A Hybrid Method for the Estimation of Power System Low-Frequency Oscillation Parameters

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Abstract—A hybrid method which combines four different algorithms for low-frequency oscillation parameter estimation using wide-area measurements is presented in this paper. The first algorithm is the discrete Fourier transform which is used to start the low-frequency oscillation estimation process. The second one is the finite-impulse response (FIR) window filter which is employed in filtering unwanted components, and window correction factor is provided to eliminate the side effect of FIR window filter. The third one is the prototype algorithm which is proposed to estimate low-frequency oscillation parameters, and the last one is the least-square error method which is employed to enhance the computational accuracy by varying the window size. This hybrid method has been implemented in wide-area phasor measurements system by Java language and is under test in Taiwan's power system. Matlab/Simulink simulation and field test results are provided in the present paper.

Index Terms—Discrete Fourier transform, least-square error method, low-frequency oscillation, wide-area measurements.

I. INTRODUCTION

POROLY damped low-frequency oscillation may cause a healthy power system into a stress condition under which the available transmission capability is reduced and even cascading outages may be initiated leading to a network collapse. Thus, estimation of low-frequency oscillation parameters for recognizing an evolving oscillation or for assessing the stability margin before a significant event occurs is essential for power system corrective and preventive control. Even post-oscillation estimation of parameters is important for analyzing the dynamic characteristics of studied power systems. Basically, there are two approaches to estimating the low-frequency oscillation parameters. They are dynamic model-based approach and measurement-based approach. The former compute the oscillation mode eigenvalue/eigenvector of dynamic system Jacobin matrix and can estimate the parameters in advance of an event, while the latter needs some sort of small oscillation measurement information to do the estimation. However, the dynamic model-based approach suffers from the inaccuracy of

modeling process which is the common case, while the measurement-based approach is independent of this problem. Wide area measurement system consisting of phasor measurement units (PMUs) has been installed in many utilities [1]–[5] over the world to provide the opportunity to monitor low-frequency oscillations. Moreover, the data captured by a wide-area phasor measurements system (WAMS) requires techniques capable of extracting or estimating the parameters of interest.

In the past ten years, many algorithms have been applied to low-frequency oscillation parameter estimation using measurements, including the discrete Fourier transform (DFT) [6]–[9], the Kalman filter [10], the Prony method [11]–[16], and wavelet transform [17], and each has its own features. We try to give a brief comment on these methods, but it is far from a rigorous analysis. Easy implementation, efficient execution, and high noise-resistance are the main advantages of DFT, but the waveform of low-frequency oscillation is not a periodic sinusoidal wave. This makes DFT unable to directly estimate the parameters of low-frequency oscillation and without a compensating method. Kalman filter is a technique for estimating an unknown state of a dynamic system which has additive noise, but the assumed availability of signal dynamic model makes it inconvenient for low-frequency oscillation parameter estimation. Prony method is a very efficient tool and is able to estimate damping, amplitude, and frequency from measurement data. The Prony method has been successfully implemented for estimating power system dynamics [11], [12]. Lastly, wavelet transform is particularly appropriate in recognizing the features of signal in both the time and frequency domains, but wavelet analysis also has its own limitation: a correct wavelet is the key to correct analysis, unfortunately however, a damped sinusoid is not a wavelet.

The proposed hybrid method is composed of four parts, and each part has its own function. The first part is DFT which is used to start the low-frequency oscillation parameter estimation process. The second part is the finite impulse response (FIR) window filter which is employed to reject unwanted components and window correction factor (WCF) is provided to eliminate the side effect of FIR window filter. The third part is the prototype algorithm which we propose to estimate the low-frequency oscillation parameters, and the last part is the least-square error (LSE) method which is utilized to enhance the computational accuracy by varying the window size.

The organization of this paper is as follows. We describe each part of this hybrid method in Section II. Next, the test results are provided in Section III. Finally, we give the conclusions of the research in Section IV.

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II. THE HYBRID METHOD

A. Starting Mechanism

Since the proposed hybrid method uses the wide-area measurements to estimate the low-frequency oscillation parameters both on-line and off-line, it requires the starting mechanism to start the estimation in order to avoid invalid computing due to no enough dynamic information contained in measurements.

