

Impulse Noise Suppression Based on Power Iterative ICA in Power Line Communication

Wei Zhang, Zhongqiang Luo, and Xingzhong Xiong

Abstract—To overcome the detrimental influence of α impulse noise in power line communication and the trap of scarce prior information in traditional noise suppression schemes, a power iteration based fast independent component analysis (PowerICA) based noise suppression scheme is designed in this paper. Firstly, the pseudo-observation signal is constructed by weighted processing so that single-channel blind separation model is transformed into the multi-channel observed model. Then the proposed blind separation algorithm is used to separate noise and source signals. Finally, the effectiveness of the proposed algorithm is verified by experiment simulation. Experiment results show that the proposed algorithm has better separation effect, more stable separation and less implementation time than that of FastICA algorithm, which also improves the real-time performance of communication signal processing.

Keywords—Power line communication(PLC); orthogonal frequency division multiplexing(OFDM) signal; independent component analysis(ICA); impulse noise

I. INTRODUCTION

POWER line communication refers to a communication technology and its system applications relying on power lines and transmission and distribution networks as transmission media[1]. It is a kind of communication technology which does not need to be rewired and uses the existing power line resources to transmit data, voice, video, etc. Compared with wireless communication, on the one hand, PLC provides users with high-speed Internet access services and voice services, thus increasing new options for users to access the Internet and make phone calls, which is conducive to other telecommunications service providers to improve their services and reduce prices[2]-[4]; on the other hand, it has low cost and ubiquitous network structure[5].

Existing power lines are mainly used for power transmission, on which there are variations in line impedance, frequency selective fading and various noises, so power lines are not suitable for signal transmission. Noise interference is one of the most critical factors affecting the performance of power line communication. It always exists in the power line communication environment, which will increase the bit error rate of the signal and reduce the quality of communication. In serious cases, the communication may be completely invalid. It

can be divided into two types: background noise and impulse noise. Among them, impulse noise has the greatest impact on signal transmission[6]. Impulse noise usually has the characteristics of large amplitude and randomness, which seriously interferes with power line communication and leads to an increase in bit error rate of information transmission. At the same time, without any prior knowledge about mixing process and source signal, the performance of traditional impulse noise suppression methods is significantly degraded or even useless[7-8]. However, independent component analysis(ICA) algorithm based on blind source separation can effectively separate impulse noise and useful signals without any prior knowledge[9]. Therefore, the accuracy of communication can be guaranteed by blind source separation.

In order to suppress impulse noise, various methods for suppressing impulse noise are proposed in many literatures. The simplest and most widely used method is non-linear method, which includes blanking, clipping, and a combination of the two to the received signal in time domain[10-11]. These methods are easy to implement and have low complexity, but the impulse noise on the power line is time-varying. In practical applications, it is very difficult to obtain the optimal amplitude blanking and clipping threshold. In [12-13], Andreadou et al. use error correction coding to suppress power line impulse noise. This technique reduces the occurrence of error bits in transmission process by increasing redundant bits of transmitted data. In [14], Zhidkov proposed a method to reduce impulse noise without noise characteristic parameters. The OFDM demodulated signal is compensated in frequency domain for impulse noise. When the amplitude of impulse noise increases or the OFDM signal is modulated by high-order modulation, the effect of noise suppression will be greatly reduced. In [15], the semi-orthogonal structure of the observation matrix is used to estimate the impulse signal in the communication process. In the power line communication system with high impulse intensity and sparsity, this method will make the impulse estimation inadequate and affect the performance of the whole communication system. In [16], the impulse noise is roughly estimated by the method of compressed sensing, then uses the matrix based on prior knowledge to estimate the position of impulse noise accurately, and finally uses the least mean square

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error to recover the signal. This method needs to know the probability density function of impulse noise in advance. However, in actual power line communication, the probability density function of impulse noise is difficult to estimate. Mehboob and Ren proposed an adaptive impulse noise suppression method to reconstruct impulse noise[17-18]. But this method needs to know the characteristic parameters of impulse noise in advance, such as variance, etc. Once the parameter estimation is not accurate, the effect of noise suppression will be difficult to meet the actual needs.

