Denoising of Lightning Electric Field Signals Based on EMD-Wavelet Method

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Abstract. In this paper, a new lightning electric field (LEF) signals denoising approach combined with empirical mode decomposition (EMD) and wavelet transform (WT) is proposed. Unlike the conventional EMD or WT denoising approaches, we use EMD to decompose the LEF signal firstly, the continuous mean square error (CMSE) criteria are used to determine a turning point in the original signal energy, then the Birge-Massart threshold wavelet denoising method is employed to denoise the high frequency component which contains lots of noise. Finally, the clean high frequency component and the remaining low frequency intrinsic mode function, and the residual of the EMD operation are employed to synthesize a cleaner LEF signal. The method is illustrated on real data, and the performance of the proposed method is evaluated in terms of several standard metrics. The results show that the proposed method is able to reduce noise from the noisy LEF signals more accurately and effectively in comparison to EMD filtering and Wavelet filtering methods.

Introduction

Lightning is a kind of atmospheric discharge phenomenon with strong destructive power and widespread. Research on occurrence, development law, physical properties of lightning will be of important significance to the lightning early warning and protection. However, one of the most important tools to understand the lightning phenomena is the lightning-generated electric field. However, the measure signals are frequently corrupted with various noise components. Sometimes the noise contamination may compromise the efficacy of the lightning signal processing. In such scenario, it is extremely useful to denoise lightning electric field signals. Some recent relevant contributions have proposed solutions using a wide range of different techniques, such as the wavelet transform[1-5], adaptive filtering[6-8]. However, these methods have not been widely used to remove the undesired components from original lightning electric field signals, except for a few techniques based on the classic Fourier transform as well as on the wavelet transform.

In this work, we propose a new method for the lightning electric field data from measurements enhancement based on the EMD-Wavelet method. First, the LEF signal is adaptively decomposed into intrinsic oscillatory components called intrinsic mode functions (IMFs) by EMD, the CMSE criteria is used to determine a turning point in the original signal
energy. Second, the Birge-Massart threshold wavelet denoising method is employed to denoise the IMFs before energy turning point which are considered to contain more noise. Finally, the clean IMFs, and the remaining IMFs and the residual of the EMD operation are employed to synthesize a cleaner LEF signal. The experimental studies show that the proposed EMD-Wavelet-based method is a good tool for LEF signals denoising.

Data and Methodology

Instrumentation and Data Acquisitions

The measurements were recorded between July and August 2009, during the simultaneous comprehensive observations of natural lightning discharges in the northeastern verge of Qinghai–Tibet Plateau area in China. In this paper, the signals recorded by the fast antenna system are chosen for the analyses. The fast electric field measuring antenna systems was composed by a flat plate antenna connected to an integrator circuit as well as a AD converter. The integrator circuit has a 1ms decay time constant and the bandwidth observed was up to 100Hz–5 MHz. The electric field signal was digitized by a 14-bit A/D converter with a rate of 2500000 samples per second and transferred from the antenna to the computer via the coaxial cable.

EMD and De-noising Principles

The Empirical mode decomposition (EMD) method was first developed by Huang et al. (1998) to analyze nonlinear and non-stationary data[9]. The objective of the method is to adaptively decompose a time-series signal into a set of intrinsic mode functions (IMFs) and a residual (i.e. expression (1)).

\[ x(t) = \sum_{j=1}^{n} IMF_{j}(t) + r_n(t) \]  

where \( x(t) \) stands for the original signal, \( IMF_{j}(t) \) for the decomposed IMFs, and \( r_n(t) \) for the residual.

The denoising method based on the conventional EMD relies on the basic idea that most of the important structures of the signal are often concentrated on the lower frequency ones (last IMFs) and decrease toward high-frequency modes (first IMFs). Thus, according to this idea, there will be a mode indexed by js, after which, the energy distribution of the important structures of the signal overcomes that of the noise and that of the high-frequency components of the signal. This particular mode IMFjs \((t)\) is the turning point of the original signal energy. The modes after IMFjs(t) are dominated by the signal, whereas the previous modes are high-frequency component dominated by the noise. Sometimes these high-frequency dominated by the noise modes are denoising by soft thresholding and be used in the signal reconstruction. Otherwise, these high-frequency modes are set to zero (hard thresholding) and not be used in the signal reconstruction. In this paper, in order to find the mode IMFjs \((t)\), we adopt the consecutive mean square error (CMSE) criteria to determine a turning point in the original signal energy. The CMSE is defined as follows:
\[
CMSE(y_k, \tilde{y}_{k+1}) \triangleq \frac{1}{N} \sum_{i=1}^{N} [\tilde{y}_k(t_i) - \tilde{y}_{k+1}(t_i)]^2 \triangleq \frac{1}{N} \sum_{i=1}^{N} [IMF_k(t_i)]^2
\] 

(2)

Where \( y \) is the reconstruction signal, \( N \) is the length of the signal. The CMSE is reduced to the energy of the \( k \)th IMF. It is considered as the turning point of the energy distribution when the CMSE value is the minimum. The detailed information about the CMSE refers to Ref. [10].

