Sensors & Transducers, Vol. 163 , Issue 1, January 2014, pp. 278-284

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The Detection of Subsynchronous Oscillation in HVDC Based on the Stochastic Subspace Identification Method

[1] Chen Shi, [1] Li Xing-Yuan, [1] Li Kuang, [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

E-mail: chenshi629@163.com

Received: 28 December 2013 /Accepted: 20 January 2014 /Published: 31 January 2014

Abstract: Subsynchronous oscillation (SSO) usually caused by series compensation, power system stabilizer (PSS), high voltage direct current transmission (HVDC) and other power electronic equipment, which will affect the safe operation of generator shafting even the system. It is very important to identify the modal parameters of SSO to take effective control strategies as well. Since the identification accuracy of traditional methods are not high enough, the stochastic subspace identification (SSI) method is proposed to improve the identification accuracy of subsynchronous oscillation modal. The stochastic subspace identification method was compared with the other two methods on subsynchronous oscillation IEEE benchmark model and Xiang-Shang HVDC system model, the simulation results show that the stochastic subspace identification method has the advantages of high identification precision, high operation efficiency and strong ability of anti- noise. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: High voltage direct current, Subsynchronous oscillation, Stochastic subspace identification, Oscillation modal.

1. Introduction

Currently, High Voltage Direct Current System (HVDC) is applied popularly because it has the advantages of large transmission capacity, high controllability, low loss and high intelligence [1-2]. However, HVDC may result in increasing the risk of subsynchronous oscillation (SSO) caused by inappropriate control strategy or some devices impact such as power system stabilizer (PSS), flexible alternating current transmission systems (FACTS), which will threaten the safety of generators and even the power grid. As a result, it is very important to identify the modal parameters of SSO and to take effective control strategies as well [3-4].

A lot of researches, although, have been done on the mechanism and control methods of SSO [5-8], it is seldom paid attention to the modal detection of SSO. In general, there are two popular methods used for the modal analysis of the power system oscillation, which are the eigenvalue analysis method on the system model’s equilibrium point and identification method base on the measured data. Eigenvalue analysis method needs the mathematics model of power system, which is very difficult to obtain in large scale power system. And further more, eigenvalue calculation may be extraordinarily difficult because of the curse of dimensionality. Identification method based on the measured data does not need any power system model, so it is suitable for large-scale power system to detect the modal of SSO.

Such as Hilbert-Huang transform method (HHT) [9], PRONY method [10], the matrix pencil method (MP) [11], estimation of signal parameters via rotational invariance techniques method (ESPRIT) [12] can be classified as identification method. Over fitting or leakage identification phenomena may take place in the process of oscillation modal identification using HHT method, hence it can not be applied to complex systems. The accuracy of the PRONY method is easily affected by noise, and it is difficult to determine the correct order of system. Literature [13], although proposing singular value decomposition (SVD) to improve PRONY method, the irrelevant modal still can not be filtered out effectively. MP algorithm can be used to identify the oscillation modal parameters, but it will lead to a risk of numerical instability in the situation of low signal-to-noise ratio. The identification accuracy of ESPRIT method is high, but the computation efficiency is low because of the two SVD decomposition in calculation process.

Stochastic subspace identification (SSI) method [14, 15], has been widely applied in mechanics field. The literature [16] adopted the SSI method to the low frequency oscillation modal identification in power system. The SSI has the advantages of high identification precision, high operation efficiency and strong ability of anti-noise [17]. In view of the advantage of SSI, this paper adopted the SSI method to identify modal parameters of SSO. The core of SSI method is dividing the output data matrix into two parts chronologically, that is, "past" and "future". By projecting the output row space of the "future" onto the output row space of the "past", the projection retains all the information of the "past". So it could be used to forecast the "future". The Xiang-Shang HVDC power system is taken as a practical study case in this paper. The simulation model is built in the PSCAD/EMTDC electromagnetic transient simulation software to detect the oscillation modal and analyze the risk of the SSO. And a comparison between the SSI method, the improved PRONY method and the ESPRITY method is made to verify the superiority of the SSI. Simulation results show that the SSI method have advantages of high accuracy, high computing efficiency, strong noise immunity in identification of SSO.