The variation in the phase angle of bus voltage phasor measurements is used to determine the start of the estimation since any small oscillation can cause changes in the phase angle. We start the process of low-frequency oscillation estimation in two types. The first type are the oscillations with larger amplitude in phase-angle difference. Usually, this type of oscillation is caused by serious disturbances. Therefore, the first type is started when the difference between the maximum angle and the minimum angle in 1 s is beyond the preset threshold. The second type is the oscillation with small amplitude. According to [6], [8], and [11], we chose Fourier analysis to start the second type of low-frequency oscillations parameter estimation, but we just do partial spectrum analysis. This is because oscillation frequency is known at about 0.8 Hz in the Taiwan power system (Taipower system). Meanwhile, the PMU uploads phasor data at a rate of 20 Hz in Taipower. Therefore, we use DFT with three different fundamental frequencies which are 0.5 Hz, 1 Hz, and 2 Hz, respectively, to compute the amplitudes of phase-angle difference in 1 s. If one of these three amplitudes is beyond the threshold, small oscillation parameter estimation is started.

B. Prototype Algorithm

Since the FIR window filters we designed have a close relationship with the prototype algorithm we provided, we have to introduce the prototype algorithm before the FIR window filter.

When low-frequency oscillation occurs in a power system, we assume that the bus phase angle difference measurement, $x(k)$, can be expressed as follows:

$$x(k) = \sum_{i=1}^p X_i e^{\alpha_i k \Delta t} \cos(2\pi f_i k \Delta t + \phi_i) + X_{\text{op}} e^{\beta k \Delta t} + X_{\text{dc}} + \text{noise} \quad (1)$$

where p is the number of oscillation modes, X_i is the amplitude, α_i is the decay constant, f_i is the frequency, ϕ_i is the phase, X_{dc} is the dc component of the signal, Δt is the time interval (0.05 s), and $X_{\text{op}} e^{\beta k \Delta t}$ is a decaying dc component which is used to represent the shift of the operating point. Since we will use the FIR window filter to filter X_{dc} and noise, we temporarily ignore these components in this section

$$x(k) = \sum_{i=1}^p X_i e^{\alpha_i k \Delta t} \cos(2\pi f_i k \Delta t + \phi_i) + X_{\text{op}} e^{\beta k \Delta t} \quad (2)$$

since we know that

$$\cos \theta = \frac{e^{j\theta} + e^{-j\theta}}{2} \quad (3)$$

then $x(k)$ can be expressed as

$$x(k) = \frac{1}{2} \sum_{i=1}^p e^{\alpha_i k \Delta t} (X_i e^{-j\phi_i} e^{2\pi f_i k \Delta t} + X_i e^{-j\phi_i} e^{-2\pi f_i k \Delta t}) + X_{\text{op}} e^{\beta k \Delta t}. \quad (4)$$

For further derivations, we use the following definitions:

$$A_i = \frac{X_i}{2} e^{j\phi_i} \quad (5)$$

$$a_i = e^{j2\pi f_i \Delta t} \quad (6)$$

$$b_i = e^{\alpha_i \Delta t} \quad (7)$$

$$c = e^{\beta \Delta t} \quad (8)$$

$$z_i = \text{Re}(a_i). \quad (9)$$

Then (4) can be expressed as

$$x(k) = \sum_{i=1}^p b_i^k (A_i a_i^k + \bar{A}_i a_i^{-k}) + X_{\text{op}} c^k. \quad (10)$$

Therefore, we can find the following relations between $x(k-1)$ and $x(k)$

$$\begin{aligned} x(k-1) &= \sum_{i=1}^p b_i^{k-1} (A_i a_i^{k-1} + \bar{A}_i a_i^{-(k-1)}) + X_{\text{op}} c^{k-1} \\ &\quad \downarrow \times b_i \downarrow \times a_i \downarrow \times a_i^{-1} \downarrow \times c \\ x(k) &= \sum_{i=1}^p b_i^k (A_i a_i^k + \bar{A}_i a_i^{-k}) + X_{\text{op}} c^k. \end{aligned}$$

