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Research on Lightning Warning Method Based on the Characteristics of Atmospheric Electric Field

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***Abstract*—Aiming at the shortcomings of traditional lightning protection measures in active defense for lightning accident, it is necessary to carry out studies on lightning warning method. On the basis of lightning warning information, measures can be taken to avoid lightning risk in advance. This paper makes comparative analysis between fair-weather electric field and thunderstorm-weather electric field by using Hilbert-Huang Transform, and analyses their intrinsic oscillation characteristics for lightning warning. Combining the amplitude of atmospheric electric field with its proportion of energy on high frequency band, a lightning warning method is proposed. Then typical thunderstorm-weather is utilized to verify this lightning warning method workable and accurate.**

Keywords-active defense; lightning warning method; atmospheric electric field; Hilbert-Huang Transform

I. Introduction

Lightning is a nature phenomenon going with strong discharge, which is regarded as one of the top ten serious natural disasters by United Nations. According to statistics, there are two thousand thunderstorms happening around the world per minute on the average. And there are more than ten thousand casualties caused by lightning stroke. It is clear that lightning poses an enormous threat to people's normal life. Meanwhile, lightning may bring damage to buildings, power supply systems, communication equipments, household electric appliances, etc. Furthermore, it can lead to fires, even explosions, which can cause heavy casualties and big economic losses. In recent years, the technologies of lightning protection have been greatly improved, which make people capable of lightning real-time capture and lightning damage afterward evaluation. Nevertheless, there is still a lack of initiative lightning protection measures for lightning incidents. Accordingly, emergency plans can’t be made before the coming thunderstorm[1-3].

Lightning warning is the key technology for initiative lightning protection. Current researches focus on multi-stage lightning warning method based on the characteristics of atmospheric electric field[4-8]. In engineering applications, lightning warning function is realized by set multi-level alarm thresholds on atmospheric electric field or differential atmospheric electric field. And the characteristics of atmospheric electric field can be acquired according to the statistics for atmospheric electric field amplitude’s changes within the detection area. This lightning warning method is simple and convenient. However, its false positive and false negative rates are high, and the alarm thresholds are closely related to local atmospheric environment. Therefore, this method does not have a universal applicability on actually engineering project.

Time sequence of atmospheric electric field can reflect the changes of charge distribution during thunderstorm-weather from the side. To analyze its inherent oscillation characteristics can improve the accuracy and applicability of lightning warning method[9-10]. But at the moment of thunderstorm, atmospheric electric field waveform is non-linear, non-stationary, weakly dependent and highly variant in time-frequency domain. These characteristics result in the invalidation of conventional signal processing methods such as Fourier Transform. On the basis of above considerations, this paper adopts Hilbert-Huang Transform (HHT) to decompose the time sequence of atmospheric electric field. Then, detailed comparative analysis has been done between fair-weather electric field and thunderstorm-weather electric field. The result of researches shows that the proportion of high frequency component of thunderstorm-weather electric field is obviously higher. From this finding, a lightning warning method based on the characteristics of atmospheric electric field is proposed. And application effect shows that the prediction lightning range basically tallies with the actual lightning area.

II. Methodology of HHT

Hilbert-Huang Transform (HHT) provides an effective method in analyzing and processing non-linear and non-stationary signals. It has characteristics of self-adaptation and good efficiency, and analysis of Hilbert spectrum can clearly express the energy distribution with time and frequency in details[11]. HHT is developed through integrating empirical mode decomposition (EMD) and classical Hilbert transform. When HHT is employed for signal processing, the complicated original data sequence is decomposed into a series of intrinsic mode functions (IMF) and a residue by EMD firstly. The IMF components are all stable, which can be transformed into signal amplitudes and instantaneous frequencies as the functions of time by the Hilbert transform method. The resultant Hilbert spectrum can accurately reflect the physical processes of energy in various frequency scales and time distribution[12].

