Distributed Electromechanical Oscillation Mode Online Estimation

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Abstract. For the existence of low frequency oscillation phenomena in the interconnection power systems, a new style of distributed algorithm for detecting the low frequency oscillation modes was proposed to avoid the disadvantages of previous methods that require large amount of concentrated computation and communication. The whole structure of oscillation detection contains two levels, namely the substation level and control center level. In the substation level, damped sinusoid model based on atomic decomposition is employed to represent atomic library. Using the power angle trajectory, the modal parameters were identified from the atomic library by atomic decomposition method and atomic decomposition energy entropy was calculated during the identification process. In the control center level, the oscillation detection result of the substations are uploaded and combined to generate overall oscillation frequency and damping ratio by a weighted linear function. The results of a simulation case show that this algorithm can quickly detect the oscillation mode and the simulation results are identical to that of the normal form theory, and the accuracy and effectiveness of the proposed method were validated.

Introduction

The analysis of electromechanical oscillatory modes is very important to the stability of power systems. Wide-area monitoring systems (WAMS) has been deployed in many power systems recently. With many implementations of WAMS based on phasor measurement units (PMUs), oscillation detection especially of low frequency using output-only responses has drawn great attention in power system since the 1990s. Compared to traditional fundamental steady parameters based analysis methods, PMU based approach allows real-time identification of oscillatory modal. The identified modal parameters are directly useful in monitoring and control.

Electromechanical oscillations of synchronous generators are excited by changes in the power system, such as load variations and grid faults [1-8]. Since poorly damped oscillations may lead to the instability of the entire system, the oscillations must be effectively damped to maintain a secure system operation. The oscillatory stability of power systems can be analyzed by monitoring the electromechanical oscillatory modes. Based on signals of PMU data from vast locations and large amount of devices, decomposition is a useful method to analyze the components of the oscillation modes. Decompositions of signals over family of functions that are well localized both in time and frequency have found many applications in signal processing and harmonic analysis. Such functions are called time-frequency atoms. Depending upon the choice of time-frequency atoms, the decomposition might have very different properties.

Window Fourier transforms and wavelet transforms are examples of time-frequency signal decomposition that have been studied thoroughly. To extract information from complex signals, it is often necessary to adapt the time-frequency decomposition to the particular signal structures.

Recent paper [4] introduced a distributed frequency domain optimization (DFDO) method that the estimation task is divided between the substation level estimators and the control center level estimator in a closely coordinated fashion. The two-level estimation in [15] requires full-resolution PMU data (or equivalent FFT values) from substations, and conversely the substation level estimators need detrending angle reference and other supervisory guidance from the control center for local
modal estimations. That is, the communication between substations and central processor in DFDO is bidirectional which requires higher network bandwidth and is rather expensive to implement.

Most of the researches on low frequency detection are based on Fourier Decomposition or Wavelet Decomposition [3-16]. In [2], a new algorithm based on Atomic Decomposition Energy Entropy for detecting the dominant low frequency oscillation modes was proposed. According to oscillation signal characteristics, damped sinusoid model was selected to represent atomic library. Using the power angle trajectory, the modal parameters were identified from the atomic library by atomic decomposition method and atomic decomposition energy entropy was calculated during the identification process. By comparing the energy entropies, the dominant inertial modes were identified.

In this paper, distributed low frequency detection based on atomic decomposition is performed in the substation level. In the control center level, the result of oscillation evaluation of the substation are uploaded and combined.

Two Level Oscillation Detection Structure

The whole structure of oscillation detection can be illustrated in Fig.1, which contains two levels, namely the substation level and control center level. In the substation level, damped sinusoid model based on atomic decomposition is employed to represent atomic library. Using the power angle trajectory, the modal parameters were identified from the atomic library by atomic decomposition method and atomic decomposition energy entropy was calculated during the identification process. In the control center level, the oscillation detection result of the substations are uploaded and combined to generate overall oscillation frequency and damping ratio by a weighted linear function.

Oscillation Detection in Substation Level

The general issue behind adaptive time-frequency decompositions is to find procedures to expand functions over a set of waveforms, selected appropriately among a large and redundant dictionary. A signal $x(t)$ can be represented as a sum of other predefined signals $f_k(t), k \in \{0,1,\ldots,K\}$ as

$$x(t) = \sum_{k=0}^{K-1} \alpha_k f_k(t)$$

(1)
$f_i(t)$ is referred as atoms or structures. The set of all possible atoms $f_i(t)$ is the so-called dictionary $D$. Signals given by $f_i(t)$ are used to represent $x(t)$. $\alpha$ is an energy factor for the signal $f_i(t)$.

In the research of power system signals, a good model is based on damped sinusoids. In this model the signals are represented as

$$x(t) = \sum_{q=0}^{Q} A_q \cos(2\pi F_q t + \phi_q) e^{-\lambda_q(t-t_s)} \times [u(t-t_s) - u(t-t_e)]$$

Each component is represented by a 6-type $(A_q, F_q, \lambda_q, \phi_q, t_s, t_e)$, where $A_q$ represents the amplitude, $F_q$ represents the frequency, $\lambda_q$ represents the damping factor, $\phi_q$ represents the phase, $t_s$, $t_e$ represents the starting and ending times of a component. $u(t)$ is the unit step function.