After some algebraic manipulations, we find

$$\sum_{i=0}^{2p+1} C_i x(k-i) = 0 \quad (11)$$

$$\begin{aligned} C = \{ \{c, -1\} * \{b_1, -2z_1, b_1^{-1}\} * \{b_2, -2z_2, b_2^{-1}\} * \dots * \\ * \{b_{p-1}, -2z_{p-1}, b_{p-1}^{-1}\} * \{b_p, -2z_p, b_p^{-1}\} \} \end{aligned} \quad (12)$$

where $*$ represents the convolution operator. From (11) and (12), we have very useful consequences for follow-up development. We can use these two equations in two different ways. First, if the parameters of low-frequency oscillation are unknown, we can utilize (11) and the LSE method, which will be described in the last subsection to get the parameters. Second, if we already know the parameters of low-frequency oscillation, then we can apply (12) as a FIR window filter, which will be described in the next subsection.

Besides, from (12), it is obvious that the complexity of getting parameters is in direct proportion to the value of p . Larger value of p means more complicated algorithms and more computational time. Therefore, in the Taipower system, the value of p is chosen to be 1 for on-line application. As such, the waveform can be simplified as follows:

$$x(k) = X_1 e^{\alpha_1 k \Delta t} \cos(2\pi f_1 k \Delta t + \phi_1) + X_{\text{op}} e^{\beta k \Delta t} + X_{\text{dc}} + \text{noise}. \quad (13)$$

C. FIR Window Filter

Noise and some unwanted components are always in the signal. As these components will affect the accuracy of the computational results, a well-designed filter is essential to get rid of them.

Since digital filters are easy to design and implement, they have been widely used in signal processing. To get the precise low-frequency oscillation parameters, we have to design specific FIR window filters to filter not only noise but also dc component, decaying dc component, and decaying sinusoid component, respectively.

According to (12), the FIR window filters we designed are as follows:

$$W_a = \{W_F * \{1, -1\}\} \quad (14)$$

$$W_b = \{c, -1\} \quad (15)$$

$$W_c = \{b_1, -2z_1, b_1^{-1}\} \quad (16)$$

where W_a is designed to filter noise and the dc component, W_b is designed to filter the decaying dc component, and W_c is designed to filter the decaying sinusoid component, and the chosen Blackman window is W_F .

By these FIR window filters, we can separate the decaying dc component and decaying sinusoid component, respectively from signal. Since there are two different decaying components in the signal and the decay constant of these two components should not be the same, one of them will fade faster than the other one. Therefore, to prevent the LSE method from encountering singular matrix or noise sensitivity, we estimate the parameters of these components separately.

The steps we take to separately estimate the parameters of low-frequency oscillation are as follows.

- Step 1) When low-frequency oscillation has been detected, the signal $x(k)$ will be filtered by W_a to get rid of noise and dc component and to get $\tilde{x}_1(k)$. Therefore, the main components in the $\tilde{x}_1(k)$ are the decaying dc component and the decaying sinusoid component.
- Step 2) The initial value of c is 1.
- Step 3) $\tilde{x}_1(k)$ is filtered by W_b to get rid of the decaying dc component and to get $\tilde{x}_2(k)$. Therefore, the main component in the $\tilde{x}_2(k)$ is the decaying sinusoid component.
- Step 4) By utilizing (11) and the LSE method, the parameters, b_1 and z_1 can be estimated.
- Step 5) $\tilde{x}_1(k)$ is filtered by W_c to get rid of the decaying sinusoid component and to get $\tilde{x}_3(k)$. Therefore, the main component in the $\tilde{x}_3(k)$ is the decaying dc component.
- Step 6) By utilizing (11) and the LSE method, the parameter c , can be estimated.

