Separation of Radiated EMI Noise based on Joint Approximate Diagonalization Algorithm

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Abstract **─** Power electronic devices and electrical equipment produce a large quantity of radiated electromagnetic interference (EMI) in the working process. Electromagnetic field analysis method of the near-field and far-field of the antenna can be employed to separate the radiated interference noises. However, the method has low separation accuracy and requires a lot of time. A novel method based on joint approximate diagonalization algorithm (JADA) to separate the radiated EMI noise is proposed in this paper. Compared with the traditional independent component algorithm method, the accuracy is improved by 14% and the efficiency is increased by 30%. The common-differential mode mixed noise source is taken as the experimental object to demonstrate the effectiveness and simplicity of the proposed method.

Index Terms **─** Common-differential mode mixed source, JADA algorithm, noise separation, radiated EMI.

I. INTRODUCTION

With the increasing integration and complexity, power electronic device radiates a large number of electromagnetic interference (EMI) noises, which leads to the abnormal operation of other devices and electrical equipment around [1-5]. In order to control the radiated EMI within a safe range, the prediction and separation of radiated EMI noise sources have become a burning issue to be solved [6-8].

Electromagnetic field analysis methods are widely used in the research of radiated EMI noises at the moment. A novel method has been proposed to predict the far-field radiation using the magnetic near-field component on a Huygens's box in [9-10], the effect of inaccuracy of magnetic field and the incompleteness of the Huygens's box on far-field results has been investigated. The radiated EMI has been designed as a time harmonic electromagnetic wave in [11], 3D finite elements (3DFE) model has been used to evaluate the different distributing effects that the switching frequencies may have on the radiated EMI. The far-field radiated EMI emission of a power converter caused by common-mode current on attached cables has been demonstrated in [12-13], and an antenna model has been developed to estimate the far-field radiation of a power converter. A Green's function approach for the computation of broadband stochastic radiated EMI field energy densities has been presented in [14], which predicted and separated the far-field radiated EMI. Symmetrical component theory has been applied to analyze the characteristics of EMI noises in power electronic system in [15-16], and a multiphase noise separator has been built. A method for the measurement of the field generated by multiple uncorrelated sources has been proposed in [17-18], the contribution of each source has been determined with the assistance of the blind signal separation technique. Therefore, it is meaningful to separate the radiated EMI noise effectively.

The above methods can separate the radiated EMI noise to a certain extent, but there are still some defects that need further improvement, for example, it is necessary to use electromagnetic field analysis software, which has a large amount of calculation and low precision. The motivation of this paper is to propose a JADA-based method, which can be used to separate the radiated EMI noise. Compared with the Electromagnetic field analysis method, the JADA algorithm separates the radiated EMI noise from the perspective of signal analysis, the amount of calculation of JADA algorithm is smaller, which can separate the radiated EMI noise more accurately and more efficiently. To verify the validity of the proposed method, both simulation and experiment are presented.

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II. SEPARATION OF THE RADIATED EMI NOISE BASED ON JADA ALGORITHM

A. Radiated EMI source

In this section, a radiated EMI noise source model is established, as shown in Fig. 1. There are n noise sources in the model, the total radiated noises are formed by E_1, E_2, E_3, …, E_N, which are produced by each radiated source.

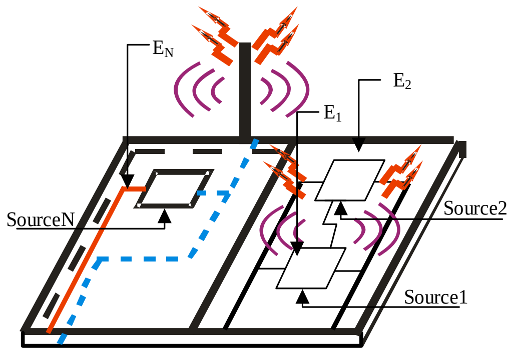


Fig. 1. Radiated EMI noise source model.

