Extraction of Sound Signals from Power Cable Impulse Discharge

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Abstract. In the fault detection of buried power cables, random noise in the shock discharge sound signal is difficult to remove by existing filtering methods. A fifth-order convergent independent component analysis (ICA) method based on empirical mode decomposition (EMD) is proposed to extract the impact discharge sound signal. The fifth-order convergence ICA is adopted, so that the eigenmode components decomposed by the EMD and the remaining signals are independent of each other. Using the strong correlation between the frequency spectrum of the discharge sound signal, the eigenmode component with the largest correlation between the frequency spectrum and the high signal-to-noise ratio shock discharge sound signal spectrum is automatically extracted. Finally, the shock discharge sound signal of unknown failure point is obtained. This method has the advantages of less constraints, small dependencies, and fast convergence. The simulation and experimental results further show that the discharge sound signal in the mixed signal can be effectively extracted.

Introduction

Buried cables are prone to failure, but the point of failure is not easily detected. If the fault cannot be dealt with in time, it will cause serious consequences. Therefore, it is of great significance to find a fast and accurate method for locating cable faults. At present, many methods are used in cable fault location, including sonic detection method, magnetic sound synchronization method, audio current induction method, etc. [1]. In these methods, the cable discharge sound signal needs to be detected and extracted. The cable discharge sound signal at the fault point of the cable is extremely susceptible to the influence of ambient noise, which makes it difficult to process the signal. The noise in the cable discharge sound signal is non-stationary random noise. Traditional filtering methods, such as the classic spectral analysis of fast Fourier transform, parametric autoregressive moving average spectral analysis [2], Kalman filter [3], etc., are difficult to remove this noise. The empirical mode decomposition method can decompose mixed signals in engineering practice [4]. However, the empirical mode decomposition method will cause aliasing of the eigenmode components of the signal, which is not conducive to the extraction of the signal. Aiming at the problems of signal decomposition by empirical mode decomposition, scholars at home and abroad have proposed many methods [5], but the processing effect is not ideal. A fifth-order convergent ICA method based on EMD is proposed to extract the impact discharge sound signal, and the effectiveness of the method is proved by simulation and field experiments.

EMD-based Fifth-order Convergence ICA

ICA, which is applied to the extraction of useful sound signals, has achieved good results [6]. However, ICA can be solved only when the number of observation channels is not less than the number of source signals in the mixed signal. In practical applications, only one observation signal can be obtained. As a result, the use of ICA has been reduced. EMD can decompose a single signal. During the decomposition process, EMD cannot completely guarantee that the decomposition components are independent or orthogonal to each other, and the modal components obtained by the decomposition have modal aliasing [7]. Through the analysis of the two methods, ICA and EMD are
combined. This method can not only decompose a single signal, but also make the decomposition results independent of each other.

The initial separation matrix in ICA is randomly selected, which will cause a large difference in the number of iterations and even non-convergence. Therefore, the relaxation factor $\alpha$ is used to overcome the dependence on the initial value and increase the convergence range. The objective function of ICA algorithm based on the largest negative entropy is Eq. 1.

$$F(W_k) = E\{Xg(W_k^T X)\} - \beta W_k$$ (1)

In the formula, $W_k$ is the separation matrix, $k$ is the number of iterations, $E$ is the mean operation, $X$ is the observation data, $g$ is a non-linear function, and $\beta = E\{W_k^T Xg(W_k^T X)\}$. $\alpha$ is a relaxation factor, which has a characteristic of continuously decreasing the objective function value. $\alpha$ is represented by Eq. 2, that is, Eq. 3.

$$\|E\{Xg(W_{k+1}^T X)\} - \beta W_{k+1}\| < \|E\{Xg(W_k^T X)\} - \beta W_k\|$$ (2)

$$\min_{\alpha_k} \|F(W_k - \alpha_k F(W_k) / JF(W_k))\|$$ (3)