From previous literatures analysis, note that the above-mentioned traditional noise suppression methods have certain limitations, and most of them depend on the characteristic parameters of noise. However, channel state information or noise characteristic parameters are difficult to estimate and have dynamic characteristics, resulting in significant performance degradation or even unavailability of existing noise suppression methods. For this problem, the blind separation mechanism is very promising and attractive for achieving adaptive interference cancellation. For the purpose of solving the problems of unobtainable dynamic channel condition and unknown noise characteristic parameters in power line communication, an ICA algorithm based on power iteration (PowerICA) is proposed to suppress impulse noise. The main work of this paper is as follows: First, the single-channel observation is constructed into multi-channel observation by weighting processing, and then the power iteration ICA algorithm is used to separate the signals, so as to suppress the impulse noise. The proposed algorithm is more stable than the traditional FastICA separation, and meets the high efficiency and accuracy of communication. Moreover, the algorithm can run on parallel nodes, which can save running time and satisfy the timeliness of communication

II. SIGNAL MODEL AND PROBLEM DESCRIPTION

Impulse noise in power line communication is mainly caused by the transient of power line switches, which has high power and unpredictable properties. Considering the amplitude characteristics of noise and the time characteristics of impulse events on power line, this paper adopts alpha stable distribution noise model to model impulse noise on power lines. The alpha stable distribution is a generalization of the Gaussian distribution, and the Gaussian distribution is a special case of alpha. Except for Gaussian distribution ($\alpha = 2, \beta = 0$), Cauchy distribution ($\alpha = 1, \beta = 0$) and Pearson distribution ($\alpha = 0.5, \beta = -1$), the probability density function of α -stable distribution has no uniform expression, and is generally described by its characteristic function. In [19], it can be expressed as follow.

$$\varphi(t) = \exp(jpt - \gamma |t|^\alpha [1 + j\beta \text{sign}(t)\omega(t, \alpha)]) \quad (1)$$

where

$$\omega(t, \alpha) = \begin{cases} \tan \frac{\alpha\pi}{2}, & \alpha \neq 1 \\ \frac{2}{\pi} \log |t|, & \alpha = 1 \end{cases} \quad (2)$$

$$\text{sign}(t) = \begin{cases} 1, & t > 0 \\ 0, & t = 0 \\ -1, & t < 0 \end{cases} \quad (3)$$

$$-\infty < p < +\infty, \gamma > 0, 0 < \alpha \leq 2, -1 \leq \beta \leq 1 \quad (4)$$

α is the characteristic index, which represents the trailing of α density function. The smaller α is, the more serious the trailing is, and the stronger the impulse characteristics of noise. On the contrary, the larger α is, the weaker the impulse characteristics of noise. p is the position parameter, $1 < \alpha \leq 2$ corresponds to the mean value, and $0 < \alpha \leq 1$ corresponds to the median value. γ is the dispersion coefficient, which indicates the degree of dispersion of the α -stable distribution process. It is similar to the variance of the Gaussian distribution. When $\alpha = 2$ (ie Gaussian distribution), it is equal to half of α . β is a symmetric exponent. When $\beta = 0$, it is called a symmetric α -stable distribution, which is denoted as $S\alpha S$. $\alpha \neq 1$, when $\beta > 0$, it means left tailing, $\beta < 0$ means right tailing; while $\alpha = 1$, the result is opposite.

In the process of signal transmission, it is assumed that both Gaussian noise and impulse noise exist at the same time. The noise model of receiving mixed signal can be expressed as follows:

$$x(t) = au(t) + bn_1(t) + n_2(t) \quad (5)$$

where $u(t)$ is OFDM source signal, $n_1(t)$ is impulse noise subject to α -stable distribution, $n_2(t)$ is Gaussian noise. a, b is equivalent to channel influence factor. The source signal in this paper is composed of OFDM signal and impulse noise signal. Due to the advantages of blind separation [9], it will be considered to achieve noise cancellation in this paper. We don't need to estimate the channel influence factor by help of blind separation.

III. BLIND SEPARATION ALGORITHM BASED ON POWER ITERATION

Blind Source Separation (BSS) refers to the extraction and separation of potential source signals from the observed mixed signals [20]. The ICA analysis method based on high-order statistical properties of signals is a classical algorithm for blind source separation. Its properties depend on the independence optimization criterion and optimization algorithm. Non-Gaussian is a common criterion for ICA. According to the generalized central limit theorem, the non-Gaussian criterion can be used as the cost function to maximize the non-Gaussian to achieve the purpose of extracting independent sources.