B. Separation of radiated EMI based on JADA

On the basis of independent component algorithm (ICA), JADA algorithm is used to separate the radiated EMI noise, which introduces the fourth order cumulative quantity matrix of multivariate data, and performs eigen-decomposition to separate the mixed signals.

Since the components of the radiated EMI noise are independent of each other, JADA algorithm makes full use of algebraic method, combines with matrix theory, simplifies the algorithm, improves the robustness of the algorithm. JADA algorithm has strong radiated EMI noise separation capability, which can also separate the small sensor noise in the original signal. In order to ensure the feasibility of algorithm separation, the signal to noise ratio (SNR) of the original noise signals is higher than 6dB.

The signals of the radiated EMI noise source model can be expressed as:

$$x(t) = A * s(t) = \sum_{p=-\infty}^{+\infty} A_p s(t-p), t = 1, 2, \ldots,$$
$$s(t) = [s_1(t), \ldots, s_n(t)]^T, n = 1, 2, \ldots, \quad (1)$$
$$x(t) = [x_1(t), \ldots, x_n(t)]^T,$$

where $x(t)$ are m mixed signals; $s(t)$ are n radiated EMI noise signals; A_p is the hybrid filter, p is time delay:

$$y(t) = B_p * x(t) = \sum_{p=-\infty}^{+\infty} B_p A_p s(t-p), \quad (2)$$

where $y(t)$ is a n-dimensional column vector and B_p is an n*n matrix. The purpose is to find a separation filter B_p such that $y(t)$ is an estimate of the signals $s(t)$.

The principle of the JADA algorithm to separate the radiated EMI noise signals includes mainly the following three sections.

B.1. Zero mean processing

Zero mean is mainly to eliminate the constant in the signal. The theory of blind signal separation is generally based on the assumption that the original signal component is zero mean, but the radiated EMI noise signals cannot meet this condition, so it is necessary to carry out zero mean processing on the actual data to meet the theoretical premise, and build a reasonable mathematical model. In fact, the zero mean processing of data is the translation transformation of data, which does not affect the overall distribution of data, but change the range of data values. This processing method is reasonable.

For the sampling data whose mean value is not zero, formula (3) is used to make the data zero mean:

$$X' = X - E(X), \quad (3)$$

where X is the collected radiated EMI data, $E(X)$ is mathematical expectation, and X' is the data after the zero mean. The actual sampling data is often discrete, so the calculation is generally replaced by the arithmetic average.

When $x(t)$ is a fourier transform data with a mean value not zero, the values in the vector $x_i(t)$ are all complex numbers, and the zero mean processing can be expressed as:

$$x_i(t)' = x_i(t) - \frac{1}{n}\sum_{i=1}^{n} x_i(t), i = 1, 2, \ldots, n. \quad (4)$$

B.2. Whitening processing

Whitening can remove the correlation between the signals and make the second-order statistics as independent as possible. In addition, whitening can effectively simplify the algorithm and speed up the calculation.

Whitening processing is a linear transformation of the data, which can be expressed as formula (5):

$$\tilde{x} = Tx, \quad (5)$$

where matrix T is a whitened matrix; the correlation matrix $R_{\tilde{x}}$ of transformed random data $\tilde{x}$ has the following property:

$$R_{\tilde{x}} = E\left[\tilde{x}\tilde{x}^H\right] = I, \quad (6)$$

where I is a unit matrix.

So the purpose of whitening is to find the whitening matrix T, which makes the data correlation matrix after whitening become a unit matrix. This section uses the eigenvalue decomposition method of correlation matrix to realize whitening.

Suppose the covariance matrix of X is C_X, has:

$$C_X = XX^T = U\Lambda U^T, \quad (7)$$

where

$$\Lambda = Diag\left[\lambda_1, \lambda_2, \cdots, \lambda_m\right], \tag{8}$$

where X^T is the transpose matrix of X, U^T is the transpose matrix of U, λ_m is the eigenvalue of C_X; each column of U is a eigenvector of C_X.

