A Recognition Method for Lightning Disturbance in Traction Power Supply System Based on Wavelet Energy Moment

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Abstract—**Traction power supply system (TPSS) is an important part of the electric railway. Lightning is one of the important factors that endanger the safe operation of TPSS. The impact of lightning on TPSS can be divided into lightning fault and lightning disturbance. Due to lightning disturbance also generates high-frequency components, which cause the relay protection mistrip in traction substation. In this paper, wavelet energy moment is used to recognition lightning disturbance of TPSS. Firstly, in order to obtain transient signals of TPSS, simulation model of the TPSS is built and it simulates three kinds of transient signals, such as normal signals, lightning fault signals and lightning disturbance signals. Then the wavelet transform is used to extract the energy moments of each frequency band of the three types of signals. Thus, wavelet energy moment statistical graphs of three types of signals are obtained, the wavelet energy moment statistical graph is analyzed and its distribution characteristics are analyzed. Based on this, the lightning disturbance recognition criterion is proposed. Finally, the recognition criterion is verified by the simulation signals. The results show that the recognition method can effectively recognize the lightning disturbance signal of the TPSS.**

Keywords—Traction power supply system(TPSS); lightning disturbance; wavelet energy moment; recognition method; feature extraction

I. INTRODUCTION

Due to its high efficiency, large volume, economical and practical advantages, the electric railway is considered to be the most ideal transportation, and it is important to ensure the safe, stable and reliable economic operation of the electric railway. As an important part of the electric railway, the TPSS transfers the power of the power system to the electric locomotive to complete the traction operation [1]. However the lightning will cause frequent tripping of the TPSS and large area of insulators damage. The fault of the TPSS caused by lightning fault is permanent, and the relay protection should act quickly and reliably. The lightning disturbance is equivalent to an disturbance for the TPSS, and the protection should not act. However, both lightning fault and lightning disturbance will generate high-frequency components. For the protection in the traction substation, the relay protection captures the high-frequency components of the lightning disturbance traveling wave, and the relay protection mistrips. Therefore, by recognizing the lightning disturbance in the TPSS, unnecessary tripping can be greatly reduced, and it can effectively improve the safety and economic benefits of the TPSS.

Many scholars have done a lot of work on lightning signal recognition and have achieved certain results. Literature [2] uses artificial neural network to recognition lightning induced overvoltage and direct lightning overvoltage, which provides a new research idea for lightning signal recognition, but it requires large sampling data. According to the different distribution characteristics of the wavelet energy matrix of the lightning disturbance signal and the lightning fault signal, in the literature [3] the wavelet energy spectrum is widely applied to the classification and recognition of lightning overvoltage. Based on the waveform characteristics of transient signals, it proposes a lightning disturbance recognition algorithm for short-time window voltage mean in the literature [4], which has high reliability. In literature [5], it uses the differences between the wavelet energy spectrum and the waveform characteristics to recognize, but it may be wrong when discriminating with the second traveling wave head. In literature[6], it proposes a criterion for recognizing between lightning disturbance, lightning fault and short-circuit faults based on the characteristics of the current traveling wave signals and the energy distribution of the signals in each frequency band. In literature [7], the transient characteristics of lightning fault, lightning disturbance and short-circuit fault are analyzed, and combined with the time domain and transient energy characteristics of lightning fault, but the relay protection setting is difficult.

The above-mentioned lightning recognition methods are adapted for the transmission lines in power system. However, the time-frequency characteristics of the lightning signal of the TPSS is different because of the different power supply mode. It's necessary to study the lightning disturbance recognition method for the electric railway TPSS. Therefore, this paper sets up the TPSS model in PSCAD/EMTDC simulation software. Based on the simulation data, the time-

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frequency characteristics of different transient signal in TPSS is analyzed. And then the wavelet energy moment based lightning disturbance recognition method is presented and verified.

II. WAVELET ENERGY MOMENT

The wavelet decomposition and wavelet reconstruction of the original signal $x(k)$ can be represented as follow:

$$x(k)=\sum_{j=1}^{j+1} D_j(k) \tag{1}$$

where: j is the decomposition level, k is the time, $D_j(k)$ is the wavelet decomposition coefficient.