According to the experiments, after repeating Steps 3 to 6 three times, the values of b_1 , z_1 , and c will be converged, where $\tilde{x}_1(k)$, $\tilde{x}_2(k)$, $\tilde{x}_3(k)$ can be obtained as follows:

$$\tilde{x}_1(k) = \sum_{m=0}^{M-1} W_{am}x(k-m) \quad (17)$$

$$\tilde{x}_2(k) = \sum_{m=0}^1 W_{bm}\tilde{x}_1(k-m) \quad (18)$$

$$\tilde{x}_3(k) = \sum_{m=0}^2 W_{cm}\tilde{x}_1(k-m) \quad (19)$$

where M is the window size of W_a .

Then, according to the definitions (6)–(9) given above, we can estimate the parameters of low-frequency oscillation by means of the following equations:

$$f_1 = \frac{\cos^{-1}(z_1)}{2\pi\Delta t} \quad (20)$$

$$\alpha_1 = \frac{\ln(b_1)}{\Delta t} \quad (21)$$

$$\beta = \frac{\ln(c)}{\Delta t} \quad (22)$$

However, other problems encountered are phase shift and amplitude modulation, which are the side effects of using FIR window filter. To eliminate these problems, the Window Correction Factor (WCF) is presented.

From (13), the signal $x(k)$ is filtered by W_a to get $\tilde{x}_1(k)$ in (17), and then $\tilde{x}_1(k)$ is filtered by W_b to get $\tilde{x}_2(k)$ in (18). Therefore, $\tilde{x}_2(k)$ can be expressed as

$$\tilde{x}_2(k) = A_1 a_1^k b_1^k \sum_{m=0}^M a_1^m b_1^m W_{dm} + \bar{A}_1 a_1^{-k} b_1^k \sum_{m=0}^M a_1^{-m} b_1^m W_{dm} \quad (23)$$

where

$$W_d = \{W_F * \{1, -1\} * \{c, -1\}\}. \quad (24)$$

According to (5), (10), and (23), we obtain

$$A_1 = \frac{a_1 b_1^{-1} \tilde{x}_2(k+1) - \tilde{x}_2(k)}{(a_1^2 - 1) \times \text{WCF}_1} \quad (25)$$

$$X_1 = 2|A_1| \quad (26)$$

$$\phi_1 = \text{angle}(A_1) \quad (27)$$

where WCF_1 is defined as follows:

$$\text{WCF}_1 = \sum_{m=0}^M a_1^m b_1^m W_{dm}. \quad (28)$$

By WCF, the side effects of using FIR window filter can be totally eliminated, and the amplitude and phase angle of low-frequency oscillation can be estimated precisely.

D. LSE Method

We utilize (11) and the LSE method to estimate the parameters of low-frequency oscillation. This is because the LSE method is easy to implement and the data window size of the LSE method can be adjusted according to the frequency of low-frequency oscillation. Since the frequency range of low-frequency oscillations is between 0.2 to 3 Hz, it is certain that a larger window size is needed for obtaining more accurate estimation when the frequency is lower than 1 Hz. Therefore,

from (18), and using the consequences of (11) and (12), we obtain

$$-b_1\tilde{x}_2(k) + 2z_1\tilde{x}_2(k+1) - b_1^{-1}\tilde{x}_2(k+2) = 0. \quad (29)$$

Rearrange (29) as

$$\begin{bmatrix} \tilde{x}_2(k) & \tilde{x}_2(k+1) \\ \tilde{x}_2(k+1) & \tilde{x}_2(k+2) \\ \vdots & \vdots \\ \tilde{x}_2(k+L-3) & \tilde{x}_2(k+L-2) \end{bmatrix} \begin{bmatrix} p_1 \\ p_2 \end{bmatrix} = \begin{bmatrix} \tilde{x}_2(k+2) \\ \tilde{x}_2(k+3) \\ \vdots \\ \tilde{x}_2(k+L-1) \end{bmatrix} \quad (30)$$

where L is the data window size, and

$$p_1 = -b_1^2 \quad (31)$$

$$p_2 = 2z_1b_1. \quad (32)$$

Here, we can simplify (30) to the following:

$$\mathbf{A}\mathbf{P} = \mathbf{B}. \quad (33)$$

By the LSE method, $\mathbf{P}$ can be obtained as

$$\mathbf{P} = (\mathbf{A}^T\mathbf{A})^{-1}\mathbf{A}^T\mathbf{B}. \quad (34)$$

By (31) and (32), we can obtain

$$b_1 = \sqrt{-p_1} \quad (35)$$

$$z_1 = \frac{p_2}{2b_1}. \quad (36)$$

We also use the LSE method to estimate the parameter c . After getting b_1 and z_1 , we utilize (16), (19), and the consequences of (11) and (12), and obtain

$$\begin{bmatrix} \tilde{x}_3(k) \\ \tilde{x}_3(k+1) \\ \vdots \\ \tilde{x}_3(k+L-3) \end{bmatrix} [c] = \begin{bmatrix} \tilde{x}_3(k+1) \\ \tilde{x}_3(k+2) \\ \vdots \\ \tilde{x}_3(k+L-2) \end{bmatrix}. \quad (37)$$

By the LSE method, we obtain

$$c = \frac{\sum_{i=0}^{L-3} \tilde{x}_3(k+i)\tilde{x}_3(k+i+1)}{\sum_{i=0}^{L-3} \tilde{x}_3^2(k+i)}. \quad (38)$$

Now, these four subsections can be summarized as illustrated in the flowchart in Fig. 1. In Fig. 1, the window size of W_a is 19. Moreover, the window size of LSE method is changing to meet the need of both quick response and accurate estimation. The smallest window size of LSE method we set is 5 and the largest window size of LSE method we set is 40 ($L = 5 \sim 40$).

III. TEST RESULTS

In this section, we present some simulation and field test results to demonstrate the performance of this hybrid method. The

Fig. 1. Computation flowchart.

simulation tests are performed by Matlab/Simulink, and the field measurement data are provided by the ADX Company.

A. Matlab/Simulink Simulation Tests

To demonstrate the online performance of this hybrid method, we simulate a two-machine transmission system by Matlab/Simulink, as shown in Fig. 2. Two simulated ADX-3000s, which are PMUs produced by ADX Company are installed in Bus 1 (B1) and Bus 2 (B2), respectively, and the

Fig. 2. Simulation structure for real-time low-frequency oscillation estimation.

TABLE I
PARAMETERS USED IN THE SIMULATION SYSTEM

Generator M1 :		Generator M2 :		Transformer :	
Pn	1000MVA	Pn	5000MVA	V1	13.8KV
Vn	13.8KV	Vn	13.8KV	V2	500KV
Fn	60Hz	Fn	60Hz	R1	0.002pu
Xd	1.305	Xd	1.305	L1	0pu
Xd'	0.296	Xd'	0.296	R2	0.002pu
Xd''	0.252	Xd''	0.252	L2	0.12pu
Xq	0.474	Xq	0.474		
Xq''	0.243	Xq''	0.243	Line :	(ohms/km)
Xl	0.18	Xl	0.18	R1	0.01755
Td'	1.01	Td'	1.01	R0	0.2758
Td''	0.053	Td''	0.053	L1	8.74E-04
Tqo''	0.1	Tqo''	0.1	L0	3.22E-03
Rs	2.85E-03	Rs	2.85E-03	C1	1.33E-08
H	3.7	H	3.7	C0	8.30E-09

length of the transmission line is 700 km. The hybrid method is performed by Embedded Matlab Function, and the input data are the phase angle difference between B1 and B2. A single-phase ground fault occurs at 0.1 s and is cleared at 0.2 s, and the total simulation time is 9 s. The parameters used in Fig. 2 are provided in Table I. Two different cases are provided in this paper. One is the unstable case, and the other is the stable case.

Case 1: These two machines turn off the power system stabilizer (PSS), and the fault occurs at the middle of the transmission line. The solid line in Fig. 3(a) shows the phase angle difference between B1 and B2, and Fig. 3(b), (c), and (d) show the frequency, decay constant, and amplitude of oscillation, respectively. From Fig. 3(a) and (3d), the phase angle difference between B1 and B2 increases rapidly after the fault occurs. Fig. 3(b) and Fig. 3(c) shows an oscillation frequency of about 0.9 Hz and positive decay constant, respectively. From these figures, it is clear that the system is unstable.