In Eq. 3, $J$ is the Jacobian matrix, $JF(W_k) \approx E\{g'(W_k^T X)\} - \beta$. By introducing a relaxation factor $\alpha$, $F(W_k)$ is brought into the convergence region of the Newton iteration method, thereby ensuring the convergence of the ICA results. The introduction of relaxation factor ICA algorithm will lead to slower solution speed. Therefore, ICA based on the fifth-order convergence Newton iteration method is used to improve the convergence speed. The basic steps of the fifth-order convergent ICA sound signal extraction method based on EMD are:

1) The sound signal $z_0$ is collected and saved in advance. The mixed signal $x_0$ is collected under a strong background noise environment in actual detection. Under different constraints such as time and environment, the signals $z_0$ and $x_0$ are collected separately.

2) The eigenmode component $imf_i$ is obtained from the signal $x_0$ through empirical mode decomposition, and the decomposition algebra $i = 1$ is set.

3) The mixed signal matrix $X = \begin{bmatrix} x_{i-1} \\ imf_i \end{bmatrix}$ composed of the signals $imf_i$ and $x_{i-1}$ is processed for centralization and pre-whitening. The separation matrix $W_0$ is randomly initialized. Convergence error is set to $\varepsilon = 1 \times 10^{-5}$.

4) The convergence factor $\alpha_k = 1$ is initialized and $\Delta W_k$ is calculated according to Eq. 4.

$$\Delta W_k = F(W_k) / JF(W_k)$$ (4)

5) Eq. 5 is judged whether it is true or not. If it is not true, let $\alpha_{k+1} = 0.5 \alpha_k$, update $\alpha_k$, and repeat this step. If true, then $W_{k+1} = W_k - \alpha_k \Delta W_k$ and proceed to the next step.

$$\|F(W_k - \alpha_k \Delta W_k)\| < \|F(W_k)\|^2$$ (5)

6) $W_{k+1}$ is calculated according to Eq. 6, and it is decorrelated and normalized.

7) Eq. 7 is judged whether it is true or not. If it is not true, go back to step 6. If it is true, the algorithm is proved to be convergent and the separation matrix $W_{k+1}$ is obtained. The two independent components of the ICA, $imf_i$ and $x_i$, are found according to $W_{k+1}^T X$, which is equivalent to $imf_i$.
according to the statistical independent meaning Separated from \( x_{i-1} \).

\[
\begin{align*}
W_k^* &= \alpha_k E\{Xg(W_k^T X)\} - E\{g(W_k^T X)\}W_k - \beta(1 - \alpha_k)W_k^* \\
W_k^{\oplus} &= 2E\{Xg(W_k^T X)\} - \{E\{g(W_k^T X)\} + E\{g(W_k^{\oplus T} X)\}\}W_k \\
W_k^* &= E\{Xg(W_k^{\oplus T} X)\} - E\{g(W_k^{\oplus T} X)\}W_k^* \\
W_{k+1} &= W_k^{\oplus} / \|W_k^{\oplus}\| \\
\end{align*}
\]

(6)

\[
\|W_{k+1} - W_k\| < \varepsilon
\]

(7)

According to the frequency, the two ICA component signals correspond to the intrinsic modal components \( \text{imf}_i \) and signal \( x_i \). The component with a high frequency and a large number of maximum points in the same time period is an intrinsic modal component \( \text{imf}_i \). The component with a low frequency and a small number of maximum points in the same time period is the signal \( x_i \).

9) Empirical mode decomposition algebra is judged whether it reaches a predetermined value. If the predetermined value is reached, the spectral distributions of the signal \( z_0 \) and the eigenmode components \( \text{imf}_i \sim \text{imf}_i \) are calculated respectively. The spectrum distribution of \( \text{imf}_1 \sim \text{imf}_i \) is compared with the spectrum distribution of the signal \( z_0 \). If it does not reach the predetermined value, \( i = i + 1 \). The empirical mode decomposition of the signal \( x_{i-1} \) is continued to obtain the eigenmode component \( \text{imf}_i \), and return to step 3.