The wavelet energy moment of the signal in each frequency band can be calculated as follow:

$$T_j=\sum_{j=1}^{N}(k\Delta t)\left|x_j(k\Delta t)\right|^2 \tag{2}$$

where: Δt is the sampling interval, N is the total number of sampling points. The wavelet energy moment not only considers the size of energy, but also considers the distribution of energy with time t, and the distribution law and characteristics of energy along each time band are considered. The steps of signal feature extraction based on wavelet energy moment are as follows:

(1) Perform wavelet decomposition on the signal $x(k)$, and select the appropriate wavelet base (db1-db10, Meyer, etc.) and the decomposition level j. $x(k)$ is the original signal, $D_j(k)$ represents the wavelet decomposition coefficient of the signal at the decomposition level j in time k.

(2) Perform a single reconstruction on the wavelet decomposition coefficients $D_j(k)$ to extract signals $S_j(k)$ in each frequency band.

(3) Calculate the wavelet energy moment T_j of the signal $S_j(k)$ in each frequency band.

(4) Normalize the wavelet energy moment to construct a feature vector T

$$T=\left[T_1,T_2,..,T_{J+1}\right]\Bigg/\left[\sum_{j=1}^{J+1}(T_j^{\ 2})\right]^{1/2},\ j=1,2,...,J \tag{3}$$

III. TPSS SIMULATION

A. Lightning simulation model for TPSS

The lightning current model is built in PSCAD/EMTDC. The double exponential function waveform is used to simulate the controlled current source waveform. The amplitude I=50kA, the head wave time is 1.2us and the tail wave time is 50us in the simulation model. Lightning simulation model is built as shown in Figure. 1.

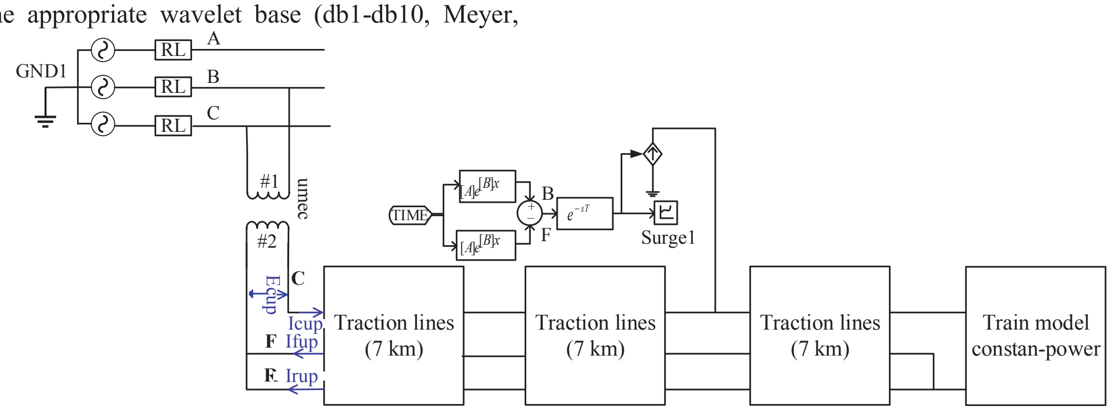

Figure 1. Lightning simulation model diagram

B. Simulation results of normal

Normal simulation is built, the system simulation time is set to 2s, and the locomotive is placed at 21km of the traction network. The current I_{cup} which is the current of the head contact line can be obtained. The simulation result is shown in Figure.2.

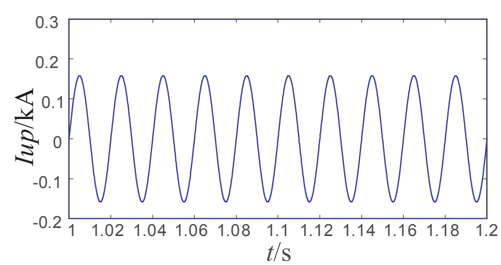

Figure 2. Current Iup of head contact line simulation results

It can be seen from Figure.2, the current I_{cup} of the contact line is stable and has no fluctuation, the stable amplitude is 0.151kA, and the locomotive normally takes the flow.

C. Simulation results of lightning disturbance

Lightning disturbance simulation is built, when lightning disturbance occurs, it is equivalent to inject lightning waves into the traction network, and the lightning point does not form a fault current into the ground, and the TPSS will not cause a fault. At t=1.1s, the locomotive is located 21km at the end of the traction network. A standard lightning impulse wave of 1.2us/50us with amplitude I=50kA is added at 17km of the contact line. The simulation waveform of the current I_{cup} of the contact line is shown in Figure. 3.