A. Empirical mode decomposition

EMD is the core of Hilbert-Huang transformation. The iterative process in EMD is called sifting procedure, which has the following steps: finding the extreme of the signal, constructing the upper and lower envelopes of the signal by the extreme and subtracting the mean of the two envelopes from original signal. The steps are repeated until the mean envelope is close to zero and the residue signal is called IMF. An IMF is defined as a function satisfying the following conditions[13]:

(1) The number of extremes and the number of zero-crossings must either equal or differ at most by one.

(2) At any point, the mean value of the envelope defined by the local maxima and the envelope defined by the local minima is zero.

Suppose the detection signal is $x(t)$, in EMD $x(t)$ is represented as expression (1), $c_i(t)$ is the ith order IMF, the number of IMFs is m, $r_0(t)$ is the trend function whose frequency is the lowest.

$$x(t)=\sum_{i=1}^{m}c_i\left(t\right)+r_0\left(t\right) \tag{1}$$

B. Hilbert transform

An IMF defined as above admits well-behaved Hilbert transform. For an arbitrary function, $X(t)$, its Hilbert transform, $Y(t)$, is defined as[14]

$$Y(t)=\frac{1}{\pi}P\int_{-\infty}^{\infty}\frac{X(\tau)}{t-\tau}d\tau \tag{2}$$

P indicates the Cauchy principal value. Consequently an analytic signal, $Z(t)$ can be produced by

$$Z(t)=X\left(t\right)+iY\left(t\right)=a\left(t\right)e^{i\theta(t)} \tag{3}$$

Where

$$a\left(t\right)=\left[X\left(t\right)^2+Y\left(t\right)^2\right]^{\frac{1}{2}},\theta(t)=\arctan(\frac{Y\left(t\right)}{X\left(t\right)}) \tag{4}$$

are the instantaneous amplitude and phase of $X(t)$.

Since Hilbert transform Y(t) is defined as the convolution of $X(t)$ and $1/t$ by formula (2), it emphasizes the local properties of $X(t)$ even though the transform is global.

In formula (3), the polar coordinate expression can further clarify the local nature of this representation. With formula (3), the instantaneous frequency of $X(t)$ is defined as

$$\omega(t)=\frac{d\theta\left(t\right)}{dt} \tag{5}$$

EMD is a necessary pre-processing of the data before the Hilbert transform is applied. It reduces the data into a collection of IMFs and each IMF, which represents a simple oscillatory mode, is a counterpart to a simple harmonic function, but is much more general.

Therefore, by formula (1) to formula (5), $x(t)$ can be expressed as the IMF expansion as follows[14]

$$x\left(t\right)=real\left[\sum_{j=1}^{n}a_j\left(t\right)\exp\left(i\int\omega_j\left(t\right)dt\right)\right]+r_0\left(t\right) \tag{6}$$

Formula (6) enables us to represent the amplitude and the instantaneous frequency as functions of time in a three-dimensional plot, in which the amplitude is contoured on the time-frequency plane, denoted by $H(\omega, t)$.

$$h\left(\omega\right)=\int_0^T H\left(\omega,t\right)dt \tag{7}$$

The marginal spectrum offers a measure of total amplitude (or energy) contribution from each frequency value.

III. CHARACTERISTICS ANALYSIS ON ATMOSPHERIC ELECTRIC FIELD

The changes of atmospheric electric field are closely related with thunderstorm activities. When the atmospheric potential gradient reaches the breakdown value, there will be a lightning. Therefore, characteristics analysis of atmospheric electric field in a certain area not only can contribute to the understanding of electrical characteristics in different weather, but also can contribute to lightning warning[15]. In order to obtain the premonition of thunderstorm, this paper does a detailed comparative analysis on atmospheric electric field between fair-weather and thunderstorm-weather by using HHT.