Case 2: Machine M1 turns on the PSS, but M2 still turns off the PSS, and the fault occurs at 550 km from the distance of B1. The dotted line in Fig. 3(a) shows the phase angle difference between B1 and B2, and Fig. 3(b), (c), and (d) show the frequency, decay constant, and amplitude of oscillation, respectively. In this case, the system is stable, because the decay constant is negative. Moreover, the computation stopped when the amplitude of oscillation is less than the threshold.

From these two cases, we can find that the hybrid method can be applied for online application and the decay constant is a good index to show the tendency of the system. Therefore, the damping ratio, as shown in (39), is a very important index in field application

$$\text{damping ratio} = \frac{-\alpha_1}{\sqrt{\alpha_1^2 + (2\pi f_1)^2}} \times 100\%. \quad (39)$$

B. Field Data Tests

Low-frequency oscillation phenomena have been observed in the Taipower system from 1984. To prevent the damage caused by low-frequency oscillation, several generators in the Taipower system have been installed with power system stabilizers (PSSs). However, with the increase of load and shortage of transmission capacity, low-frequency oscillation is still a threat to Taipower system. More than ten PMUs, which were produced by the local ADX Company, have been installed into the backbone of Taipower system, and each PMU uploads its time-tagged phasor data at a rate of 20 Hz to the central servers in Taipower building and Taipower Company Power Research Institute. This quantity of information is enough for Taipower Company to monitor the dynamic state of the Taipower system or to develop more applications. Low-frequency oscillation parameters estimation is one of these applications.

Fig. 3. Simulation and computation results (on-line version).

The measured data of PMUs in the Taipower system can be categorized into two types: the real-time data which is updated at a rate of 20 Hz and historical data which are contained in the database. Hence, to meet the on-line and off-line applications and requirements, we have developed two different versions of this hybrid method. Furthermore, these two versions are implemented by Java language and are under test in Taipower system.

The off-line version provides easy-reading information for the administrative department. It gives data such as the time when oscillation actually started, the principal frequency and damping ratio, and the duration of the oscillation. Since the off-line version uses historical data for estimation, it can estimate the parameters when oscillation occurs.

Moreover, the on-line version is provided to help central operators of Taipower Company understand the real dynamic state. Since the on-line version uses real-time data for estimation, it is restricted by the data rate and estimates the parameters in a fixed window.

Fig. 4 shows the map of Taipower system. Taiwan is a long, narrow, and mountainous island. Since most of its mountains are

Fig. 4. Diagram of Taipower system.

Fig. 5. Field data.

in the east, the major development area is in the west. Accordingly, the major electric transmission lines are almost located in the western Taiwan as shown in the bold solid lines on the map. Since the major loads are located in northern Taiwan and most generating plants are in the middle and southern Taiwan, significant power had been transferred from south to north. Therefore, inter-area mode oscillations are the major concerns of Taipower system.

On January 24, 2004, some faults happened in the Taipower system, which caused a mild oscillation in the Taipower system. The field data is shown in Fig. 5 and computational results are shown in Fig. 6.

Fig. 6. Computational results (off-line version).

Fig. 5(a) shows the phase angle difference between Lung Tan and 2nd Nuclear which are in the northern Taiwan and Fig. 5(b) shows the phase angle difference between Lung Chi and 3rd Nuclear, which are in the southern Taiwan. It is clear that the oscillation in northern and southern Taipower system is smaller than the oscillation between 3rd Nuclear and 2nd Nuclear as shown in Fig. 5(c). This means that Taipower Company still has to keep an eye on inter-area mode oscillations.

Fig. 6(a) shows the frequencies of oscillation, which are all lower than 0.8 Hz. Fig. 6(b) shows the damping ratios of oscillation, and the damping ratio of inter-area mode is worse than that of local mode. Moreover, Fig. 6(c) shows the amplitudes of oscillation, and it is obvious that the amplitude of inter-area mode oscillation is bigger than the others.

