MSD). For a recorded digitized time signal $c_0(n)$ (which is a sampled copy of $y(t)$), the approximation coefficient

$c_j(n)$ and the wavelet coefficient $d_j(n)$ after the decomposition at j scales (j =1, 2, …, J, J represents the total number of resolution levels) are given by fast Mallat's algorithm as follows:

$$c_j(n) = \sum_k h(k-2n)c_{j-1}(k) \qquad (16)$$

$$d_j(n) = \sum_k g(k-2n)c_{j-1}(k) \qquad (17)$$

where $h(n)$ has a low-pass filter response and $g(n)$ has a band-pass filter response. The coefficients of the filters $h(n)$ and $g(n)$ are associated with the selected mother wavelet. The above MSD procedure (16)(17) can be illustrated as the original signal (0~100kHz) divided into several frequency bands with DWT as depicted in Fig.4.

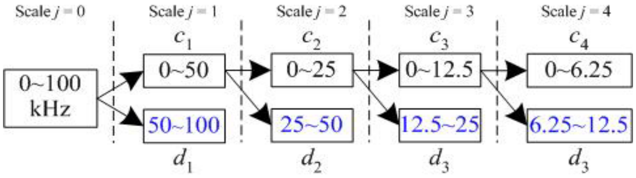


Fig. 4. Wavelet decomposition of signal sampled at 200 kHz

3.2 Wavelet-transform-spectrum-energy

According to the Parseval's theorem, if the WT is orthonormal, the energy of the signal $y(t)$ can be partitioned in terms of wavelet coefficients [12]

$$E_s = \int |y(t)|^2 dt = \sum_k |c_J(k)|^2 + \sum_{j=1}^{J} \sum_k |d_j(k)|^2 \qquad (18)$$

With reference to the last segment of equation (21),

$$E_j^{\mathrm{W}} = \sum_k |d_j(k)|^2 \qquad (j = 1, 2, \ldots, J) \qquad (19)$$

where E_j^{W} represents the energy of the signal component at the *j*-th frequency band. Thus E_j^{W} is named as the wavelet transform spectrum energy (WTSE) corresponding to scale *j*.

In order to ensure (19), the orthonormal mother wavelet $\psi(t)$ should be chose. The choice depends on the nature and kind of signal to be extracted, and in the present work it primarily involves the detection, localization and recognition of fast transient signals. Fortunately, the Daubechies' wavelet family satisfies with such applications requirement [10]. In this study, the Daubechies' wavelet (symlets4) of symmetrical version and shorter support has been employed.

3.3 Directional relay algorithm using WTSE

Associated with WTSE calculational formula (19), the directional discriminant (13) can be achieved as

$$\lambda = E_P / E_R \qquad (20)$$

where λ is named as directional factor, and E_P , E_R is WTSE of the relay signals S_R and S_P. Then the directional criteria becomes as the following:

- If $\lambda \le \lambda_0$, the fault direction is positive.
- Else, the fault direction is reverse.

where the threshold λ_0 is set to be more than 1.

In direction discriminant (20), the WTSE E_P and E_R should be at the same scale of traveling-wave wavelet transform during the time period Δt . As for the scale selection, take the following for example. In order to extract and represent a transient traveling-wave that mainly contains 5~100kHz frequency components, the signal-sampling rate is suggested 200kHz. It can be seen from Fig.4 that the proper scale for WTSE is between 1 and 4. Considering the reliability, the λ results at four scales can be used synthetically.

3.4 Directional relay design

The block diagram of the proposed directional relay is shown in Fig.5. The modal mixing circuit receives the phase signals $u_{a,b,c}$, $i_{a,b,c}$ and combines them to form aerial mode signals u_m , i_m . Then outputs of the modal mixing circuit are passed to the digital circuit through an A/D converter. From here, the software inside the signal processor takes over the control. The digital processing includes such units as relaying-signal forming (S_P , S_R), wavelet transform, spectrum energy calculation (E_P , E_R), direction discriminating ($\lambda = E_P / E_R \le \lambda_0$?) and decision-making (positive or reverse direction).

