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A Method Based on the Improved Matrix Pencil Algorithm Designed for Voltage Flicker Detection

[1] Chen Shi, [1] Li Xing-Yuan, [1] Zhu Rui-Ke, [2] Luo Xiao-Yi

[1] School of Electrical Engineering and Information, Sichuan University Chengdu, 610065, China

[2] Sichuan Business Operation Monitoring Center of State Grid, Chengdu, 610023, China

[1] Tel. :(86) 13808081052

[1] E-mail: chenshi629@163.com

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Abstract: Voltage fluctuation and flicker are becoming more and more serious, which need necessary detection and further management. An improved algorithm designed for detecting voltage flicker parameters has been proposed. The method transformed voltage flicker signal model into a sum of series exponential signal model. Two matrices were constructed and combined into a matrixpencil. Thus, the nonlinear problem was converted into a linear problem. Not only voltage amplitude and frequency but also phase information of voltage flicker can be extracted through the method. Moreover, due to the difficulty of modal order determination in the noise environment, a method of Hankel matrix rank estimation was put forward to determine modal order accurately. Voltage flicker experiments were taken in the noise background. The results show that the proposed method is superior in computational accuracy, order determination and anti-noise capability. As a result, the method could contribute a new idea for the voltage flicker signal parameter extraction. *Copyright © 2013 IFSA.*

Keywords: Voltage flicker, Matrix pencil algorithm, Model order determination, Harmonics.

1. Introduction

With the rapid growth of electric power system load, the extensive utilization of impact load causes more and more serious voltage fluctuation and flicker in the power system. Voltage fluctuations and flicker may cause malfunction to some important electronic instruments, control systems or protective devices under some serious circumstances, thus more and more attention has been paid on the voltage flicker problem. In order to avoid voltage fluctuation and flicker, the SVC is applied in power system, which requires accurate flicker parameters so as to make a correct management decision [1-7].

The detection method of voltage flicker is to extract voltage fluctuation signal and to analyze the frequency spectrum of fluctuation signal, frequency and amplitude of low frequency harmonic components. The common methods of voltage flicker test contain half-wave RMS method, square detection method and full-wave rectifier method [1]. Square detection method is a flicker measuring method recommended by IEC. With the development of mathematical tools, several mathematical methods have been widely used for flicker detection. Literature [8-9] proposed a method based on the voltage fluctuation and flicker detection method with FFT. Because of the non-integer relationship between voltage flicker frequency and the base frequency, analyzing the voltage flicker by using the FFT method directly can lead to spectrum aliasing due to the non-synchronous sampling, which affects the accuracy of the measurement results. By using the Kalman filter algorithm, literature [10-12] has achieved the voltage flicker detection, but the detection method is complicated. The wavelet algorithm can also be used to detect the voltage flicker [13-15]. However, it is difficult to choose appropriate wavelet bases in practice. Literature [16-18] adopts Hilbert transform method, which require narrowband signal, to detect the for flicker detection, While the actual flicker signals do not accommodate the requirement due to the higher harmonics noises.

In addition to the methods above, MP (Matrix Pencil) method can also be used to extract flicker parameters of the voltage flicker. MP algorithm is a pole extraction method proposed by Y.B Hua and T.K Sarkar et al. As MP algorithm uses the inner product forms to improve noise immunity, better effects are obtained in the aspect of digital signal processing [19-21]. MP is a non-iterative algorithm which could avoid the convergence problem and the numerical difficulty of computation. Thus the MP algorithm is an efficient numerical method [22]. This paper proposes some improvements to the MP method for voltage flicker detection. The basic idea is: By constructing two matrices and merging them into one matrix pencil, the nonlinear problem can be transformed into a linear issue which is easy to be solved. Furthermore, considering the inaccuracy problem on order determination, this paper utilizes the Hankel matrix rank estimation method to determine system order accurately, which improves the MP method, inhibits the noise and achieves the purpose of obtaining the signal parameters accurately. The stimulation results show that the method has the characteristics of accurate order determination, strong noise immunity, high efficiency and high precision. The improved MP method cannot only extract the voltage flicker amplitude wave parameter of frequency and amplitude accurately, but the phase information can also be obtained, which provides a new thought in flicker detection.