Through analysis of the time sequence of atmospheric electric field, it turns out that the fair-weather atmospheric electric field changes comparatively slowly and has a high proportion of lower-frequency component. On the contrary, the thunderstorm-weather atmospheric electric field changes quickly and contains a lot of high-frequency component. In addition, the time sequence of atmospheric electric field is non-linear and non-stationary, so HHT is adopted to calculate the proportion of energy on various frequency bands accounting for total energy. Then, distinguishing between fair-weather atmospheric electric field and thunderstorm-weather atmospheric electric field has been made. Following the outcome, lightning warning can be realized.

A. Characteristics Analysis on Fair-weather Atmospheric Electric Field

In order to analyze the characteristics of fair-weather atmospheric electric, the time sequence of atmospheric electric field on October 1th of 2015, $x(t)$, is taken as a typical example in this paper.

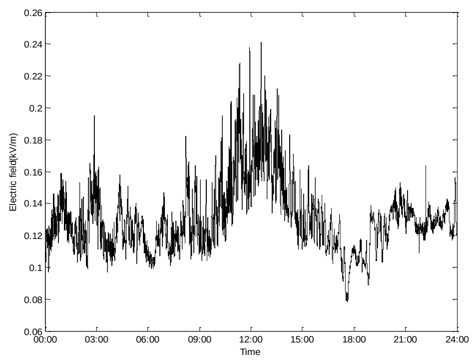

Figure 1. Waveform of fair-weather atmospheric electric field

Through taking 30 minutes as time interval, the average $x(t)_{avg}$, maximum $x(t)_{max}$ and minimum $x(t)_{min}$ of the atmospheric electric field $x(t)$ in each interval are calculated to understand the electrical characteristics during fair-weather as shown in Table.1.

Table 1. Statistical analysis of fair-weather atmospheric electric field

Index	Average(kV/m)	Range(kV/m)
$x(t)_{avg}$	0.1310	0.0962~0.1815
$x(t)_{max}$	0.1596	0.1140~0.2410
$x(t)_{min}$	0.1109	0.0780~0.1430

The average of fair-weather atmospheric electric field on land is 0.115kV/m ranging from 0.019kV/m to 0.310kV/m. And the statistical results in Table.1 have perfectly verified these characteristics. Thus, there is a very good reference value to take $x(t)$ as research object.

As an example, the time sequence of atmospheric electric field from 09:00 to 09:30, $x(T)$, is selected to undertake feature analysis. After EMD decomposing $x(T)$, six IMFs are extracted as shown in Figure.2.

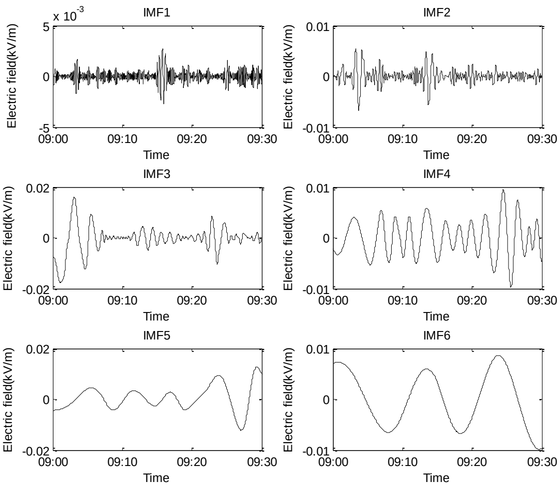

Figure 2. EMD on fair-weather atmospheric electric field

Then, Hilbert transform is used to obtain the amplitude distribution of IMF1~IMF6, respectively.