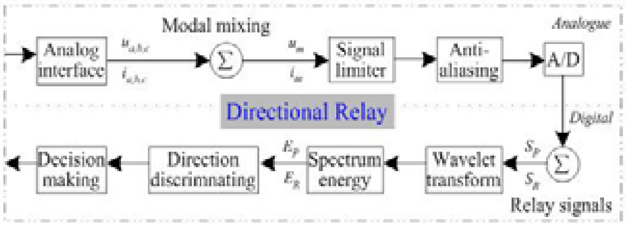


Fig. 5. Block diagram of directional relay (DR)

4 EMTP Simulation Study

The well-known EMTP [13] is employed to simulate the fault transients of the typical 500kV system as shown in Fig.1. The simulatin model of transmission lines is frequency dependent. The line length of section I and II is l_1 = 100km and l_2 = 160km, repectively. The aerial mode surge impedance is Z =248.4 Ω , which is derived from the tansmission line parameters. A stray capacitance of 0.01μF is assumed at each bus-bar.

The proposed directional relay (DR) is installed at the end of section II near bus-bar M. The signal sampling rate is 200 kHz. The WTSE of relay signals is caculated at scale 2 of the symlets-4 wavelet transform during the time period Δt = 0.5ms (which is less than $2l_1/c$ and $2l_2/c$). The directional threshold is set to be λ_0 =1.2.

Fig.6 depicts the simulation results of a fault f_2 occuring in line Section II (phase A to ground, 75^0 inception angle, 10Ω fault path resistance and 150 km away). The results include the aerial mode u_m, i_m, the relay signals S_P, S_R and their wavelet transforms. From the Fig, it can been caculated that, during the time period 0.5ms after fault, the 2-scale WTSE ratio $\lambda = E_P / E_R$ =0.13< λ_0 =1.2, so the fault is determined to be in positive direction, and the directional relay shoule be work rapidly.

Fig.7 illustrates the simulation results of another fault f_1 occuring in line Section I (phase B-C to ground, 60^0 inception angle, 50 Ω fault path resistance and 50 km away). The WTSE ratio can be caculated to be λ =510.2>> λ_0 =1.2, thus the fault direction is determined to be reverse, so the directional relay will not maloperate.

A great number of various fault scenarios has been simulated to evaluate the DR validity. Fig.8 shows the curves about the WTSE ratio λ with different fualt conditions involving fault position, fault inception angle, fault type and fault path resistance. As can be seen, in the case of positive direction fault, λ value is less than 0.2 and the threshole λ_0 (=1.2), but in the case of reverse direction fault, λ value is generally by the hundred and much greater than the threshole λ_0 (=1.2). Therefore, the proposed UHS directional relay is stable and reliable, and its performance is not infunced by such fault circumtances as various fault distance, inception angle, fault type and fault path resistance.