2. Voltage Flicker Mathematical Model

Usually, the voltage with characteristics of fluctuation and flicker is viewed as modulation signal. The carrier wave is power frequency voltage (50 Hz or 60 Hz) whose RMS (Root Mean Square) or peak value is modulated by the amplitude-modulated wave that mainly contains voltage fluctuation components. The frequency fluctuation of voltage signal ranges from 0.05 Hz to 35 Hz, while the amplitude varies from 0 to 10 % of power frequency carrier wave amplitude. The characters of voltage fluctuation and flicker are reflected through the amplitude-modulated wave. So the method to extract parameters from the amplitude-modulated wave is equal to that from the voltage flicker. Voltage flicker can be divided into two categories, periodicity and aperiodicity. The former has a more important effect on people's life, thus researches on parameter extraction from periodic voltage flicker is the main content in this paper. Usually, harmonics are contained in voltage flicker signals. To make the analysis simple, the parts related to harmonics will be discussed in the following section 3.2. Given ignoring the harmonics, voltage flicker signal $u(t)$ can be expressed as a power frequency sinusoidal signal which is linear amplitude modulated by the amplitude-modulated signal A_i .

$$u(t) = [A_0 + \sum_{i=1}^{n} A_i \cos(2\pi f_i t + \theta_i)] \cdot \cdot \cos(2\pi f_0 t + \theta_0), \quad (1)$$

where A_0 , f_0 , θ_0 denote the amplitude, the frequency and the initial phase of the fundamental components respectively. A_i denotes the amplitude of AM(amplitude modulation) wave components whose frequency is f_i and phase is θ_i . Expand (1) by trigonometric decomposition:

$$\begin{aligned} u(t) = & A_0 \cos(2\pi f_0 t + \theta_0) + \\ & \sum_{i=1}^{n} 0.5 A_i \cos[2\pi (f_0 - f_i)t + (\theta_0 - \theta_i)] + \\ & \sum_{i=1}^{n} 0.5 A_i \cos[2\pi (f_0 + f_i)t + (\theta_0 + \theta_i)], \end{aligned} \quad (2)$$

where $f_0 - f_i$ and $f_0 + f_i$ are called side frequency. If the parameters of the side frequency components can be obtained by detecting $u(t)$, the information in voltage flicker about amplitude, frequency and phase of amplitude modulation wave can also be acquired sequentially.

3. The MP Algorithm

3.1. The Basic Principle of the Algorithm

Assuming that Δt is the sampling interval, the systemic discrete response sequence $y(k)$ can be expressed as the sum of exponential function.

$$y(k) = \sum_{i=1}^{M} R_i z_i^k + n(k) \qquad k = 0,1,2,...,N-1 , \quad (3)$$

where $R_i = A_i e^{j\theta_i}$ is the residue, $z_i = e^{(\alpha_i + j\omega_i)\Delta t}$ is the systemic response pole, k is the sampling points, Δt is the sampling interval, N is the sum of the sampling points, $n(k)$ is the noise in the system; M is the number of poles in the signal and the modal order of system as well, A_i , θ_i , α_i , ω_i are the amplitude, initial phase, damping factor and angular frequency of ith sinusoid , respectively.

The calculation steps of the MP algorithm [21] are as follows:

1) Construct a $(N-L)\times(L+1)$ Hankel matrix with sampling series $y(k)$ $(k = 0,1,2,...,N-1)$:

$$\boldsymbol{Y}=\begin{bmatrix} y(0) & y(1) & \cdots & y(L) \\ y(1) & y(2) & \cdots & y(L+1) \\ \vdots & \vdots & \ddots & \vdots \\ y(N-L-1) & y(N-L) & \cdots & y(N-1) \end{bmatrix}_{(N-L)\times(L+1)}, \quad (4)$$

where L is the matrix parameter. An appropriate choice can suppress interference to some extent. Generally, L=N/4~N/3.

2) SVD.