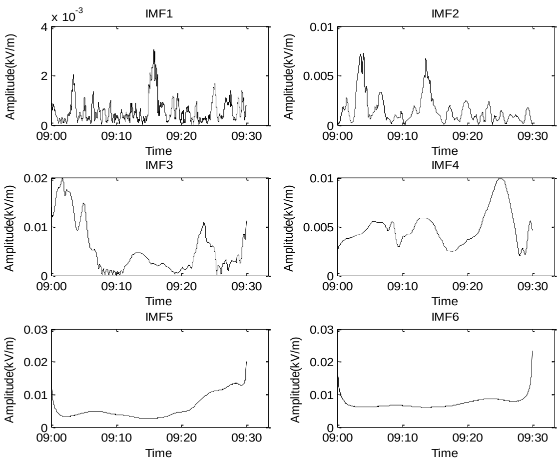

Figure 3. Amplitude distribution of fair-weather atmospheric electric field on various frequency bands

As the amplitude distribution of IMF1~IMF6 are tremendously complicated, it is difficult to identify their inherent oscillation characteristics. So this paper calculates the proportion of energy on high frequency band accounting for total energy as characteristic parameters.

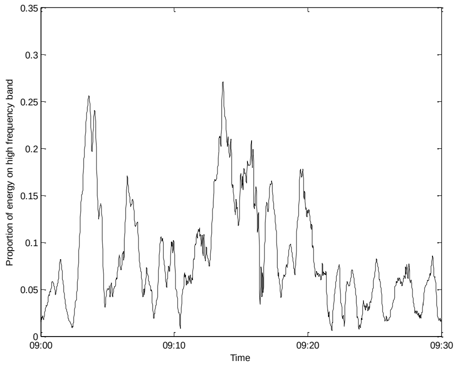

Figure 4. The proportion of energy on high frequency band of fair-weather atmospheric electric field

Comprehensive factors were considered, the amplitude of fair-weather atmospheric electric field is small and its average is about 0.1310kV/m. In addition, the proportion of energy on high frequency band is relatively low, and the maximum is only 27.32%.

B. Characteristics Analysis on Thunderstorm-weather Atmospheric Electric Field

The time sequence of atmospheric electric field on August 1th of 2015, $y(t)$, is taken to analyze the characteristics of thunderstorm-weather atmospheric electric field. The waveform representing its changes with time is shown in Figure.5.

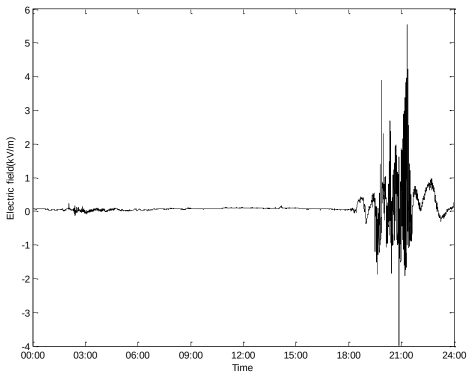

Figure 5. Waveform of thunderstorm-weather atmospheric electric field

Similarly, through taking 30 minutes as time interval, the average $y(t)_{avg}$, maximum $y(t)_{max}$ and minimum $y(t)$min of the atmospheric electric field $y(t)$ in each interval are calculated to understand the electrical characteristics during thunderstorm-weather as shown in Table.2.

Table 2. Statistical analysis of thunderstorm-weather atmospheric electric field

Index	Average (kV/m)	Range (kV/m)
$y(t)_{avg}$	0.0827	-0.0734~0.6993
$y(t)_{max}$	0.4590	0.0560~5.5490
$y(t)_{min}$	-0.2353	-3.9930~0.0950

Based on data of lightning location system on August 1th of 2015, there are lightning activities at 20:15:54 as shown in Table.3.

Table 3. Lightning activities at 20:15:54 on August 1th of 2015

Time	Microsecond	Longitude (°)	Latitude (°)	Current (kA)	Distance (m)
20:10:54	2713150	112.9883	38.54342	-30.6	3130.284
20:10:54	3303959	112.9891	38.54257	-21.8	3088.069
20:10:54	3889230	112.9961	38.54539	-32	3699.801
20:10:54	4215691	112.9828	38.53749	-16.7	2321.657
20:10:54	6666710	112.9902	38.54482	-16.4	3350.893
20:10:54	7544408	112.9885	38.54306	-25.7	3104.578
20:10:54	8384558	112.9918	38.54425	-24.6	3371.951
20:10:54	9591224	112.99	38.54378	-15.3	3244.226

Then, this paper selects the time sequence 30 minutes before the occurrence of lightning, namely from 19:40 to 20:10, $y(T)$, to undertake feature analysis. After EMD decomposing $y(T)$, eight IMFs are extracted as shown in Figure.6.

