Semi-blind Source Separation Based on the Inner Product of the Feature Ranking Vector

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Abstract. To solve the problem of single-channel blind source separation for the aggregated current signal of the multiple home appliances, a novel method of semi-blind source separation extracting the principal component based on inner product of the feature ranking vectors of multiple hidden states was proposed in this paper. The fuzzy feature ranking vector is acquired by setting the corresponding spectrum value to 1 or 0 according to the sequence of the harmonics of the signal, the inner product between the feature ranking vector of observed signal and the feature ranking vector of each standard state is calculated, and the principal components of source signal are extracted according to the maximum inner product step by step. We chose an air conditioner, a microwave oven and a washing machine as the test object to testify the proposed method. The experimental results showed that the aggregated current signal of the multiple home appliances can be fast and accurately separated using this method and which can be widely used in the field of remote Prognostics and Health Management for home appliances.

Introduction

Monitoring the working state is very important to realize the remote Prognostics and Health Management for home appliances [1]. But within the most of the residential spaces only has one current sensor, with which we can not gather the current signal of each home appliance directly. Therefore we must separate the aggregated current signal of the multiple home appliances, which means solving the problem of single-channel blind source separation.

Separating the single-channel blind source is a problem of extreme underdetermined, conventional blind source separation algorithm based on matrix computation can not be applied. To solve this problem, some researchers used the random matrix to construct multi-channel signals, and adopted Independent Component Analysis (ICA) to separate the power signals[2]. The random matrix who used does not meet the actual physical channel model, and can not be practical.

There are some scholars who used different time-frequency transform methods to construct the virtual multi-channel signals from single-channel signal, and combined principal component analysis (PCA) and ICA algorithm to separate signals. In [3], the author acquired multi-channel signal through cycle-spinning method, and then used PCA to reduce dimension, and used ICA to separate the independent harmonic and inter-harmonic sources finally. In [7], the author constructed the multi-channel signals by empirical mode decomposition (EMD), which contains the single-channel mechanical signal and the intrinsic mode function (IMF), and separated the sources with Fast-ICA algorithm. Without the statistical properties of sources, the separation effect of the above methods is not ideal for the single-channel signal containing multi-states of home appliances. There are a series of problems such as long operation time, mixed modes and edge effect in the process of constructing the multi-channel signals by EMD and other methods.

The current signals of home appliances have strong statistical repeatability under limited control modes, so the multiple hidden states models and the state time-series models of the corresponding control mode can be built through proper feature extraction [10]. Based on deeply research on the statistical analysis for the electrical characteristics of home appliances, a novel method of
The proposed methods

The current signals of home appliances contain a permutation and combination of finite steady-state signals and transient signals, with different series and hold time for different control modes. The features of home appliances are extracted through off-line learning, then the standard state sample library is established. Based on the library, the principal component extracted method based on inner product of the feature ranking vectors is done to separate the single-channel observed signal. The method is as follows:

Assuming that the number of home appliances is $M$ within the residential spaces, and each home appliance owns $I$ kinds of working states named as $s_{mi}(t)$, where $m = 1, 2, \cdots, M$, and $i = 1, 2, \cdots, I$, $I$ is a positive integer and $I$ may be different value for different home appliances. The single-channel observed signal $x(t)$ is a combination of a certain states of some of the $M$ home appliances, the relationship between the source signals and the observed signal can be written as:

$$x(t) = As(t) + v(t) = \sum_{m=1}^{M} k_m a_m s_{mi}(t) + v(t) \quad \{i = 1, 2, \cdots, I\}$$

where $k_m$ represents the on or off state of the $m$ appliance, $k_m = \{0, 1\}$. There is no intermediate sensor within the residential spaces, so $a_m = 1$. $v(t)$ is noise. The Eq.(1) can be expressed as:

$$x(t) = \sum_{m=1}^{M} k_m s_{mi}(t) + v(t) \quad \{i = 1, 2, \cdots, I\}$$

we define $S_{mi}(k)$, $V(k)$ and $X(k)$ as the FFT result of $s_{mi}(t)$, $v(t)$ and $x(t)$. the three transformation value are shown in Eq.(3)-Eq.(5):

$$S_{mi}(k) = \sum_{n=0}^{N-1} s_{mi}(n)e^{-j\frac{2\pi kn}{N}}$$

$$V(k) = \sum_{n=0}^{N-1} v(n)e^{-j\frac{2\pi kn}{N}}$$

$$X(k) = \sum_{n=0}^{N-1} x(n)e^{-j\frac{2\pi kn}{N}}$$

where $N$ is the total points of FFT. From Eq.(2), Eq.(3), Eq.(4), Eq.(5), Eq.(6) can be derived as follow:
The derivation of the Eq.(6) shows that the principal components of the spectrum $X(k)$ of the observed signal $x(t)$ definitely originate from one or several signal sources. In addition, the features also can come from any other transforms with linear superposition. Thus we use the property of linear superposition to solve the problem of the single-channel blind source separation in this paper, the separation algorithm is described in detail as follows:

step1  Given the sequence of aggregated current signal readings $x = [x_0, x_1, \cdots, x_{N-1}]$ of $M$ appliances and the sequence of power voltage signal readings $u = [u_0, u_1, \cdots, u_{N-1}]$, do $N$ points FFT transform for $x$, form a vector $F = [c_0, c_1, \cdots, c_{N/2-1}]$ with the $0 \sim (N/2-1)$ th harmonic component. The corresponding vector elements for the top 20 of all the spectrum value are set to 1, the others set to 0, so the fuzzy feature ranking vector $F$ of the observed signal is acquired.