C. Multi-Mode Tests

For further analysis and application, we demonstrate this hybrid method can be used in two multi-mode examples.

From the flowchart in Fig. 1, it is easy to understand that this hybrid method estimates the parameters of each component in the signal by separating them with FIR window filters. It is the same for multi-mode cases. Although this way takes more computational time on iteration, it makes sure this hybrid method would not suffer singular matrix when some components fade away.

The first multimode example is shown in Table II. A simulated signal $x(k)$ containing three different decaying sinusoid components is provided to be the input data, and the data length is 50. We change the frequencies of each component to observe

TABLE II
COMPUTATIONAL RESULTS OF DIFFERENT FREQUENCIES

$f_1 = 0.5, f_2 = 0.8, f_3 = 1.1$			
Hybrid Method	frequency	decay constant	amplitude
f_1	0.5000	-0.1000	1.0000
f_2	0.8000	-0.4000	4.0000
f_3	1.1000	-0.2000	0.5000

(a)

$f_1 = 0.6, f_2 = 0.8, f_3 = 1.0$			
Hybrid Method	frequency	decay constant	amplitude
f_1	0.6000	-0.0999	0.9997
f_2	0.8000	-0.4000	4.0001
f_3	1.0000	-0.2001	0.5002

(b)

$f_1 = 0.7, f_2 = 0.8, f_3 = 0.9$			
Hybrid Method	frequency	decay constant	amplitude
f_1	0.7049	-0.0352	0.9469
f_2	0.8025	-0.3399	4.2909
f_3	0.9023	-0.0715	0.3556

(c)

Fig. 7. Simulated signals.

the discrimination performance as shown in Fig. 7. It is clear from Tables II(a), (b), and (c) that as the frequencies of each component close, the computational results become worse. However, the discrimination performance can be restrictedly improved by increasing the number of iteration or the data length.

In the second multimode example, we extract the input data (as shown in Fig. 8) from the field data provided in Fig. 5(a). After the input data is filtered by W_a to eliminate noise and dc component, the filtered data is computed by the hybrid method. Since we do not exactly know the number of oscillation modes in the filed signal, we estimate the parameters by assuming $p = 1$, $p = 2$ and $p = 3$ to evaluate the affect of p value on parameters estimation. Table III shows that the computational results of different number of oscillation modes, and one can see the

Fig. 8. Test data for hybrid method.

TABLE III
COMPUTATIONAL RESULTS FOR $p = 1$, $p = 2$ AND $p = 3$

$p = 1$			
Hybrid Method	frequency	decay constant	amplitude
f_1	0.7345	-0.3249	0.4555

(a)

$p = 2$			
Hybrid Method	frequency	decay constant	amplitude
f_1	0.6990	-0.3153	0.4547
f_2	1.4124	-1.0925	0.1268

(b)

$p = 3$			
Hybrid Method	frequency	decay constant	amplitude
f_1	0.6982	-0.3461	0.4858
f_2	1.4470	-1.1615	0.1248
f_3	3.7617	-27.0575	0.1234

(c)

estimated parameters of oscillation are insensitive to assumed p value. This is a remarkable feature of the proposed method.

D. Very Small Oscillation Tests

By reducing the threshold of the starting mechanism, this hybrid method can be used in very small oscillations as shown in Fig. 9. The raw data in Fig. 9(a) is phase angle difference between Lung Chi and Lung Tang at 12:24 on July 13, 2006. Fig. 9(b), (c), and (d) shows the computational results of frequency, damping ratio and amplitude. From these results, the proposed hybrid method can indeed estimate low-frequency oscillation parameters for both small and large oscillations. This feature makes the proposed method can be used as a warning signal for operators to take necessary preventive actions before a significant event indeed occurs.

Fig. 9. Field data and computational results.

IV. CONCLUSIONS

In this paper, we present a hybrid method which combines four different algorithms including DFT, FIR window filter, LSE, and a prototype algorithm for low-frequency oscillation parameter estimation, each part having its own function. We also use four different kinds of tests to verify this hybrid method, and the computational results are encouraging.

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