Make an SVD on Y:

$$Y = UDV^T, \quad (5)$$

where $D \in R^{(N-L)\times(L+1)}$ is the diagonal matrix, the main diagonal elements d_i are the singular values arranged in non-increasing sequence. $U \in R^{(N-L)\times(N-L)}$ and $V \in R^{(L+1)\times(L+1)}$ are both orthogonal matrix.

For the actual system, considering the noise impact, a nonzero-singular-value sequence can be obtained by making a SVD (Singular Value Decomposition) on the matrix Y. Since the singular value of the real modal is big while that of the noise modal is small, we select the maximum singular value $d_{\max}$ from d_i and record the maximum subscript i satisfying the constraint condition(6) as the system maximum modal number.

$$d_i / d_{\max} \geq \mu \quad (6)$$

Meanwhile, combine the first M non-zero singular values of D into a new matrix D'.

$$D' = \begin{bmatrix} d_1 & 0 & \cdots & 0 \\ 0 & d_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & d_M \\ & [0]_{(N-L-M)\times M} & & \end{bmatrix}_{(N-L)\times M} \quad (7)$$

3) Solution to the modal damping factor and oscillation frequency

V' is made up of the first M right singular vectors of the V matrix . The rest but the last line of V' makes V_1 and the left except the first line of V' forms V_2. Then define

$$\begin{cases} Y_1 = UD'V_1^T \\ Y_2 = UD'V_2^T \end{cases} \quad (8)$$

Make up a matrix pencil $Y_2 - \lambda Y_1$. It can be proved that solving the poles in (3) is equal to finding a solution to the generalized eigenvalues of (9).

$$G = Y_1^+ Y_2, \quad (9)$$

where Y_1^+ is the pseudo-inverse matrix of Y_1. There are M non-zero eigenvalues $z_i (i = 1,2,3,\cdots M)$ in G.

3.2. Improvement on the MP Algorithm

MP method accuracy lies in the determination of modal order M . A lower modal order can result in a leakage identification phenomenon with modal information missed; while excessive modal order may lead to a phenomenon of over-fitting which can result in false modal and reduce the MP algorithm accuracy. Therefore the choice of the threshold μ in (6) plays a decisive role in the determination of modal order M . However, the threshold μ is generally selected by experience and it is difficult to determine the order of the system accurately, which affects the accuracy of the MP algorithm. So the Hankel matrix rank estimation [23] method is presented in this paper to determine the modal order, which improves the identification accuracy of matrix pencil by accurate order determination.

According to the dynamic theory, for a dynamic system whose degree of freedom is P, its discrete impulse response (or the free response) can be expressed as (3). At this point, $M = 2P$, which means that a dynamic system with P degrees of freedom has 2P modal . Without considering noise, the mathematical form of a dynamical system with P degrees of freedom is an M-order differential equation. When the system is discrete, its mathematical form is surely an M-order difference equation. Hence, its impulse response (or free response) sequence satisfies the difference equation (10).

$$y(M+n) + \sum_{i=0}^{M-1} \beta_i y(i+n) = 0 \quad n = 0,1,2,..., \quad (10)$$

where $\beta_i (i = 0,1,2,...,M-1)$ is the real coefficient. Formula (10) can be written in the form of the regression equation as (11).

$$y(M+n) = -\sum_{i=0}^{M-1} \beta_i y(i+n) \quad n = 0,1,2,... \quad (11)$$

The regression equation (11) shows that each value in the response sequence is the linear combination of M values just ahead of that. Further, the discrete impulse response (or free response) of this dynamical system can be completely expressed by M arbitrary consecutive sample values. As a result, the rank of the Hankel matrix constituted by the impulse response (or free response) is no more than M. As long as the number of rows and columns in the Hankel matrix is large enough, the rank will necessarily be M.

The matrix rank is the number of non-zero singular values which can be obtained by using the SVD. Without noise, after making an SVD to the Hankel matrix, the number of non-zero singular values is the system modal order M.