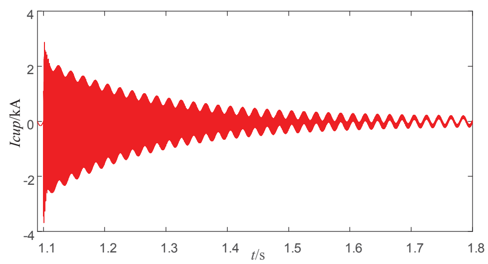

Figure 3. Lightning disturbance,current *I*up of head contact line simulation results

It can be seen from Figure.3,when the lightning disturbance occurs, the current I_{cup} of the contact line will produce a significant transient waveform of 3.97kA. The lightning current propagates along the contact line with a certain oscillation attenuation and lasts for a long time, and basically returns to normal at 1.6s.

D. Simulation results of lightning fault

Lightning fault simulation is built, and the lightning current is first injected into the traction network, which is the same as the lightning disturbance. When the traction network insulator flashes due to overvoltage, a current path into the ground is formed, which becomes a short circuit fault. At t=1.1s, the locomotive is located at 21km at the end of the traction network, and the standard lightning impulse wave of 1.2us/50us with I=50kA is added at F=17km of the contact line. The position of the short circuit is d=17km, and the simulation waveform of the current I_{cup} of the contact line is shown in Figure. 4.

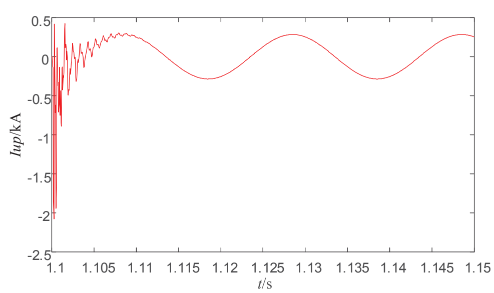

Figure 4. Lightning disturbance,head contact line current I_{cup} simulation results

It can be seen from Figure.4,when the lightning fault occurs, the current I_{cup} of the head contact line will also produce a significant transient waveform of 2.23kA. The lightning current propagates along the contact line and decays, but the duration of transient signal is relatively short and returns to normal at 1.11 s.

In summary, from the time domain characteristics, there is no fluctuation when the lightning current is stable. The time domain characteristics of the lightning disturbance and the lightning fault signal are complex and the peak of the mutation is not much different. It is impossible to visually recognize the three transient signals from the time domain angle. Therefore, the wavelet energy moment is used to perform feature extraction and recognition from the frequency domain.

IV. Signal Feature Extraction Based on Wavelet Energy Moment

The simulation sampling frequency is 20kHz. The db4 wavelet base and the decomposition level 8 are selected for the signal after the start of.1.1s The wavelet coefficient is d_1(k)~d_8(k) and d_9(k). Since the fundamental frequency is not included in the d_9(k), d_9(k) is not helpful for this paper, so it is eliminated. The wavelet energy moment is used to analyze in each simulation signal, and the wavelet energy moment statistics of each frequency band are obtained as shown in Figure.5, Figure.6, and Figure.7.

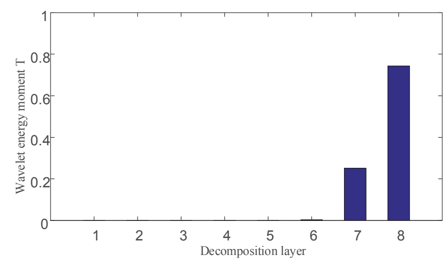

Figure 5. Wavelet energy band statistics without lightning

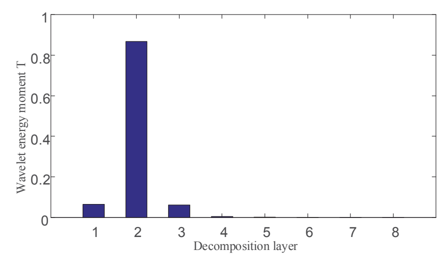

Figure 6. Wavelet energy band statistics of frequency bands of lightning interference signals

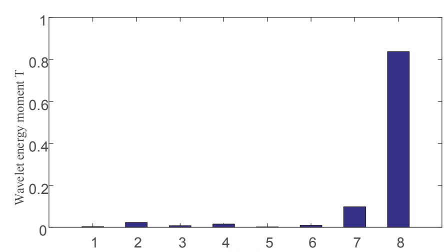

Figure 7. Wavelet energy band statistics of frequency bands of lightning fault signal

It can be seen from Figure.5, Figure.6, and Figure.7:

1) The T8 of the wavelet energy moment is the highest in normal and lightning fault., while the T2 of the lightning disturbance transient signal is the highest. Therefore, the lightning disturbance can be accurately recognized by $T_m=T_2$.