10) The \( \text{imf}_i \) is used to represent the eigenmode component with the greatest correlation between the extracted spectrum and the signal \( z_0 \) spectrum, which is the final required sound signal.

Algorithm Simulation and Experimental Verification

Algorithm Simulation

An exponentially decaying oscillating signal is used to represent a shock discharge sound signal. The mixed signal is constituted by superposing a discharge sound signal on white Gaussian noise. The mixed signal with noise has an initial signal-to-noise ratio of -14 dB. As shown in Fig. 1, Fig. a is an impulse discharge sound signal, and Fig. b is a mixed signal. After the improved ICA method, the mixed signal is processed as shown in Fig. 2. The other interference noise is basically removed. The signal to noise ratio of the signal is -6 dB, which is 8 dB higher than the original signal to noise ratio.

![Figure 1. Shock discharge sound signals and mixed signals.](image1.png)

![Figure 2. The impact discharge sound processed with this method.](image2.png)
Experimental Verification

In order to verify the actual effectiveness of the algorithm, the fault point was completely broken down with a voltage of 15 ~ 30 kV, and an impact discharge sound was generated. Mixed signals directly above the failure point in the experimental environment and 5M from the failure point in the actual working environment were collected separately. As shown in Fig. 3, Fig. a is the mixed signal in the experimental environment, and Fig. b is the mixed signal in the actual working environment.

The improved ICA method is used to process the mixed signal of the cable fault point discharge. The result is shown in Fig. 4. It can be seen from Fig. 4 that the impact discharge sound signal is clearly separated. It can be found by comparing Fig. 3 with Fig. 4. Under different circumstances of time, cable, environment, and number of signals, mixed signals and shock discharge sound signals are collected. Due to the strong correlation between the discharge sound spectrum, the shock discharge sound signal can be effectively separated from the mixed signal.

In order to compare the convergence speed of the algorithm, ICA and improved ICA were randomly performed 10 times to extract the shock discharge sound signal experiments. In the vicinity of the factory and on the sidewalk of the road, the mixed sound signal of cable fault discharge was collected 10 times at a distance of about 3 to 6 meters from the fault point. ICA and improved ICA were used to extract the sound signals of shock discharge. In the experiment, the initial value is randomly given, and the number of each iteration is recorded. Table 1 shows the specific experimental results. Observing Table 1 shows that the number of iterations of the ICA algorithm fluctuates between 214 and 425, and the number of iterations of the improved ICA algorithm fluctuates between 176 and 258. It can be seen that the algorithm proposed in this paper has a small number of iterations and a small fluctuation range, which effectively reduces the dependence on the initial value.

| Algorithm | Operation Number | Average times |
|-----------|------------------|---------------|
| ICA       | 214 313 308 401 295 425 233 336 405 271 | 320.1         |
| Pro-ICA   | 176 254 232 258 217 239 180 251 178 193 | 217.8         |

Summary

In cable fault detection, the current localization algorithm has the problem that it cannot effectively extract the discharge sound signal. A fifth-order convergent ICA method based on EMD is proposed...
to extract the shock discharge sound signal. After simulation and field experiments, the results prove that the proposed algorithm has the following advantages:

1) The shock discharge sound signal was extracted by using an EMD-based fifth-order convergence ICA method. Mixed signals with non-stationary, unknown mixing modes, and overlapping source signals can be processed by algorithms.

2) The convergence factor is used to overcome the dependence of the algorithm on the initial value. This algorithm has the advantages of fast convergence speed, less calculation, and efficient data processing capabilities.

3) According to the strong correlation between the spectrum of each discharge sound, the eigenmode components with the largest correlation between the frequency spectrum and the known discharge sound spectrum can be automatically extracted by the algorithm. The algorithm is adaptive. The algorithm can be applied to the extraction of discharge sound signals with low signal-to-noise ratio. By combining cable fault location methods such as the acousto-magnetic synchronization method, the problem of accurate cable fault location can be solved.

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