2. The Identification Algorithm

The process of power system electromechanical transient caused by small perturbation could represent the oscillation character of the power system, which could be expressed as:

$$y(t)=\sum_{i=1}^{n} R_i e^{\sigma_i t}\cos(2\pi f_i t+\varphi_i) \tag{1}$$

where R_i is the oscillation amplitude, σ_i is the attenuation factor , f_i is the oscillation frequency, and ϕ_i is the initial phase.

2.1. The SSI Method

Stochastic subspace identification (SSI) is a kind of linear identification method. By using SSI method, the oscillation modal parameters of the system could be obtained from the raw space of the matrix, which is composed with output data of system.

The stochastic state space model of linear system excited by white noise can be expressed as:

$$\begin{cases} x_{k+1}=\mathbf{A}x_k+w_k \\ y_k=\mathbf{C}x_k+v_k \end{cases}, \tag{2}$$

where $y_k\in\mathbf{R}^{l\times l}$ is the output vector of the l-th measuring point in the k-th ($k\in N$) sampling intervals (Δt); $x_k\in\mathbf{R}^{n\times l}$ is the state vector of the system; n is the order of the system; $\mathbf{A}\in\mathbf{R}^{n\times n}$ is the system matrix; $\mathbf{C}\in\mathbf{R}^{l\times n}$ is the output matrix; $w_k\in\mathbf{R}^{n\times l}$ is the noise of the system; $v_k\in\mathbf{R}^{l\times l}$ is the measure noise; w_k and v_k are independent of each other.

According the system output y_k, construct the Hankel matrix $\mathbf{H}$:

$$\boldsymbol{H}=\boldsymbol{Y}_{0/2i-1}=\frac{1}{\sqrt{j}}\begin{bmatrix} y_0 & y_1 & y_2 & \cdots & y_{i-1} \\ y_1 & y_2 & y_3 & \cdots & y_i \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ y_{i-1} & y_i & y_{i+1} & \cdots & y_{i+j-2} \\ y_i & y_{i+1} & y_{i+2} & \cdots & y_{i+j-1} \\ y_{i+1} & y_{i+2} & y_{i+3} & \cdots & y_{i+j} \\ y_{i+2} & y_{i+3} & y_{i+4} & \cdots & y_{i+j+1} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ y_{2i-1} & y_{2i} & y_{2i+1} & \cdots & y_{2i+j-2} \end{bmatrix}= \begin{bmatrix} \boldsymbol{Y}_{0/i-1} \\ \hline \boldsymbol{Y}_{i-1/2i-1} \end{bmatrix}=\begin{bmatrix} \boldsymbol{Y}_p \\ \boldsymbol{Y}_f \end{bmatrix} \tag{3}$$

where $0/2i-1$, the subscript of $\mathbf{Y}_{0/2i-1}$, denotes the first line block and the last line block. Subscript p and subscript f denotes the "past" and the "future" respectively.

Define the covariance matrix $\mathbf{R_i}$, where the output y_k comes from, as:

$$\boldsymbol{R}_i=E\left[y_{k+1}y_k^{\mathrm{T}}\right] \tag{4}$$

Construct Toeplize matrix $\mathbf{T}_{1/i}$ by covariance sequence.

$$\boldsymbol{T}_{1/i} = \boldsymbol{Y}_f \boldsymbol{Y}_p^{\mathrm{T}} \quad (5)$$

Singular value decomposition is made on matrix $\mathbf{T}_{1/i}$, the rank is the number of non-zero singular values that is the system order.

$$\boldsymbol{T}_{1/i} = \boldsymbol{SVD}^{\mathrm{T}} = \begin{pmatrix} \boldsymbol{S}_1 & \boldsymbol{S}_2 \end{pmatrix} \begin{pmatrix} \boldsymbol{V}_1 & 0 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} \boldsymbol{D}_1^{\mathrm{T}} \\ \boldsymbol{D}_2^{\mathrm{T}} \end{pmatrix} = \boldsymbol{S}_1 \boldsymbol{V}_1 \boldsymbol{D}_1^{\mathrm{T}} \quad (6)$$

where $\mathbf{S_1} \in \mathbf{R}^{li \times n}$, $\mathbf{V_1} \in \mathbf{R}^{n \times n}$, $\mathbf{D_1} \in \mathbf{R}^{li \times n}$, n denotes the system order, which could be obtained by the SVD decomposition method.