The ICA linear mixed model can be expressed as:

$$x = As + n \quad (6)$$

x is an M -dimensional observation signal, A is a $M \times N$ dimensional mixed matrix ($M \geq N$), s is N mutually statistical independent source signals, and n is a Gaussian white noise. The observed signal x needs to be pre-processed before the algorithm separation: mean and whitening. It is noteworthy that considering that equation (5) is only a single-channel observation, another pseudo-received signal is constructed by weighting factor method, and then the system is modeled as a multi-channel (2-channel) observation signal. According to the

ICA principle, combined with the signal noise model in this paper, the signal separation diagram is shown in Figure 1.

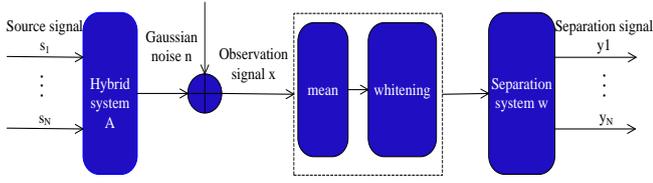


Fig. 1. Signal separation diagram

A. FastICA Algorithm

Fast Independent Component Analysis (FastICA), also known as Fixed Point Algorithms, was proposed and developed by Hyvarinen, a computer and information science experiment at the Institute of Technology, Alto University, Finland. It is based on the principle of non-Gaussian maximization. Under $\|w\|^2 = w^T w = 1$ the condition, the unmixed matrix w uses the fixed point iterative theory to find the non-Gaussian maximum of $\left|E\left[G(w^T x)\right]\right|$. G represents the non-quadratic function and $G(0) = 0$. the maximization of the unit FastICA estimator can be represented by Lagrange:

$$L(w; \lambda) = \left|E\left[G(w^T x)\right]\right| - \frac{\lambda}{2}(w^T w - 1) \quad (7)$$

λ is a Lagrangian multiplier, $g = G'$ and $g' = G''$ respectively represent the primary and secondary derivation of G , and g is called the nonlinearity of ICA. By setting the gradient of Lagrange w to zero, the local optimal solution of formula (7) is verified.

$$F(w) = m(w) - \lambda(w)w = 0 \quad (8)$$

where $m(w) = E\left[g(w^T x)x\right]$ and $\lambda(w) = w^T m$ can be obtained by multiplying w^T from the left on both sides of equation (8). In [21], to equation (8), the one-unit fixed point FastICA algorithm is used as an approximate Newton-Raphson iterative update. The iteration of this algorithm can be further expressed as:

$$w \leftarrow \frac{m(w) - \beta(w)w}{\|m(w) - \beta(w)w\|} \quad (9)$$

until convergence. $\beta(w)$ is a scalar multiplier, it can be described as $\beta(w) = E\left[g'(w^T x)\right] \in \mathbb{R}$.

In order to solve $F(w) = 0$, Newton-Raphson further iteration is expressed as:

$$w \leftarrow w - [J_F(w)]^{-1} F(w) \quad (10)$$

where J_F is the Jacobian of $F(\cdot)$ in (8).

The Lagrangian multiplier $\lambda(w) = w^T m$ in equation (8) is a constant, and its variation does not depend on w . Therefore, in order to keep the updated results in the feasible set, it is necessary to solve the further normalization steps in the later stage of formula (11).

$$\begin{cases} w \leftarrow w - [M(w) - \lambda I]^{-1} F(w) \\ w \leftarrow w / \|w\| \end{cases} \quad (11)$$

when λ is regarded as a constant, $M(w) = E\left[g'(w^T x)xx^T\right]$ and $[M(w) - \lambda I]$ is the Jacobian of $F(\cdot)$, In addition, the special values set by $M(w)$ are also used:

$$M(w) \approx E\left[g'(w^T x)\right]E\left[xx^T\right] = \beta(w)I \quad (12)$$

by substituting equation (12) into equation (11) is recursive.

$$\begin{cases} w \leftarrow w - F(w) / (\beta(w) - \lambda) \\ w \leftarrow w / \|w\| \end{cases} \quad (13)$$

substituting equation (8) for $F(w)$ in equation (13), we get the one-unit fixed point FastICA algorithm iteration (9).