**Wavelet Transform and De-noising Principles**

The wavelet transform is invented to overcome the limits of the Fourier transform and partitions the time-frequency plane in a non-uniform fashion and shows finer frequency resolution than time resolution at low frequencies and finer time resolution than frequency resolution at higher frequencies. It has emerged as a powerful mathematical tool in digital signal processing area. The Continuous Wavelet Transform of a signal \( f(t) \) is defined as:

\[
CWT_f(a,b) = \sqrt{a} \int_{-\infty}^{\infty} f(t) \psi^* \left( \frac{t-b}{a} \right) dt, a, b \in \mathbb{R} \quad a \neq 0
\]

(3)

where \( a \) and \( b \) are the real numbers that represent the scale and the location parameter of the transform respectively. The \( CWT_f(a,b) \) are wavelet transform coefficients and the asterisk indicates that the complex conjugate of the wavelet function is applied.

The principle of thresholding denoising method in the wavelet domain relies on the basic idea that the wavelet transform coefficients describing the signal of interest and noise are assumed to be different. In general, it is assumed that the small wavelet coefficients are due to noise and can be set to zero, while the signal is stored in a few large coefficients, which should be retained as the signal of interest. In this paper, we adopt db5 wavelet functions, decomposition level is 5 layers. The Birge-Massart threshold wavelet denoising method is employed.

**Proposed Denoising Method**

In this paper, a new denoising approach combined with EMD and WT is proposed, which is called E-W algorithm. The procedure of the proposed method can be described as follows:

(i) Decompose the original signal into a set of IMFs and a residual by EMD;

(ii) Use the CMSE criteria to decide a turning point of the original signal energy in order to further determine which IMFs should be retained and which IMFs should be de-noised;

(iii) Choose an appropriate mother wavelet and the decomposition level, use the Birge-Massart threshold wavelet method to denoise the previous modes are high-frequency component dominated by the noise;

(iv) Use the de-noised high-frequency IMFs, the remaining lower-frequency IMFs, and the residue of the EMD operation to synthesize a cleaner signal.

**Experimental Results and Analysis**

In this section, in order to further discuss validity and efficiency of the proposed method for the task of denoising, the proposed method was applied to the experimental data and the results along with a test stand and experiment description are presented below. The measured signals analyzed in this section were acquired using the measuring system described in section 2.1. The performance of our method is compared with the wavelet method, EMD method and FIR low-pass filtering method.
in terms of several conventionally used metrics. The simulations were carried out in MATLAB 2010 environment and the comparisons were performed both qualitatively and quantitatively.

First, we evaluate the performance in lightning denoising for all the methods under consideration and compare them qualitatively by visual inspection. Fig.1 presents the enhanced LEF signals in time domain obtained by using the methods as mentioned above, where the original LEF signal CG1 is considered. This figure reveals that the enhanced signals are more distorted in case of the other methods, specially, when merely EMD is used. The signal obtained from the FIR method seems smoother in comparison to the proposed method, it can remove more noise, but it may lose more useful information. It is to be mentioned that the pattern of the enhanced LEF signal resulting from the proposed method resembles the original LEF signal more.

Figure 1. Enhanced LEF Signals in Time Domain Obtained by Using Different Denoising Methods.

Then, we compare the performance of the proposed method quantitatively with respect to the other methods based on three metrics: the signal-to-noise-ratio (SNR) in dB, the mean square error (MSE), and the correlation coefficient (R), which can be used to analyze similarity between the original signal and the denoising signal. At a particular SNR, for a denoising effect to be said better, it is desirable that the smaller the MSE is, the larger the R and SNR in dB are. The metrics are computed as follows:

\[
\text{SNR} = 10 \log \left\{ \sum_{n=1}^{N} y^2(n) / \sum_{n=1}^{N} [\hat{x}(n) - y(n)]^2 \right\} \quad (4)
\]

\[
R = \sum_{n=0}^{N-1} \hat{x}(n)y^*(n) / \left[ \sum_{n=0}^{N-1} |\hat{x}(n)|^2 \sum_{n=0}^{N-1} |y(n)|^2 \right]^{1/2} \quad (5)
\]

\[
\text{MSE} = \frac{1}{N} \sum_{n=1}^{N} [\hat{x}(n) - y(n)]^2 \quad (6)
\]