So the whitening matrix W_p is:

$$W_p = \Lambda^{-\frac{1}{2}} U^T. \tag{9}$$

B.3. Eigen-decomposition transformation

Let Z be the signal after whitening:

$$Z = W_p A_p S = W_p A_p * s(t). \tag{10}$$

Suppose M is an n*n matrix, and the four-dimensional cumulant matrix $Q_Z(M)$ of Z is defined as:

$$[Q_Z(M)]_{ij} = \sum_{k=1}^{n}\sum_{l=1}^{n} K_{ijkl}(z) m_{kl},\ i, j = 1, 2, ..., n, \tag{11}$$

where $K_{ijkl}(z)$ is the fourth-order tensor of the four components i, j, k, l in vector Z.

Let $V = W_p A_p$, according to formula (10), has:

$$Z = VS. \tag{12}$$

Because the variance of the source signal S and the whitened data Z is 1, each element in S is independent of each other, and each element in Z is orthogonal to each other, thus V must be orthogonal and unified. Make $M = v_i v_i^T$, the fourth-order tensor matrix with M as the weight matrix can be transformed into:

$$Q_Z(M) = \lambda M, \tag{13}$$

where $\lambda = k_4(s_i)$ is the kurtosis of source s_i, so M is called the eigen-matrix of $Q_Z(M)$, while $\lambda = k_4(s_i)$ is the eigen-value of $Q_Z(M)$.

So as long as the eigen-decomposition of $Q_Z(M)$ is completed, the eigen-matrix M and eigen-value λ can be obtained. If the kurtosis of each source are different, the v_i and λ_i are also different. We can get the column vectors of V, and then we can get the independent components of A_p.

When the eigen-values have multiple roots, the results of formula (9) and formula (11) are unstable, so the algorithm needs to be improved. The basic idea is: according to formula (13), find a matrix V that can diagonalize $Q_Z(M)$ through $V^T Q_Z(M) V$:

$$\begin{aligned}\Lambda(M) &= V^T Q_z(M) V \\ &= Diag[k_4(s_1) v_1 M v_1^T, ..., k_4(s_n) v_n M v_n^T].\end{aligned} \tag{14}$$

In fact, the result of taking only one matrix M is not very accurate. We can use a group of matrix $M = [M_1, M_2, \ldots, M_p]$ to find $Q_Z(M_i)$ for each M_i, and find matrix V to satisfy the maximum possible diagonalization of each $Q_Z(M_i)$ at the same time. The square sum of the non-diagonal elements in $V^T Q_Z(M) V$ can be used as a measure degree of diagonalization:

$$D_M(V) = \sum_{M_1 \in M} Off[V^T Q_Z(M_i) V]. \tag{15}$$

According to formula (11), if V is found to make the criterion of $D_M(V)$ minimum, the estimation $\bar{A}$ of the mixed matrix and the estimation $y(t)$ of the original signal $s(t)$ can be obtained:

$$\bar{A} = T^{-1} V = T^T V, \tag{16}$$

$$y(t) = V^T T X(t). \tag{17}$$

C. Implementation steps of separating the radiated EMI noise sources based on JADA algorithm

The radiated EMI noises are separated based on the JADA algorithm in this paper, and the specific steps are as follows.

Step 1: The mutually independence and identically distributed radiated EMI noise signals $s(t)$ are collected by testing, and the mixed signals $x(t)$ are obtained by formula (1).

Step 2: Make the sampling data zero mean, eliminate the constant in $s(t)$.

Step 3: Design the whitening matrix W_p remove the correlation between the signals.

Step 4: $Q_Z(M)$ is decomposed by formula (13), the kurtosis of each source can be gained.