step2  Calculate each inner product $d_j = \langle F, F_j \rangle$ between the feature ranking vector $F$ of the observed signal and the feature ranking vector $F_j$ of each standard state signal $s_j$, where $\langle \cdot, \cdot \rangle$ is the usual vector inner product.

step3  The principal components are extracted according to the principle of maximum inner product. Judge the number of states of the maximum value of $d_j$, if the number is 1 and the state ID is $j$, extracting the corresponding standard state waveform of the ID as the principal component $p_i = s_j$; else if there are multiple states of the same value of inner product, we firstly calculate the sums of harmonic energy of the top 20 of all the spectrum value of these states, and find the maximum value to extract the principal component, then choose the corresponding standard state waveform as the principal component $p_i = s_j$, entering the step4.

step4  Calculate the residual $e_m = x - p_j$.

step5  Judge whether the $m$ meets $m \leq M_{on}$ ($M_{on}$ is the number of home appliances in operation). If $m > M_{on}$,entering the step6; else if $m \leq M_{on}$, $i = i + 1, x = e_m, m = m + 1$, jump to step1.

step6  Calculate the average power $P(e_m) = (\sum_{n=0}^{N-1} u(n)e_m(n))/N$ of the residual $e_m$, if $P(e_m) < \text{threshold}$, $e_m$ equals to the noise $v$, end the loop; Otherwise, choose the other standard state waveform of ID of the same value of inner product again, jump to step3.

Experimental and Analysis

Experimental Data
We chose an air conditioner, a microwave oven and a washing machine as the test object to testify the proposed method. Normally a transient signal appears between two different steady-state signals, we only need to decompose the aggregated current signal of steady-state signals. The complete separation waveform can be acquired by splicing of the state waveforms and judging of the time-series. This paper focused on the separation of the single cycle of the steady-state signals. We collected a large number of data of voltage and independent current signals of the three home
appliances with different state types, and some data are used as training samples, the others are used as testing samples. The ID of states including five categories of steady-state signals of the air conditioner, three categories of steady-state signals of the microwave oven, two categories of steady-state signals of the washing machine are from 1 to 10. Choose test sample randomly from each category steady-state training sample library to do the combined cross validation experiment of mixing and separating for $5 \times 3 \times 2 = 30$ times.

**Separation Results and Analysis**

The length of sample $N = 200$, the number of home appliance $M_{on} = 3$, the residual of power threshold $= 2.5$ (This value is the half of statistical minimum value for the average power of all steady-state standard sample). Experimental results are shown in Tab.1. Fig.1 showed the separated experimental results for a group of 3, 6, 9 of the ID corresponding sample as the mixed source signal.

From Tab.1 we can see that the estimated signal ID acquired from 30 groups of different observed source signal match with the source signal ID, the separation accuracy rate is 100%, and the correlation coefficients between the three principal components and the source signals are all higher than 0.9. From the Fig.1 we can find that the time-domain waveform and spectrum distribution of the 3 separated signals acquired are exactly the same as that of source signal. In conclusion, the experimental results showed that the aggregated current signal of the three home appliances were accurately separated.

Note: List of symbols in Tab.1: $A$: the state ID of the air conditioner; $M$: the state ID of the microwave oven, $W$: the state ID of the washing machine, $y_1$ – $y_3$: the corresponding state ID of the three separated principal components, $\rho_1$ – $\rho_3$ : the correlation coefficients between the three principal components and the source signals.

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Conclusions

To solve the problem of single-channel blind source separation for the aggregated current signal of the multiple home appliances, a novel method of semi-blind source separation extracting the principal component based on inner product of the feature ranking vectors of multiple hidden states was proposed in this paper. Implement the FFT for the single-channel observed signal and standard state signals, the corresponding harmonic vector elements for the top 20 of all the spectrum value are set to 1, the others are set to 0, the fuzzy feature ranking vectors are acquired. The inner products were calculated between the feature ranking vector of observed signal and the feature ranking vector of each standard state, and the principal components of source signal are extracted according to the maximum inner product step by step. The experimental results showed that the aggregated electrical working states of multiple home appliances can be fast and accurately separated with this method and which can be widely used in the field of remote Prognostics and Health Management, etc.

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References