In the actual system with noise, if making an SVD to the Hankel matrix, the zero singular values become nonzero. First, we can calculate the singular values by a normalized formula (12) for plotting the normalized singular value curve. Since the singular value of the noise mode is much less than that of the intrinsic mode, an inflection point can be detected by plotting the normalized singular value curve. On the left of the point, the curve decreases steep firstly and then the curve changes smoothly on the right of it. As a result, the modal corresponding to the singular value on the right of the inflection point is the noise model, and that corresponding to the left part of the point is the system modal. Hence, the index of singular value is the system order M.

$$d_i^* = (d_i - d_{\min}) / (d_{\max} - d_{\min}) \quad (12)$$

The concrete steps of the Hankel matrix rank estimation method is described as follows:

1) Construct the Hankel matrix using sampling sequence. The number of rows and columns cannot be so small to ensure that the rank of the matrix is large enough to contain all the intrinsic modal information.

2) Make an SVD to the Hankel matrix; make normalized calculation of (12) and plot the normalized singular value curve.

3) Detect the inflection point according to aforementioned method and the system intrinsic modal order M is determined also.

After the system intrinsic modal order M is determined, all the eigenvalues $z_i (i = 1, 2, ..., n)$ can be calculated by (9) and the residue R_i can be acquired by utilizing the least squares method as specified in (13).

$$\begin{bmatrix} y(0) \\ y(1) \\ \vdots \\ y(N-1) \end{bmatrix} = \begin{bmatrix} 1 & 1 & \cdots & 1 \\ z_1 & z_2 & \cdots & z_M \\ \vdots & \vdots & \ddots & \vdots \\ z_1^{N-1} & z_2^{N-1} & \cdots & z_M^{N-1} \end{bmatrix} \begin{bmatrix} R_1 \\ R_2 \\ \vdots \\ R_M \end{bmatrix} \quad (13)$$

All the parameters corresponding to each modal characteristic can be calculated through (14).

$$\begin{aligned} A_i &= |R_i| \\ \theta_i &= \arctan\left[\mathrm{Im}(R_i) / \mathrm{Re}(R_i)\right] \\ \omega_i &= \arctan\left[\mathrm{Im}(z_i) / \mathrm{Re}(z_i)\right] / \Delta t \end{aligned} \quad (14)$$

In summary, the improved MP algorithm suppresses the actual noise through the following steps. First, construct two matrices with the sampling signal and merge them into one matrix pencil. Then determine the accurate order with the Hankel matrix rank estimation method. The eigenvalues are calculated based on the order determination and the residues are acquired by the least squares method. At last, voltage flicker parameters are extracted accurately by the equation (14), (1) and (2).

4. Stimulations

4.1. The Ideal Examples

In order to verify the effectiveness of the method in voltage flicker parameter estimation proposed in this paper, an ideal single frequency flicker signal is taken for an example as (15).

$$\begin{aligned} u(t) = {} & [1 + 0.06\cos(50\pi t + \pi / 4)] \cdot \\ & [\cos(100\pi t + \pi / 6)] \end{aligned} \quad (15)$$

According to (2) and Euler equation, the theoretical modal order of the signal is 6. Since the actual measurement signal contains high frequency noise, the white Gaussian noise with 30 db SNR (Signal Noise Ratio) is injected into the ideal signal. The simulation is done with Matlab, the signal sampling frequency is 1 kHz and the sampling time is 0.4 s.

First, determine the modal order with the traditional MP algorithm. According to (6), select the threshold to determine the modal order M. When the thresholds are 1 %, 2 % and 5 % respectively, the modal orders determined by the Hankel matrix singular decomposition are shown in Table 1. As can be seen from Table 1, with noise, the experience threshold selection is very important which is directly related to the accuracy of the voltage flicker parameters extraction. In this example, 3 % is a reasonable selection, while 1 % and 5 % cannot determine the order accurately and thus the voltage flicker parameters cannot be accurately extracted.

Table 1. The modal order under different threshold.

Threshold	1 %	3 %	5 %
Modal order	18	6	2
Detected Results	Over fitting	Correct order	leakage id

*leakage id is leakage identification

Then the improved MP method is adopted to analyze the signals above. Firstly, the Hankel matrix formed by the sampling signal are decomposed with the SVD, the normalized singular value curve is shown in Fig. 1. As can be seen from Fig. 1, the curve becomes smooth at the point of six. As a result, six is the modal order of the system, which is the same as the theoretical value. Therefore the effectiveness of the proposed method is proved.