$\mathbf{T}_{1/i}$ could be decomposed into,

$$\boldsymbol{T}_{1/i} = \boldsymbol{O}_i \boldsymbol{\Gamma}_i \quad (7)$$

where $\mathbf{O}_i$ is the considerable matrix, $\mathbf{\Gamma_i}$ is the inverse randomized controllable matrix.

Matrix $\mathbf{A}$ and $\mathbf{C}$ could be expressed as (8).

$$\begin{cases} \boldsymbol{A} = \boldsymbol{V}_1^{-1/2} \boldsymbol{S}_1^{\mathrm{T}} \boldsymbol{D}_1 \boldsymbol{V}_1^{-1/2} \\ \boldsymbol{C} = \boldsymbol{O}_i(1:l) \end{cases} \quad (8)$$

2.2. Modal Parameter Identification

Make the eigenvalue decomposition on the system matrix $\mathbf{A}$.

$$\boldsymbol{A} = \boldsymbol{\Psi} \boldsymbol{\Lambda} \boldsymbol{\Psi}^{-1} \quad (9)$$

where $\boldsymbol{\Lambda} = \mathrm{diag}[\lambda_1, \lambda_2, \cdots, \lambda_i, \cdots, \lambda_n] \in \boldsymbol{C}^{n \times n}$; λ_i is the system eigenvalue; $\boldsymbol{\Psi} = [\psi_1, \psi_2, \cdots, \psi_n] \in \boldsymbol{C}^{n \times n}$ is the system eigenvector matrix, and n denotes the system order.

According to the formula (10), calculate the oscillation modal parameter.

$$\lambda_i^c = \frac{\ln(\lambda_i)}{\Delta t}$$
$$\lambda_i^c, \lambda_i^{c*} = \sigma_i \pm j2\pi f_i \quad (10)$$

where λ_i^c denotes the system eigenvalue, λ_i^c and λ_i^{c*} are conjugate to each other, Δt denotes the sampling interval, σ_i is the attenuation factor, f_i is the oscillation frequency. According to the formula (11), calculate the system damping ratio ξ_i.

$$\xi_i = \frac{-\sigma_i}{\sqrt{\sigma_i^2 + (2\pi f_i)^2}} \quad (11)$$

3. Case Study

3.1. Ideal Signal Example

In order to verify the effectiveness and the noise immunity of the SSI algorithm, the ideal signal is constructed as follows and the Gaussian white noise is added into it, whose mean value is 0 and variance is 1.

$$\begin{aligned} x(n) = {} & 1.7e^{-0.14t}\cos(2\pi \times 6.8t + \pi/3) + \\ & 2.3e^{-0.17t}\cos(2\pi \times 12.9t + \pi/6) + \\ & 4.9e^{-0.27t}\cos(2\pi \times 25.9t + \pi/12) \end{aligned} \quad (12)$$

Improved PRONY method, ESPRIT method and SSI method were used to identify the oscillation character of the ideal signal example respectively. The identification results are shown in Table 1. It is shows that maxium relative error of frequency, attenuation factor using SSI is 0.0397 %, 1.929 % respectively, which is the smallest among the three algorithms. That is to say the SSI is the most accurate method among the three methods. Meanwhile the identification time of the SSI method is just 12.87 milliseconds, which is the fastest among these three methods.

Table 1. Comparison of three identification methods.