2) The two signal wavelet energy moments of normal and lightning fault are mainly concentrated in the frequency band 8. The ratio of $k=T_8/T_7$ of normal is less than 3, and the other frequency bands are almost 0; However, the ratio of $k=T_8/T_7$ is greater than 8, while the other frequency bands are small but not 0. Therefore, combined with T_8 and T_7, the ratio of $k=T_8/T_7$ can be used to recognize normal and lightning fault. Therefore, considering a certain margin of $k=T_8/T_7$, the threshold value k_0 is set to $k_0=3\times1.5=4.5$. The threshold value k_0 can be used to recognize normal and lightning fault.

In summary, a flow chart of transient signal recognition as shown in Figure. 8.

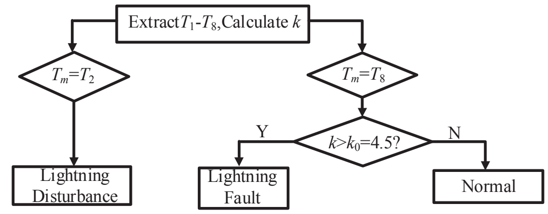

Figure 8. Three kinds of transient signal recognition algorithm flow

V. SIMULATION VERIFICATION

Based on the simulation model of the TPSS of Figure. 1, the simulation is set in normal, lightning disturbance and lightning fault. The recognition results are shown in TABLE I below, L is the length of the traction network; T is the position of the locomotive at the traction network; A is the lightning current amplitude; F is the lightning distance; d is the short-circuit distance; R is the transition resistance.

TABLE I. RECOGNITION RESULTS OF DIFFERENT SIGNALS

Signal	**Condition**	T_2	T_7	T_8	T_m	k	**Result**
Normal	L=21km T=21km	/	0.2519	0.7441	T_8	2.95	Normal
	L=21km T=17km	/	0.2525	0.7435	T_8	2.94	Normal
Lightning Disturbance	A=50kA F=17km	0.8672	0.0005	0.0008	T_2	/	Lightning Disturbance
	A=50kA F=14km	0.8800	0.0005	0.0008	T_2	/	Lightning Disturbance
Lightning Fault	A=50kA F=17km d=17km R=100Ω	/	0.0976	0.8371	T_8	8.58	Lightning Fault
	A=50kA F=14km d=14km R=100Ω	/	0.0985	0.8397	T_8	8.52	Lightning Fault

It can be seen from TABLE I, for the three different transient signals, the recognition result based on the transient signal recognition algorithm shown in Figure. 8 is correct, and the recognition algorithm can accurately and reliably recognize three different types of transient signals.

Change the lightning strike distance, and count the values of T_2, T_7 and T_8 of signals under different working conditions. The results are shown in TABLE II below, A is the lightning current amplitude; F is the lightning strike distance; d is the short circuit distance; R is the transition resistance.

TABLE II. RECOGNITION RESULTS UNDER DIFFERENT LIGHTNING DISTANCE

Signal	**Condition**	T_2	T_7	T_8	T_m	k	**Result**
Lightning Disturbance	A=50kA F=17km	0.8672	0.0005	0.0008	T_2	/	Lightning Disturbance
	A=50kA F=14km	0.8800	0.0005	0.0008	T_2	/	Lightning Disturbance
	A=50kA F=7km	0.5435	0.0081	0.0108	T_2	/	Lightning Disturbance
Lightning Fault	A=50kA F=17km d=17km R=100Ω	/	0.0976	0.8371	T_8	8.58	Lightning Fault
	A=50kA F=14km d=14km R=100Ω	/	0.0985	0.8397	T_8	8.52	Lightning Fault
	A=50kA F=7km d=7km R=100Ω	/	0.0962	0.9010	T_8	9.73	Lightning Fault

It can be seen from TABLE II, for the lightning disturbance and lightning fault signals, the position of the lightning point is changed, and the recognition result of the recognition algorithm is correct, and three different types of transient signals can be accurately and reliably recognized, and the recognition algorithm is not affected by the lightning distance.