B. PowerICA Algorithm

The FastICA algorithm can be seen as a single vector iterative method, such as Power Iteration (PI), Reverse Iteration (RI), and Rayleigh Quotient Iteration (RQI) [22]. Many single vector iterative methods are derived from the Newton-Raphson method [23]. In [22], FastICA is studied as a power iteration method. Its separation principle can be expressed as follows:

$$w \leftarrow \frac{[H(w) - \beta(w)I]w}{\|[H(w) - \beta(w)I]w\|} \quad (14)$$

where $H(w) = E\left[\frac{g(w^T x)}{w^T x}xx^T\right] \in \mathbb{R}^{d \times d}$ is positive definite for

all conventional ICA nonlinearities including pow3, tanh and gauss. The FastICA algorithm of formula (14) is similar to PI method, which is more stable than FastICA algorithm. In (14), $[H(w) - \beta(w)I]$ and $H(w)$ have the same eigenvectors. In order to design an algorithm insensitive to finite sample errors, we did not utilize the spectral offset in (14). Instead, we use two parallel PowerICA algorithms, whose initial assumptions are the same, and find the local maximum w_{k1} and the local minimum w_{k2} of $\gamma(w)$. Then, we use non-Gaussian metric to evaluate the superiority of the two extracted components, and the component with less non-Gaussian is discarded.

All conventional ICA nonlinearities, including pow3, tanh, and gauss, $H(w)$ are positive, ie, $\gamma(w) > 0$. Therefore, the PowerICA algorithm can be expressed as:

$$w \leftarrow \frac{H(w)w}{\|H(w)w\|} = \frac{m(w)}{\|m(w)\|} \quad (15)$$

finds w_{k1} as a local maximizer of $\gamma(w)$, references [24] gives a detailed derivation of the PowerICA algorithm. In order to obtain a local minimizer of $\gamma(w)$, we need to shift $\gamma(w)$ by a constant scalar c , the solution process of c is found in [25], such that $\{\forall w \in S^{d-1} : \gamma(w) - c < 0\}$, where S^{d-1} denotes the set of unit vector $w \in \mathbb{R}^d$, so the local minimum of $\gamma(w)$ is translated into the local maximum of $|\gamma(w) - c|$, which can be expressed as:

$$w \leftarrow \frac{[H(w) - cI]w}{\|[H(w) - cI]w\|} \quad (16)$$

We use $\delta(w)$ as a measure of non-Gaussianity to select the extracted component farther from Gaussianity. When multiple sources need to be extracted, we follow the same steps of FastICA algorithm, but in the process of algorithm separation, (15) and (16) replace the original (9), optimize the separation algorithm, so that the separation results are more accurate.

The PowerICA iterative algorithm steps are as follows, where Π_{k-1}^\perp is an orthogonal projection operator, which is projected to the separation vector w_1, w_2, \dots, w_M of the FastICA algorithm, (15) and (16) can be run in parallel, ie, mode 1 And mode 2, running in parallel can greatly save signal separation time and realize the timeliness of communication. Specific steps are as follows:

Input: Preprocessed whitening matrix $x = (x_1, x_2, \dots, x_N)$

Output: Independent component of the demixing matrix

$w = (w_1, w_2, \dots, w_N)$.

k from 1 to N-1

1) Initialization $j = 0$;

2) $\Pi_{k-1}^\perp \leftarrow I - \sum_{i=1}^{k-1} w_i w_i^T$;

3) mode 1:
$$\begin{cases} j \leftarrow j+1 \\ w_{k1}^{[j]} \leftarrow m_{k1}^{[j-1]} \\ w_{k1}^{[j]} \leftarrow \Pi_{k-1}^\perp w_{k1}^{[j]} \\ w_{k1}^{[j]} \leftarrow w_{k1}^{[j]} / \|w_{k1}^{[j]}\| \end{cases},$$

mode 2:
$$\begin{cases} j \leftarrow j+1 \\ w_{k2}^{[j]} \leftarrow m_{k2}^{[j-1]} - c w_{k2}^{[j-1]} \\ w_{k1}^{[j]} \leftarrow \Pi_{k-1}^\perp w_{k2}^{[j]} \\ w_{k2}^{[j]} \leftarrow w_{k2}^{[j]} / \|w_{k2}^{[j]}\| \end{cases};$$

4) Repeat the third step until convergence, use $\delta(w)$ to determine the value of w_k .

5) $w_N = \Pi_{N-1}^\perp x_N / \|\Pi_{N-1}^\perp x_N\|$.

By comparing FastICA algorithm with PowerICA algorithm, firstly, when solving local optimum, PowerICA algorithm improves FastICA algorithm, optimizes the separation steps to make the separation signal closer to the source signal; secondly, PowerICA algorithm can run in parallel, and FastICA algorithm can not run in parallel, which greatly saves the time of PowerICA algorithm for mixed signals and realizes real-time transmission of information.