Step 5: Find V to make the criterion of $D_M(V)$ minimum, according to formula (17), the estimated signals $y(t)$ can be obtained.

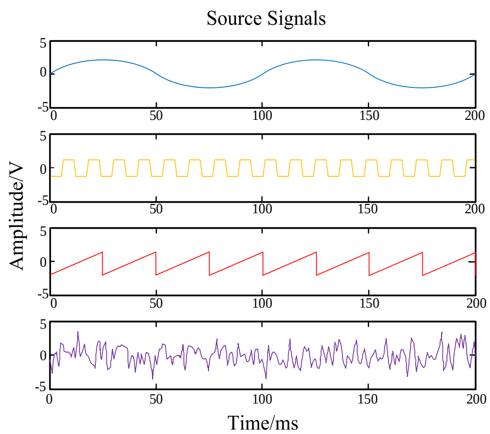
Step 6: For the purpose of judging the separation performance of the JADA algorithm, the similarity coefficient (SC) is applied to measure the approximation between the source signals and the separated signals. When SC is closer to 1, the separation effect of the algorithm is better:

$$SC_{i,j} = \left|\sum_{t=1}^{n} s_j(t) y_i(t)\right| \Big/ \sqrt{\sum_{t=1}^{n} s_j^2(t) \sum_{t=1}^{n} y_i^2(t)}. \tag{18}$$

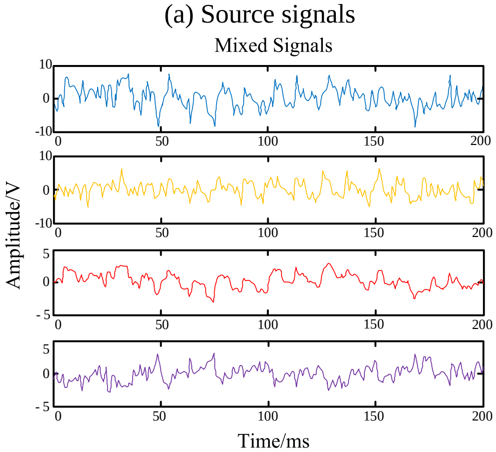
III. SIMULATION OF THE SIGNALS BASED ON JADA ALGORITHM

To verify the effectiveness of the proposed algorithm, the separation simulation of the signals is studied. As shown in Fig. 2 (a), sine signal (blue line), trapezoidal wave signal (yellow line), sawtooth signal (red line) and random signal (purple line) are created. A four order hybrid filter is used to mix the signals, and the waveforms are shown in Fig. 2 (b). According to the JADA algorithm theory, the mixed signals are separated into four mutually independent signals, the waveforms of separated signals are shown in Fig. 2 (c). In addition, the ICA algorithm is employed to separate signals, the waveforms are shown in Fig. 2 (d).

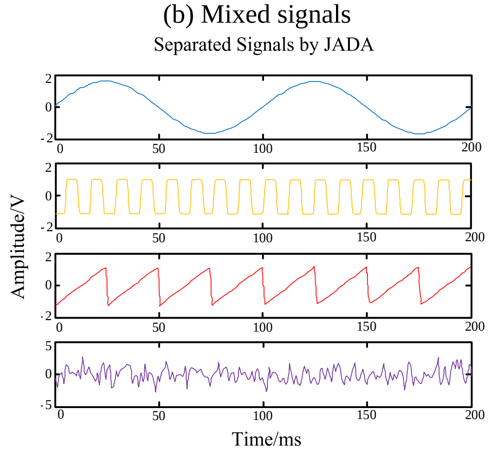
Comparing the source signals in Fig. 2 (a) with the separated signals in Fig. 2 (c), it can be concluded that the mixed signals in Fig. 2 (b) can be successfully separated into the four signals by the JADA algorithm, and the separated results are similar to the source signals. The similarity coefficient *SC* of the sine signal is 0.97, and other three signals are 0.96, 0.95 and 0.96, respectively. In addition, by comparing the results in Fig. 2 (c) and Fig. 2 (d), it can be seen that the accuracy of JADA algorithm is better than that of ICA algorithm. Therefore, the JADA algorithm is employed to the signal separation.