Change the amplitude of the lightning current, and count the values of T_2, T_7 and T_8 of the signal under different conditions. The results are shown in TABLE III below. A is the lightning current amplitude; F is the lightning distance; d is the short-circuit distance; R is transition resistance.

TABLE III. RECOGNITION RESULTS UNDER DIFFERENT LIGHTNING CURRENT AMPLITUDE CONDITIONS

Signal	**Condition**	T_2	T_7	T_8	T_m	k	**Result**
Lightning Disturbance	A=50kA F=17km	0.8672	0.0005	0.0008	T_2	/	Lightning Disturbance
	A=35kA F=14km	0.8610	0.0006	0.0012	T_2	/	Lightning Disturbance
	A=50kA F=7km	0.5435	0.0081	0.0108	T_2	/	Lightning Disturbance
	A=35kA F=7km	0.4944	0.0086	0.0122	T_2	/	Lightning Disturbance
Lightning Fault	A=50kA F=14km d=14km R=100Ω	/	0.0985	0.8397	T_8	8.52	Lightning Fault
	A=35kA F=14km d=14km R=100Ω	/	0.0998	0.8661	T_8	8.68	Lightning Fault
	A=50kA F=7km d=7km R=100Ω	/	0.0962	0.9010	T_8	9.73	Lightning Fault
	A=35kA F=7km d=7km R=100Ω	/	0.0962	0.9010	T_8	9.37	Lightning Fault

It can be seen from TABLE III ,for the lightning disturbance signals and lightning fault signals, when the lightning current amplitude is changed and the recognition result is correct. The recognition algorithm has certain adaptability to the lightning current amplitude change.

when the lightning distance and the short-circuit distance are different, the position of the lightning point and the position of the short-circuit point are changed, and the values of T_2, T_7 and T_8 of the signal under different conditions are counted. The results are shown in TABLE Ⅳ below, and A is the lightning current amplitude; F is the lightning distance; d is the short-circuit distance; R is the transition resistance.

TABLE IV. IDENTIFICATION RESULT OF LIGHTNING STRIKE AND SHORT CIRCUIT DISTANCE

Signal	**Condition**	T_2	T_7	T_8	T_m	k	**Result**
Lightning Fault	A=50kA F=17km d=7km R=100Ω	/	0.0805	0.7878	T_8	9.79	Lightning Fault
	A=50kA F=14km d=7km R=100Ω	/	0.0850	0.8313	T_8	9.78	Lightning Fault
	A=50kA F=7km d=14km R=100Ω	/	0.0737	0.7245	T_8	9.83	Lightning Fault
	A=35kA F=17km d=7km R=100Ω	/	0.0854	0.8409	T_8	9.85	Lightning Fault
	A=35kA F=14km d=7km R=100Ω	/	0.0879	0.8660	T_8	9.85	Lightning Fault
	A=35kA F=7km d=14km R=100Ω	/	0.0799	0.7951	T_8	9.95	Lightning Fault

It can be seen from TABLE Ⅳ, for the lightning fault signal, the lightning distance and the short-circuit distance are changed, and the recognition result is also correct. The recognition algorithm has adaptability to the different of lightning distance and the short-circuit distance.

In summary, the recognition algorithm has strong adaptability and is not affected by conditions such as lightning distance, lightning current amplitude and short-circuit distance, and can correctly recognize three kinds of transient signals.

VI. CONCLUSION

In this paper, the wavelet energy moment is used to extract the transient signals of the TPSS, and the wavelet energy moment recognition method is applied to the signal recognition of the TPSS. The lightning disturbance is recognized by $T_m=T_2$, and the threshold $k_0=4.5$ of T8/T7 is further utilized to form a criterion to recognize normal conditions and lightning faults. Finally, it can reliably recognize the three types of transient signals of the TPSS, normal,lightning disturbance and lightning fault. And it can provide the theoretical basis with recognizing the lightning disturbance of the TPSS effectively and avoiding the mistripping of the relay protection in the traction substation,thereby it can improve the safety and economic benefits of the TPSS effectively. The simulation and recognition of other transient signals in the TPSS need to be further researched.

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