IV. SIMULATION ANALYSIS AND DISCUSSION

In this paper, the simulation experiment of the algorithm is used to evaluate the effect of the algorithm on noise suppression in the power line communication environment. In the simulation experiment, the signal noise model is shown in the second section. The pure signal $u(t)$ is the OFDM signal, and $n_1(t)$ is the impulse noise. They are used as two input signals, the carrier frequency is 1000, the maximum number of iterations is 100, and the number of sample points is 500. Frequency 1600, the original input signal is shown in Figure 2. The α of the α -stable distributed noise takes different values in the specific

experiment, $\beta = 0, \gamma = 1, \lambda = 0$, and the mixing matrix A is the 2×2 dimensional random moment.

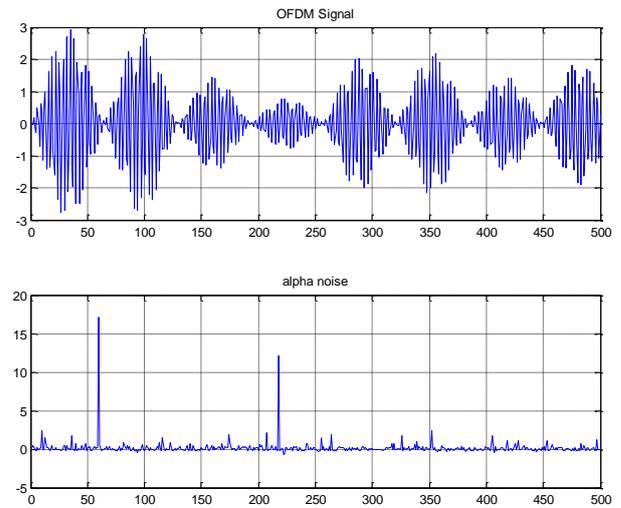


Fig. 2. Input source signal

The impulse noise in power line communication is time-varying. In order to be closer to the actual transmission of signals in the real environment, it is necessary to generate two random mixed observation signals. The two random number pairs are multiplied by OFDM signals and impulse noise signals as mixed weighting vectors, respectively. Then the results are added together with the external interference Gaussian white noise, produces a vector of mixed observation signals. The signal waveform is shown in Figure 3.

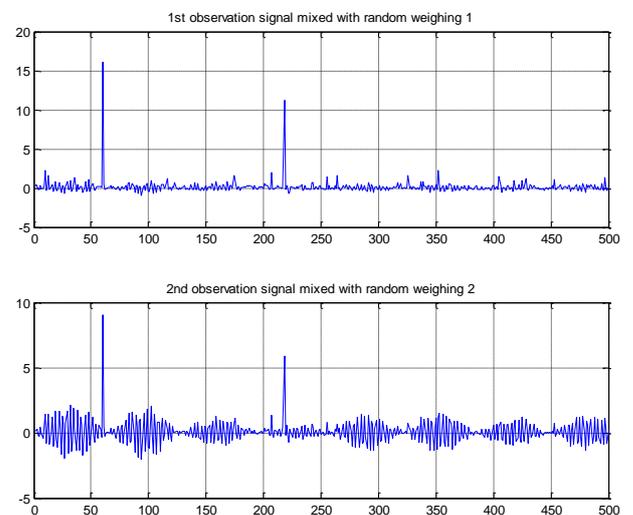


Fig. 3. Observation signal with random weight

Non-Gaussian is a commonly used criterion for ICA. Compared with Gaussian white noise and OFDM signals, the α -stable Gaussian distribution noise is the strongest. Therefore, according to the non-Gaussian, for the FastICA algorithm and the PowerICA algorithm, the α -stable distributed impulse noise can be extracted first, and the separation result is shown in (a) and (b) of Figure 4. The impulse noise separated by the FastICA algorithm and the PowerICA algorithm is very close to the original impulse noise. When the

impulse noise $\alpha = 1.2$ and Gaussian noise variance $\sigma^2 = 0.02$, the calculated correlation function reaches 0.99.