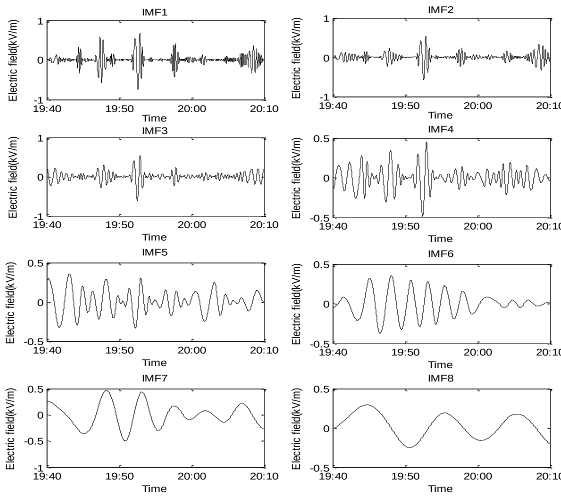

Figure 6. EMD on thunderstorm-weather atmospheric electric field

Also, Hilbert transform is used to obtain the amplitude distribution of IMF1~IMF8, respectively.

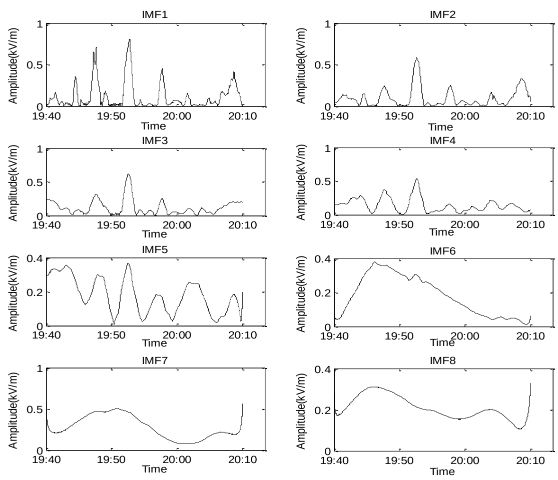

Figure 7. Amplitude distribution of thunderstorm-weather atmospheric electric field on various frequency bands

The proportion of energy on high frequency band is calculated as shown in Figure.8.

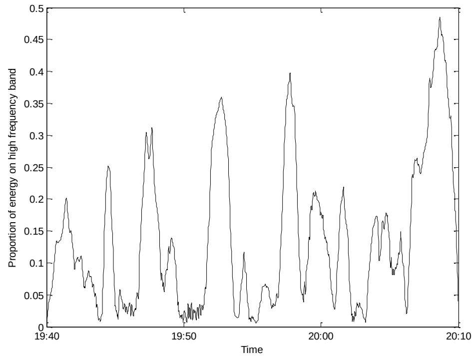

Figure 8. The proportion of energy on high frequency band of thunderstorm-weather atmospheric electric field

Comprehensive factors were considered, the amplitude of thunderstorm-weather atmospheric electric field is large and its average is about 5.5490kV/m. Also the proportion of energy on high frequency band is relatively high, and the maximum can reach 60.9%.

IV. Lightning Warning Method Base on the Characteristics of Atmospheric Electric Field

Through the above comparative analysis on atmospheric electric field between fair-weather and thunderstorm-weather by using HHT, it is to be concluded that the amplitude of thunderstorm-weather atmospheric electric field and its proportion of energy on high frequency band are relatively larger, which can be treated as characteristic parameters for lightning warning.

The amplitude of atmospheric electric field is used for getting the level of lightning strength. Through statistical analysis of historical atmospheric electric field during thunderstorm-weather, warning threshold is set as 2kV/m, 5kV/m and 8kV/m corresponding to three-level lightning warning as shown in Table.4.