Where \( \hat{x}(n) \) is the measured signal, and \( y(n) \) is the reconstructed enhanced signal, and \( N \) is the length of the signal.
Fig. 2 shows the results of the correlation coefficient (R) for all the comparison methods using different LEF signals (5 cloud-to-ground (CG) lightning flashes and 5 intracloud (IC) lightning flashes). This figure implies that the highest correlation coefficient (R) is obtained by using our proposed denoising method for all the LEF signals.

![Figure 2](image-url)

Table 1 presents the comparison of the MSE results obtained by using different denoising methods for the same group of LEF signals as used in Fig. 2. It is vivid from this table that for a particular LEF signal, the proposed method yields the smallest MSE thus attest its capability to yield enhanced LEF signal with better quality.

Table 1. Comparison of the MSE Obtained by Using Different Denoising Methods.

<table>
<thead>
<tr>
<th>LEF Signal</th>
<th>Wavelet method</th>
<th>FIR method</th>
<th>EMD method</th>
<th>E-W method</th>
</tr>
</thead>
<tbody>
<tr>
<td>CG1</td>
<td>0.00092342</td>
<td>0.00079579</td>
<td>0.00080195</td>
<td>0.00078567</td>
</tr>
<tr>
<td>CG2</td>
<td>0.000013684</td>
<td>0.00001164</td>
<td>0.00016535</td>
<td>0.0001126</td>
</tr>
<tr>
<td>CG3</td>
<td>0.00033734</td>
<td>0.00036598</td>
<td>0.00032737</td>
<td>0.00029899</td>
</tr>
<tr>
<td>CG4</td>
<td>0.000055472</td>
<td>0.00006432</td>
<td>0.000040413</td>
<td>0.00003994</td>
</tr>
<tr>
<td>CG5</td>
<td>0.000017542</td>
<td>0.00002470</td>
<td>0.00015859</td>
<td>0.0001165</td>
</tr>
<tr>
<td>IC1</td>
<td>0.00097673</td>
<td>0.00072691</td>
<td>0.0004686</td>
<td>0.00046612</td>
</tr>
<tr>
<td>IC2</td>
<td>0.00042496</td>
<td>0.00094666</td>
<td>0.00087746</td>
<td>0.00040416</td>
</tr>
<tr>
<td>IC3</td>
<td>0.00080634</td>
<td>0.0005667</td>
<td>0.00051707</td>
<td>0.00013616</td>
</tr>
<tr>
<td>IC4</td>
<td>0.0082823</td>
<td>0.0062122</td>
<td>0.0054337</td>
<td>0.0047478</td>
</tr>
<tr>
<td>IC5</td>
<td>0.006</td>
<td>0.0026126</td>
<td>0.0024643</td>
<td>0.0010484</td>
</tr>
</tbody>
</table>

A bar diagram presenting the SNR results obtained by using different denoising methods are plotted in Fig. 3 for all the LEF signals. This bar diagram clearly portrays that for any LEF signal, the other comparison methods result in a relatively lowest SNR while the proposed method is best in performance as it yields the higher SNR.
Conclusion

In conclusion, a new method of LEF Signal denoising based on effective noise reduction algorithms combined with EMD and wavelet transform is proposed. The LEF signal is decomposed by EMD method firstly, the continuous mean square error (CMSE) criteria is used to determine a turning point in the original signal energy, then the Birge-Massart threshold wavelet denoising method is employed to denoise the high frequency component which contains lots of noise. Finally, the clean high frequency component and the remaining low frequency intrinsic mode function, and the residual of the EMD operation are employed to synthesize a cleaner LEF signal. The performance of the proposed method is evaluated in terms of several standard metrics: mean square error (MSE), and correlation coefficient (R), and the signal-to-noise-ratio (SNR). The results show that the proposed method outperforms the other existing methods including the wavelet method, EMD method and FIR low-pass filtering method. It is able to reduce noise from the noisy LEF signals more accurately and effectively. This work presented the filtering process by E-W as a good alternative to analyze other lightning events such as preliminary breakdown pulses, bipolar pulses or various pulse trains of electric and magnetic fields produced by a lightning flash, as well as other electromagnetic disturbances.

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References