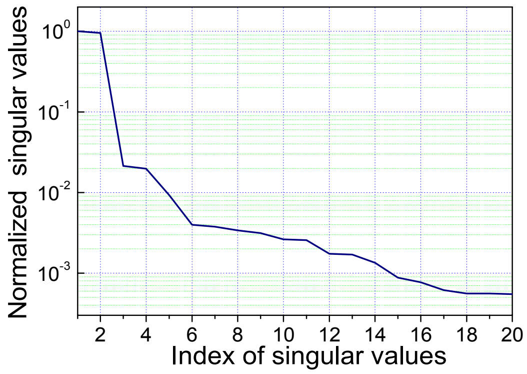

Fig. 1. Normalized singular values.

The parameters extracted by the improved MP method are shown in Table 2. Amplitude wave parameters are calculated through adopting the formula (1), (2) and using the data in Table 2.

Table 2. The extracting parameters for simple flicker.

Parameter	Amplitude/V	Frequency/Hz	Phase/°
Base frequency	0.996	49.9998	30.0611
Side frequency 1	0.0293	75.0963	72.7069
Side frequency 2	0.0315	24.9887	-15.3452

The comparison with the ideal parameters is shown in Table 3.

Table 3. Parameters of flicker and detected values.

Parameters	Ideal parameters	Calculation parameters		
		40 db white noise	30 db white noise	25 db white noise
u/V	0.06	0.0602	0.0608	0.63
f/Hz	25	24.98	25.0538	24.851
θ/°	45	44.95	44.026	42.13

As can be seen from Table 3, with the 30 db noise, the identification is pretty accurate. The errors of the amplitude and frequency of the amplitude modulated wave are 1.333 %, 0.215 % respectively, which are small. To validate the noise immunity, Table.3 also shows the parameter values while the SNR is 40 db and 25 db respectively. It can be analyzed from Table 3 that the maximum error of the modulated wave parameters is not over 0.5 % when the noise is 40 db. With the noise rising, the identification error is also increasing. But the errors are within a reasonable range. The results of the simulation show that the improved MP method has high noise immunity and detection accuracy in a case of a simple flicker.

4.2. Examples with Harmonics

Actual flicker signals often contain multiple frequency flicks and the harmonic pollution also exists in the signal. Now, an amplitude modulated wave whose amplitude and frequency are 0.08 and 10 Hz respectively, mixed with a harmonic signal whose amplitude and frequency are 0.1 and 100 Hz respectively, is added into the detection signal. The complex flicker signal is:

$$u(t) = [1 + 0.06\cos(50\pi t + \pi/4) + 0.08\cos(20\pi t)]\cdot[\cos(100\pi t + \pi/6) + 0.1\cos(200\pi t + \pi/3)] + e(t) \quad (16)$$

It can be acknowledged by analyzing the signal modal (16) that the system order should be 18. Since the voltage flicker parameters calculation only requires the side frequency components of the base wave, the side frequency components of the harmonic almost have no impact on the voltage flicker parameter calculation. Therefore, the side frequency components corresponding to the harmonic are negligible and only the 12-order approximation system model is considered.

First, determine the mode order with the traditional MP algorithm. When the threshold is selected as 1 %, 3 % and 5 % respectively, the modal order is shown in Table 4. Either over-fitting or leakage identification is existed. The order determination can be accurately obtained only when the threshold is selected as 2.8 %.

Table 4. The modal order under different threshold.

Threshold	1 %	2.8 %	3 %	5 %
Modal order	22	12	8	4
Detected Results	Over fitting	Correct order	Leakage id	Leakage id

* leakage id is leakage identification

It can be acknowledged by consolidating this case and the examples in 3.1 that the correct thresholds are different under different circumstances (the threshold is 2.8 % in this case and 3 % in examples of section 3.1). The traditional MP method which adopts empirical threshold selection will affect the order determination, and thereby reduce the accuracy of the algorithm. Especially with actual noise, the threshold value selected by experience will reduce the reliability of the MP algorithm and even cause flicker parameters extraction failure.