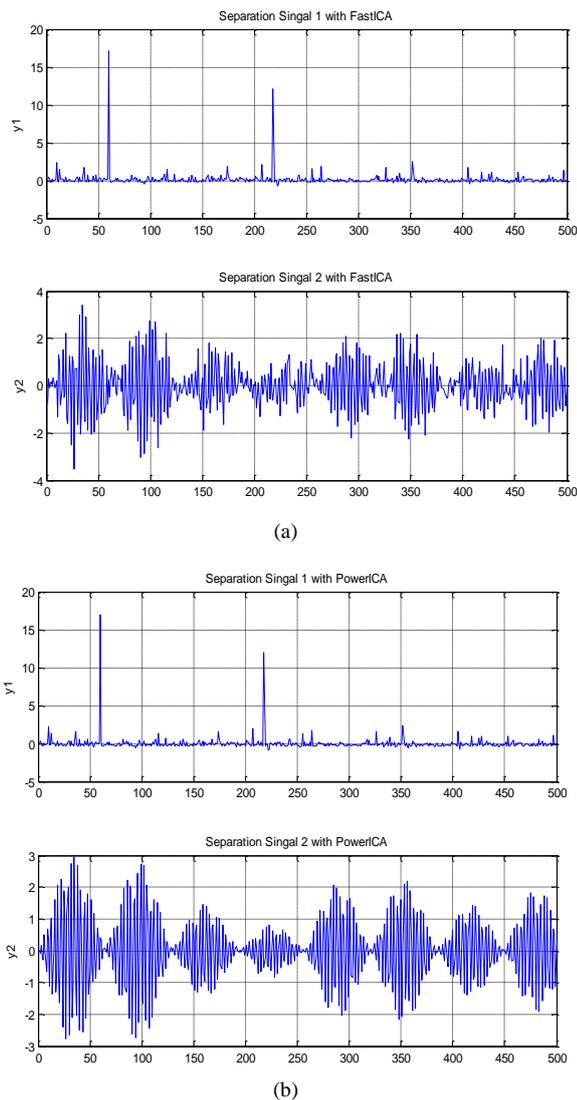


Fig. 4. (a) Result of FastICA algorithm separation (b) Result of PowerICA algorithm separation

However, in our 1000 experiments, the variance of Gauss white noise remains unchanged and the value of impulse noise is changed. The average number of successful separation of FastICA algorithm decreases, and the average value of separation correlation function decreases. The separation effect of PowerICA algorithm does not decrease with the increase of the value. The PowerICA algorithm proposed in this paper is more stable than FastICA algorithm. The specific data are shown in Table 1.

TABLE I
COMPARISON OF IMPORTANT PARAMETERS BETWEEN FASTICA AND POWERICA

	FastICA algorithm		PowerICA algorithm	
	correlation function value	number of successes	correlation function value	number of successes
$\alpha = 1.2$	0.9976	985	0.9995	1000
$\alpha = 1.5$	0.9957	979	0.9995	1000

$\alpha = 1.8$	0.9931	964	0.9995	1000
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On the other hand, during the test, when $\alpha = 1.5$, the variance σ^2 of Gaussian white noise is changed, the separation effect of FastICA algorithm is gradually deteriorated, and the decreasing trend is faster than PowerICA algorithm, once again indicating the instability of FastICA algorithm. The specific change trend is shown in Figure 5.

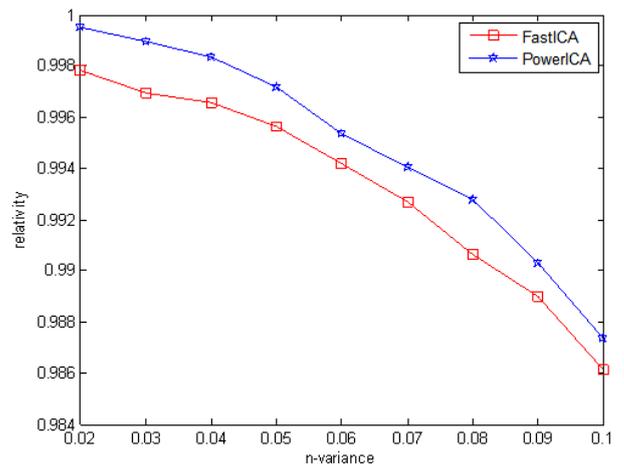


Fig. 5. Separation efficiency comparison between FastICA and PowerICA with increasing noise variance

V. CONCLUSION

In this paper, aiming to eliminate the problem of impulse noise in power line communication, a PowerICA algorithm based on power iteration is studied. The research shows that the proposed algorithm is more stable than FastICA algorithm and has better separation effect. It can run on parallel nodes, which greatly saves the processing time of communication signal and improves the real-time performance of communication. In the future, we will further study and explore the methods of blind separation and interference elimination of strong impulse noise.

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