Table 4. Warning level based on the amplitude of atmospheric electric field

Index \ Warning Level	Lightning Yellow warning	Lightning Orange warning	Lightning Red warning
Atmospheric Electric Field	2kV/m	5 kV/m	8 kV/m

The proportion of energy on high frequency band accounting for total energy is used to determine whether the lightning occurs. Basing on lots of analysis and statistics, the proportion for lightning warning is set as 40%. When the proportion calculated by HHT reaches the threshold value, lightning warning information about the lightning warning level, lightning warning time and so on, will be issued. The concrete steps are listed as follows.

(1) Monitoring the atmospheric electric field $E(t)$ in real-time.

(2) Comparing atmospheric electric field $E(t_i)$ with the threshold at each moment, if $E(t_i) < 2$ kV/m, it is evaluated as fair-weather, and going to step (6), otherwise going to step (3).

(3) If $E(t_i)$ >8 kV/m, lightning warning information is previously set as lightning red warning, else if $E(t_i)$ >5 kV/m, lightning orange warning, else if $E(t_i)$ >2 kV/m, lightning yellow warning.

(4) Selecting the time sequence 30 minutes before time t_i to calculate the proportion of energy on high frequency band accounting for total energy, $r(t)$.

(5) If there exists a time t_j satisfying $r(t_j)$>0.4, sending the lightning warning information as be set previously.

(6) Repeating step (2) to step (5) at the next time t_{i+1}.

The time sequence of atmospheric electric field on July 5th of 2015 is selected to test the lightning warning method proposed in this paper. And the result of lightning warning is shown in Figure.9.

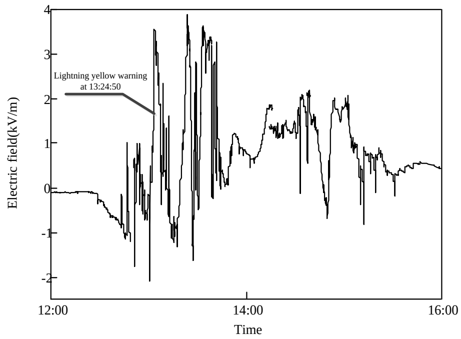

Figure 9. The result of lightning warning on July 5th of 2015

Based on this lightning warning method, lightning yellow warning is issued at 13:24:50, while at 13:35:26 by traditional method. Actually, there are lightning activities occurring from 13:43:07 to 13:44:39 through querying the lightning location system. The results of the query are shown in Table.5.

Table 5. Lightning activities from 13:43:07 to 13:44:39 on July 5th of 2015

Time	Longitude (º)	Latitude (º)	Current (kA)
13:43:07.106	111.9127	37.8410	-23.4
13:43:07.106	111.9127	37.8410	-23.4
13:43:24.959	111.4037	37.9627	-10.6
13:43:24.959	111.4037	37.9627	-10.6
13:43:49.089	111.8700	37.9592	47.0
13:43:49.089	111.8700	37.9592	47.0
13:44:39.512	111.9531	37.8480	-24.2
13:44:39.512	111.9531	37.8480	-24.2
13:44:39.620	111.9573	37.8471	-22.1
13:44:39.620	111.9573	37.8471	-22.1

This lightning warning method can improve the accuracy of lightning warning by 25% to 35%. Also the lightning warning information can be issued 10~30 min earlier.

V. CONCLUSION

Based on the traditional threshold value method for lightning warning, this paper adds the proportion of energy on high frequency band as characteristic parameter to determine whether the lightning occurs. The characteristic parameter is extracted by using HHT to decompose the atmospheric electric field. HHT is proved very useful and effective in analyzing and processing non-linear and non-stationary signals. Therefore, the proposed lightning warning method is very workable in engineering application. Also the test result indicates that it can reduce the false positive ratio of lightning warning. When the proposed lightning warning method is applied, it can supply accurate lightning warning information.

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