Method	Frequency		Attenuation factor		Time
	Result (Hz)	Relative error (%)	Result	Relative error (%)	Result (ms)
SSI	25.8991	0.0034	-0.2711	0.407	12.8701
	12.9012	0.0093	-0.1695	0.2941	
	6.7973	0.0397	-0.1424	1.929	
ESPRIT	25.9131	0.051	-0.2714	0.5185	14.6485
	12.9065	0.0504	-0.1716	0.9412	
	6.8034	0.05	-0.1356	3.1428	
Improved PRONY	25.8971	0.0112	-0.2669	1.1481	14.6017
	12.8756	0.1892	-0.1678	1.2941	
	6.7793	0.3044	-0.1447	3.3571	

To verify the strong noise immunity of the SSI algorithm, a colorful noise, whose SNR is 6, is added to the ideal signal, the identification result is shown in Table 2.

According to the Table 2, in the case that white noise and the colored noise are both added, the maximum error of the frequency parameters identified by the SSI is only 0.33 %, and the maximum errors of the ESPRIT and the improved

PRONY are 5.96 % and 8.3 % respectively. Obviously, the proposed method obtained a more accurate result than other 2 methods.

Table 2. Comparison of three identification methods.

Method	Frequency		Attenuation factor		Time
	Result (Hz)	Relative error (%)	Result	Relative error (%)	Result (ms)
SSI	25.8957	0.0166	-0.2974	10.148	12.449
	12.9048	0.0372	-0.1495	11.882	
	6.7774	0.3323	-0.1608	14.857	
ESPRIT	25.5465	1.3648	-0.3144	16.444	15.21
	13.246	2.6821	-0.1324	22.11	
	6.395	5.9559	-0.1698	21.286	
improved PRONY	25.5782	1.2425	-0.3195	18.333	13.931
	12.7905	0.8488	-0.2237	31.588	
	6.2357	8.2985	-0.1736	24.01	

The maximum errors of the attenuation factors from the identification in these three aforementioned methods are 14.86 %, 22.11 % and 31.59 % respectively. Although relative error of the SSI is bigger than that of the ideal signal example, the accuracy has been improved greatly, compared to relative error of the other two methods. Therefore, when the white noise and the colored noise are both exist, the result of the SSI identification is more accurate, and the noise immunity of the SSI method is stronger. Considering the efficiency of algorithm, the time spent by these three algorithms are 12.45, 15.21, 13.93 milliseconds respectively, hence the SSI algorithm operation efficiency is relatively the highest.

3.2. IEEE First Benchmark Model

In this section, the SSO first benchmark model recommended by the IEEE working group is taken as study case. The model is build in PSCAD/EMTDC program, a three-phase short disturbance is imposed at the time of 1.5 s, which lasts 0.075 s. 1000 sample points are extracted from the generator rotation rate signal to identify the oscillation modal. To verify the noise immunity of the three methods, the white noise and colored noise aforementioned were added into the sample sequence.

To determine the oscillation frequency of the IEEE the first benchmark model preliminary, the fast Fourier transform (FFT) method is firstly adopted to obtain the oscillation frequency roughly, which could provide the preliminary basis for comparison.

The identification results using FFT are shown in Fig. 1, As shown in Fig. 1, there are about five oscillation frequencies around 15 Hz, 20 Hz, 26 Hz, 32 Hz, 47 Hz respectively.

To compare the performance of 3 identification methods, the SSI algorithm, ESPRIT method and the improved PRONY method are used respectively to identify oscillation characteristics of first benchmark model. The results are shown in Table 3 – Table 5.

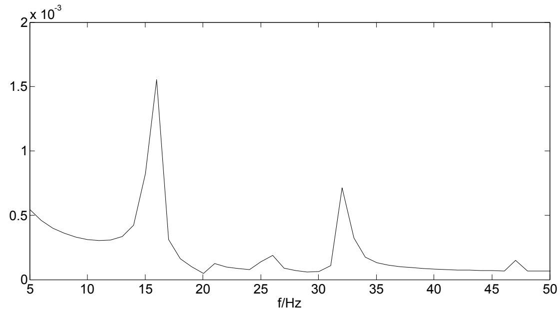

Fig. 1. Generator speed signal identified by FFT.

Table 3. Indentified results by SSI method.

Frequency (Hz)	Attenuation factor	Damping ratio (%)
15.7299	-0.0023	0.00233
20.2213	-0.00089	0.0007
25.5466	-0.00041	0.00026
32.2914	-0.0013	0.00064
47.4231	-0.1895	0.0636

Table 4. Identified results by ESPRIT method.