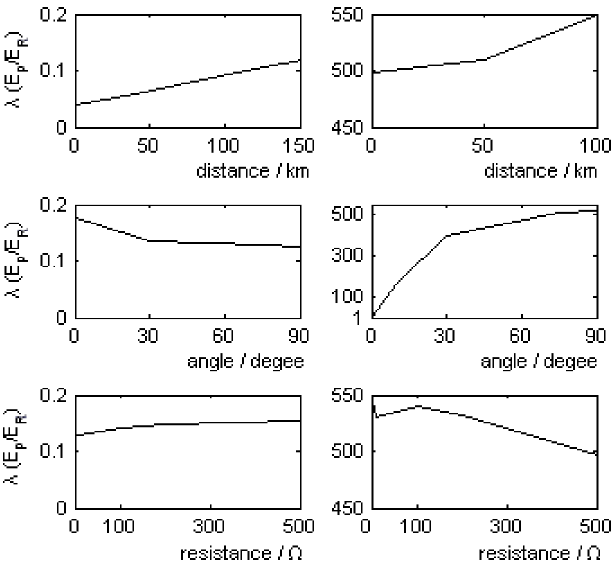
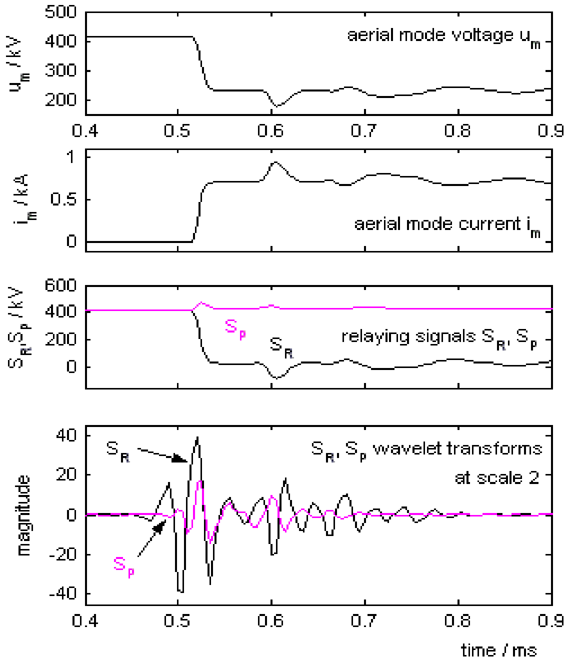
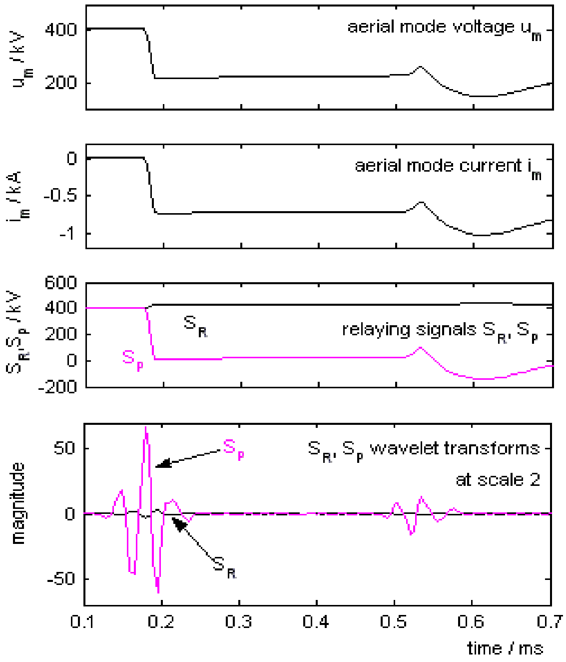


Fig. 8. Directional factor λ Curves with fault distance, fault inception angle, fault path resistance



(WTSE E_P =1.37e9, E_R =1.06e10, then λ =0.13< λ_0 =1.2)

Fig. 6. Phase-A-to-ground fault in positive direction



(WTSE E_P =1.9e10, E_R =3.4e7, then λ =510.2>> λ_0 =1.2)

Fig. 7. Phase-B-C-to-ground fault in reverse direction

5 Conclusion

A novel directional relay for tranmission lines is presented in this paper, which possess the following characteritics:

(1) Fault direction is discriminated by comparing the magnitude or energy of the difined relaying signals, which is derived from traveling-wave propagation with the strict fault analyses.

(2) The wavelet transform is used to extract the transient traveling-waves and represent the fault features with wavelet transform spectrum energy.

(3) A short data window no more than 0.5ms at 200kHz samping rate is required. And with the fast wavelet-transform algorithm, the proposed relay is in nature of ultra high speed.

(4) The simulation studies have shown the new directional relay is able to provide correct and reliable response to a fault under different fault position, type, path resistance and inception angle.

Further research and prototype development is in progress. The proposed UHS directional relay will be applied to EHV/UHV transmission lines soon.

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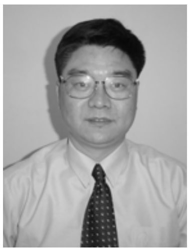

Zhang Bao-hui (S’99) was born in China in1953. He received his bachelor, master and doctor degree in the Department of Electrical Engineering of Xi’an Jiaotong University in 1977, 1982 and 1988 respectively. He is now an IEEE Senior Member and a professor of Xi’an Jiaotong University. His research areas are protective relaying, transient stability and control of power system, power system communication, etc.