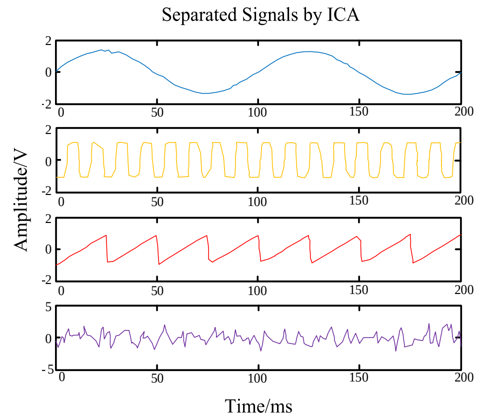
(a) Source signals



(b) Mixed signals



(c) Separated signals by JADA algorithm



(d) Separated signals by ICA algorithm

Fig. 2. JADA algorithm characteristic simulation.

IV. EXPERIMENT OF THE RADIATED EMI NOISE BASED ON JADA ALGORITHM

In this paper, the experiment of the common-differential mode radiated EMI noises is made to verify the effectiveness of the JADA algorithm. The experiment layout is shown in Fig. 3. One end of the magnetic field probe (R&S HZ-11) is connected to the channel of the oscilloscope (R&S Tektronix DPO5204), and the other end measures the radiated EMI noise.

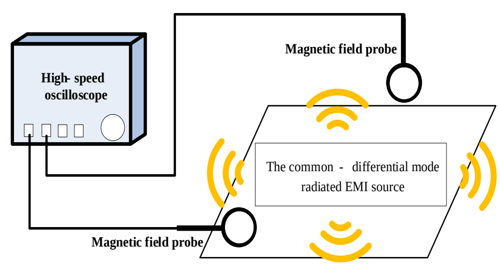
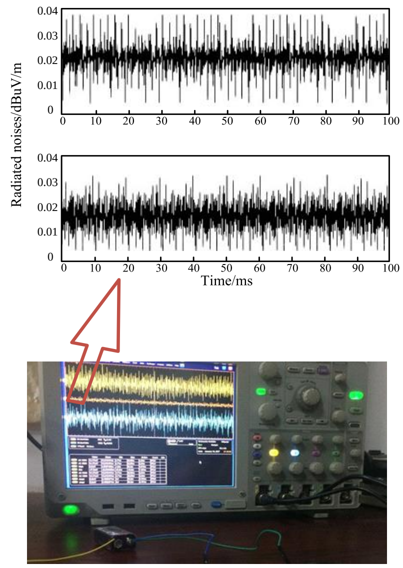


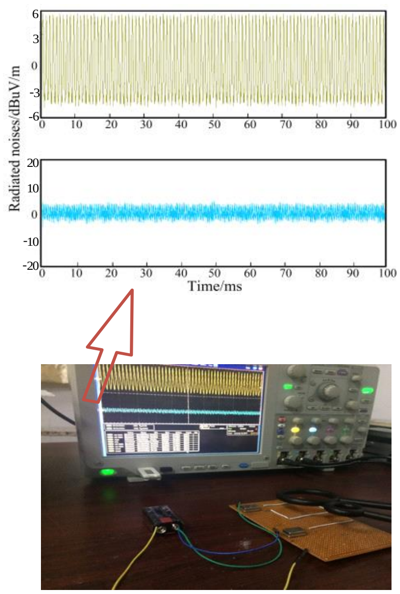
Fig. 3. Experiment layout of radiated EMI noise.