Frequency (Hz)	Attenuation factor	Damping ratio (%)
15.7352	-0.0019	0.00192
20.2578	-0.0008	0.00063
25.5161	-0.0016	0.001
32.3104	-0.0015	0.00074
47.4043	-0.5122	0.17197

Table 5. Identified results by PRONY method.

Frequency (Hz)	Attenuation factor	Damping ratio (%)
15.6641	-0.002	0.00203
20.1723	-0.00076	0.0006
25.5986	-0.0014	0.00087
32.2413	-0.0016	0.00079
47.5318	-0.2203	0.07376

According to the results in Table 3 – Table 5, the IEEE first benchmark model indeed exist five oscillation modals, which is consistent with the result obtained by the FFT. And all oscillation damping ratios of IEEE first benchmark model are positive, that is to say the oscillation could self-attenuate, but the value is small and the oscillation decays slowly, which might cause shaft fatigue accumulation. Among these three algorithms, the SSI identification result is the closest to the result of the literature [3] (see appendix A), therefore this verifies the effectiveness of the SSI algorithm. According to the results in Table 6, the identification time spent by these three algorithm are 13.24, 15.38 14.13 milliseconds respectively, obviously the operation efficiency of the SSI is the highest among the three methods.

Table 6. Identification time of IEEE model.

	Algorithm		
	SSI	**ESPRIT**	**improved PRONY**
Time (ms)	13.2445	15.3817	14.1337

3.3. Xiang-Shang HVDC System

In order to verify the effectiveness of SSI in practical system, the Xiang-Shang HVDC system is taken as the study case. The one-line diagram of the Xiangjiaba-Shanghai HVDC system is shown in Fig. 2. When the system is in islanding operating mode, which the HVDC transmission power is 2880 MW and the voltage is ±800 kV, the stimulation was carried out in PSCAD/EMTDC software.

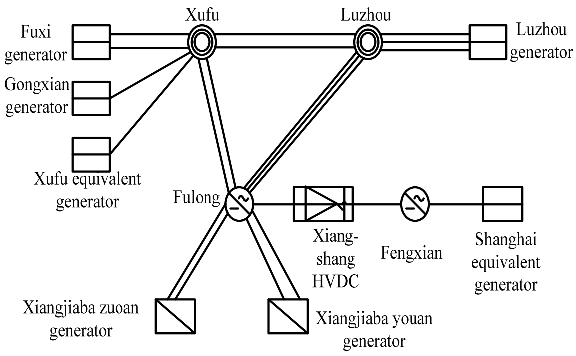

Fig. 2. Island system.

An impulse disturbance was added onto the AC bus of the rectifier, and removed after 0.1s. The generator rotation speed signals of the three thermal power plants (Fuxi, Gongxian and Luzhou) were extracted respectively. The SSI, ESPRIT, improved PRONY and FFT method were both adopted to identify characteristics of oscillation modal in Matlab.

1) Identify the oscillation frequency using FFT

First, FFT method is used to get the oscillation frequency of this actual system roughly. The identification results are shown in Fig. 3. As shown in Fig. 3, three oscillation modes exists in all of aforementioned three thermal power plants (Fuxi, Gongxian and Luzhou), which are 13 Hz, 24 Hz and 29 Hz, and the modal amplitude of 13 Hz and the 24 Hz are larger than that of 29 Hz.

2) Identify using SSI, ESPRIT, improved PRONY method.

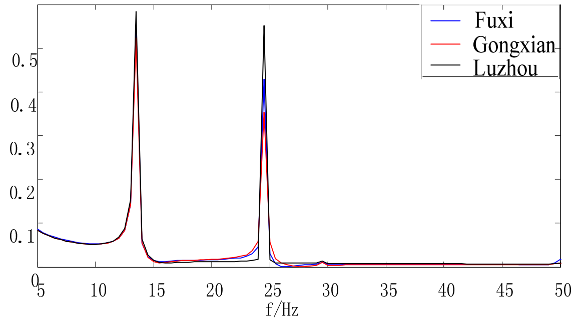

Fig. 3. Generator speed signal identified by FFT.