The order determination is further calculated by the improved MP method. Fig. 2 portrays a singular value curve. As shown in Fig. 2, the curve becomes smooth at the point of 12. Therefore the order of the system model is 12 instead of 18 as analyzing the equation of (16). It is because the side frequency components of harmonic are too weak to be detected accurately on the impact of noise. And that the order of the system model is set to be 12 will not impact the flicker parameter extraction.

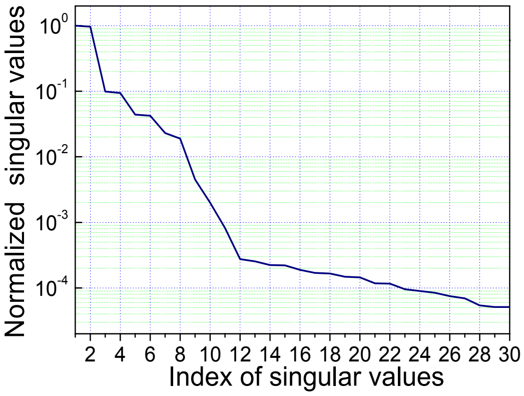

Fig. 2. Normalized singular values.

After order determination, the base frequency, the harmonic and 4 side frequency components corresponding to the base frequency are extracted and the results are shown in Table 5.

Table 5. The extracting parameters for complex flicker.

Parameter	u/V	f/Hz	θ/°
Base frequency	1.0005	50.0005	29.9514
Side frequency 1	0.0403	60.0193	28.7489
Side frequency 2	0.0401	39.9821	29.4296
Side frequency 3	0.0308	74.9794	69.4316
Side frequency 4	0.0304	25.0334	-17.0319
Harmonics	0.1008/	99.9631	60.8617

The amplitude wave parameters can be calculated by the same method with formula (1) and (2). The comparison with the ideal parameters is shown in Table 6. It can be seen that harmonics have no impact on the accuracy of the calculation results. The maximum identification errors of the amplitude and frequency of the amplitude modulated wave are 2 %, 0.19 % respectively. The maximum identification error of the phase parameter is 3.93 %, which is slightly large but the phase does not play a major role in the voltage flicker detection. As can be seen from the above, the improved MP method also has high noise immunity and detection accuracy in complex flicker cases.

It can be seen by comparing the traditional MP methods and the improved MP method that the flicker parameters can be effectively extracted only if the system order is determined accurately under noise circumstances. The traditional MP method relied on experience may degrade its accuracy. The improved MP method can accurately determinate the order and thereby extract the voltage flicker parameters precisely.

Table 6. Parameters of flicker and detected values.

Parameter Type		Ideal Parameters	Calculation Parameters	
			Parameter Value	Error
Amplitude modulation parameters1	u/V	0.06	0.0612	2.00 %
	f/Hz	25	24.973	0.11 %
	θ/°	45	43.2318	3.93 %
Amplitude modulation parameters 2	u/V	0.08	0.0804	0.38 %
	f/Hz	10	10.0186	0.19 %
	θ/°	0	0.34	------
Harmonic parameters	u/V	0.1	0.1008	0.80 %
	f/Hz	100	99.9831	0.02 %
	θ/°	60	60.8617	1.44 %

5. Conclusions

1) An improved algorithm has been proposed for detecting matrix pencil parameters in voltage flicker. The method can convert signal model of voltage flicker into sum of complex exponential. By constructing two matrices and merging them into one matrix pencil, the nonlinear problem can be transformed into a linear issue which is easy to solve. This method cannot only extract the frequency and amplitude voltage flicker modulated wave, but the phase information can also be obtained.

2) Model order calculation with traditional matrix pencil algorithm is mainly based on experience. It may not be accurate for parameter extraction from voltage flicker signals, or even be failed. Improvement has been made with the Hankel matrix rank estimation method in this paper. Numerical examples show that this method can make a precise order determination and improve the algorithm accuracy.

3) A comparison is made for both simple and complex flicker under a noise background. The simulation shows that improved MP method has the advantages of precise order determination, high accuracy and strong noise immunity, which provides a new idea for the parameter extraction from voltage flicker signal.

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