As shown in Fig. 4, in this experiment, the 20M crystal oscillator is used as common mode interference source, and the 30M crystal oscillator is used as differential mode interference source. The white noises and the radiated EMI noises are obtained through the two magnetic field probes and the high-speed oscilloscope. The two probes are fixed, and distance between the probes and the crystal oscillators is within 1cm. The experiment white noises and the radiated EMI noises generated by crystal oscillators are shown in Fig. 4 (a) and Fig. 4 (b), respectively.

The JADA algorithm is applied to separate the mixed signals obtained by the experiment, the separated results of the common mode radiated EMI noise and the differential mode radiated EMI noise are shown in Fig. 5 (a). Compared with the source noises, the *SC* of the common noise and the differential noise are 0.97 and 0.96, respectively, which suggests that the JADA algorithm is feasible to separate the radiated EMI noises.

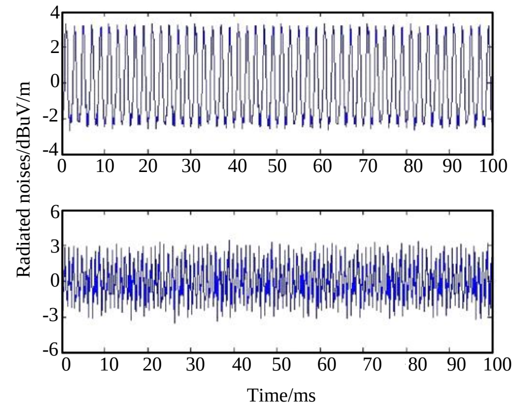


(a) The common-differential mode white noises

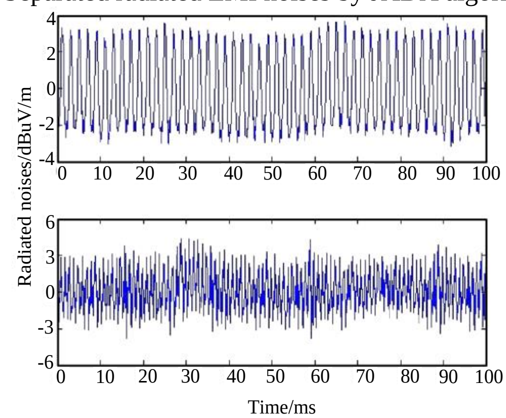


(b) The common-differential mode radiated EMI noises

Fig. 4. The common-differential mode radiated EMI experiment.



(a) Separated radiated EMI noises by JADA algorithm



(b) Separated radiated EMI noises by ICA algorithm

Fig. 5. Common-differential mode separated radiated EMI noises.

As shown in Fig. 5, compared the separated results by JADA algorithm in Fig. 5 (a) with the ICA algorithm in Fig. 5 (b), JADA algorithm can separate the radiated EMI noises more accurately and more efficiently. The *SC* of the two noises are shown in Table 1. It can be clear seen that the JADA algorithm accuracy is 14% higher than the ICA algorithm. In addition, from the number of iterations in Table 1, it can be found that the JADA algorithm is more efficient, with an increase of more than 30%. In addition, JADA algorithm introduces the the fourth-order cumulant matrix based on ICA, which has better generality.

Table 1: Comparison of separation characteristics of two algorithms

Radiated Source Model	JADA Algorithm			ICA Algorithm		
	Similarity Coefficient		Number of Iterations	Similarity Coefficient		Number of Iterations
	Common Noise	Differential Noise		Common Noise	Differential Noise	
Common-differential mode	0.97	0.96	24	0.81	0.82	36

V. CONCLUSION

A new radiated EMI noises separation method based on the JADA algorithm is proposed in this paper. Simulation and experiment results demonstrate that the JADA algorithm can successfully separate radiated EMI noise, which verify the validity of the separation method.

Compared with the ICA algorithm, the accuracy and the efficiency have been greatly improved. The work provides the reference for separating the sources which produce the radiated noise, and contributes to conduct the targeted suppression research in the near future.

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