Model identification is made using the SSI algorithm, the ESPRIT method and the improved PRONY method respectively. The results of the identification are shown in Table 7 –Table 9 respectively. According to Table 7 – Table 9, the identification results using the three methods are close, which matches the FFT result as well. In the computational efficiency aspect, the average time spent by these three algorithm are 12.6361 milliseconds, 14.9397 milliseconds and 14.3729 milliseconds respectively, the efficiency of the SSI algorithm is relatively the highest.

Table 7. Identified results by SSI method.

SSI	**frequency (Hz)**	**attenuation factor**	**damping ratio (%)**	**time (ms)**
Fuxi	13.4186	-0.0668	0.08	13.0261
	24.5013	-0.2755	0.18	
	29.3309	-0.1012	0.055	
Gongxian	13.4152	-0.1205	0.143	12.1369
	24.5115	-0.319	0.207	
	29.3432	-0.1542	0.084	
Luzhou	13.4143	0.0255	-0.03	12.7453
	24.5058	-0.0431	0.028	
	29.2316	-0.7387	0.402	

Table 8. Identified results by ESPRIT method.

ESPRIT	**Frequency (z)**	**attenuation factor**	**damping ratio (%)**	**Time (ms)**
Fuxi	13.4221	-0.0409	0.048	15.2725
	24.4987	-0.251	0.16	
	29.5187	-0.1577	0.085	
Gongxian	13.4244	-0.1096	0.13	14.8669
	24.5083	-0.2801	0.18	
	29.4912	-0.1369	0.074	
Luzhou	13.414	0.035	-0.042	14.6797
	24.5041	-0.0526	0.034	
	29.5036	-0.1541	0.084	

According to identification results, after the disturbance, oscillations will sometimes occur in these three thermal power plants (Fuxi, Gongxian and Luzhou). The oscillation of the thermal power plants in Fuxi and Gongxian can self-attenuates, which would not lead to sub-synchronous oscillation. But the attenuation rate is very slow because of small attenuation factor, which would cause fatigue accumulation problem with the generators shafts.

Table 9. Identified results by PRONY method.

Improved PRONY	Frequency (Hz)	Attenuation factor	Damping ratio (%)	Time (ms)
Fuxi	13.4237	-0.0536	0.0427	15.1789
	24.6557	-0.2519	0.1627	
	29.5263	-0.1343	0.0724	
Gongxian	13.4183	-0.1207	0.1432	14.3209
	24.5251	-0.3261	0.2117	
	29.3758	-0.1455	0.0789	
Luzhou	13.4143	0.0294	-0.0349	13.6189
	24.5061	-0.0517	0.0336	
	29.4916	-0.6995	0.3777	

The 13 Hz modes in Luzhou thermal power plant is negative damping and the attenuation factor is small, it could cause torsional model amplification phenomenon. Hence, there is always the risk of sub-synchronous oscillation at 13 Hz. It is necessary to install additional sub-synchronous oscillation damping controller.

3. Conclusions

The SSI algorithm has been proposed for subsynchronous oscillation model identification. By comparison with the improved PRONY algorithm and the ESPRIT algorithm, the effectiveness and accuracy of the SSI algorithm was verified.

According to the simulation results, the SSI algorithm has stronger noise immunity in SSO detection and is suitable for practical engineering application under strong noise environment.

Since the operation efficiency of the SSI algorithm is high, SSI could be used for SSO online detection in power system. The oscillation modal in the power system could be found quickly by SSI method, which could help inhibition SSO rapidly and design subsynchronous additional controller.

Acknowledgements

The authors sincerely acknowledge the financial support provided by The Key Program of National Natural Science Foundation of China (research project No. 51037003) and National High Technology Research and Development Program of China (research project No. 2011AA05A119) for carrying out the present research work.

Appendix A

Modal	Frequency
1	15.71 Hz
2	20.21 Hz
3	25.55 Hz
4	32.28 Hz
5	47.46 Hz

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