Matching Pursuits (MP) is a useful algorithm for signal decomposition in wide areas. It was first introduced by Mallat and Zhang[7]. The MP algorithm is iterative. At each step a function from the dictionary that has the higher inner product with the signal is chosen. Suppose we want to decompose the signal $x(t)$. Define a dictionary $D = \{g_\gamma\}, \gamma \in \Gamma$ ($\gamma$ is a set of parameters and $\Gamma$ is the set of all possible $\gamma$), such that $\|g_\gamma\| = 1$. $x(t)$ can be represented as a sum of elements of the dictionary:

$$x(t) = \sum_{n} \alpha_n g_{\gamma n}(t)$$

In order to compute the coefficients $\alpha_n$ we can choose $g_{\gamma n}$ such that $\alpha_n = \langle x, g_{\gamma n} \rangle = \max \langle x, g_{\gamma} \rangle$, and then split $x(t)$ in two parts $g_{\gamma(0)}$ and

$$R_n^0 = x - \alpha_n g_{\gamma(0)}$$

Carry out this process iteratively, we can compute the $n+1$ from the residue of step $n$. Observe the $R_n^0$ and $g_{\gamma(0)}$ are orthogonal and therefore the signal energy is conserved. That is, at a given step $m$ of the decomposition:

$$\|x\|^2 = \sum_{n=0}^{m} \|R_n^0, g_{\gamma(0)} \|^2 + \|R_n^m \|^2$$

The energy of the residual decreases in each iteration.

The Matching Pursuit algorithm was proposed using the Gabor dictionary. These atoms are defined by:

$$g_{\gamma}(t) = \frac{1}{\sqrt{8}} 2^{1/4} e^{-x(t-t_s)^2} \cos(\xi t + \phi)$$

Where $\gamma = [s, u, \xi, \phi]$. An important feature of this dictionary is that the parameter space of the atoms can be sampled while still obtaining a complete dictionary. A number of other different dictionaries has been proposed.

In the proposed approach, an indirect search for the damped sinusoids is carried out. First, the continuous-parameter Gabor atom that maximizes the inner product is found. These parameters are then used to generate a guess for the best damped sinusoid. This guess initializes a pseudo-Newton algorithm to find the parameters of the best damped sinusoid. When we perform such indirect damped sinusoid search, one cannot use correlation updates, and therefore, there is no fast MP algorithm. This is because the dictionary we effectively use has continuous parameters and, thus, infinite cardinality. Therefore, the computational complexity of the proposed method is increased when compared with
the one of the standard MP; however, the good results obtained justify the increase in complexity. The
detail procedure that searches for the damped sinusoids can be found in [3].

In order to make use of available information in the substation as much as possible, neighboring
bus parameters such as voltage can be estimated by physical transmission characteristic of the
transmission line. In this paper, the voltage of the neighboring bus can be calculated by the following
function.

\[ \hat{U}_N = i_N \cdot Z_i + U_w \]  

(7)

Where \( \hat{U}_N \) is the voltage of the adjacent bus. \( i_N \) is the current vector of the adjacent transmission
line, which can be measured by the PMU of the local bus. \( Z_i \) is the impedance of the adjacent transmission line, which can be determined offline as a constant value. By this method, PMUs are not
necessarily installed in every bus. Some voltages are obtained by state estimation.

In order to distinguish different oscillation mode, Modal Amplitude Coherence (MAC) [7] is used
to determine whether two frequencies are actually the same by error or different modes.

Another important parameter, mode shape estimates were approximated from the ratio of the cross
spectral density(CSD) between \( y_{i} (t) \) and \( y_{j} (t) \) and the power spectral density (PSD) of \( y_{k} (t) \).

\[ MS = S_{i \omega}(\omega) / S_{i \omega}(\omega) = \phi_{i,j} / \phi_{k,l} \]  

(8)

**Oscillation Detection in Substation Level**

The complete algorithm can be divided into two parts. One is performed for offline data preparation, which is seldom changed. The other is performed to generate restoration plan when fault occurs.

There is another way to deal with such indices by regard them as constraints. For example, a fixed
value can be set to limit the load on equipments. Whether to treat such indices as objectives or as
constraints depends on practical need.

For each group of modes, the final result (frequency \( F_q \) and damping ratio \( \lambda_q \)) of this system modal
estimation will be obtained by a weighted average function

\[ F_q = \sum_{i=1}^{N} \frac{ME_i^q}{\sum_{i=1}^{N} ME_i^q} F_{q,k}^i \]  

(9)

\[ \lambda_q = \sum_{i=1}^{N} \frac{ME_i^q}{\sum_{i=1}^{N} ME_i^q} \lambda^i_{q,k} \]  

(10)

Where \( N \) is the number of reporting substations in this group. \( ME_i^q \) is the mode energy for mode \( i \)
from substation \( k \). \( F_{q,i}^q \) and \( \lambda^i_{q,k} \) are the estimated frequency and damping ratio for mode \( i \) of
substation \( k \). After finding mode frequency for each mode group, the control center could search for
mode shape estimates using the weighted mode frequency sent by the substations to determine the
mode shapes for each mode.

**Illustration of the Proposed Method**

As an example, the IEEE 24-node system shown in Fig.2 is employed to test the proposed algorithm.
Generators are represented by means of a fourth order model with automatic voltage regulation.
Generally speaking, real-time oscillation monitoring can be carried out by analyzing measured responses after system events or from routine measurements. In this test system, the perturbation is obtained by varying the load as Gaussian white noise and varying the speed of generators.

It is assumed that 1% of each load (real and reactive power) consists of Gaussian white noise. The random noise represents ambient system load variations and they are assumed at be independent at each bus. It is assumed that there is a PMU installed at Bus 1, 7, 9, 10, 13, 14, 15, 17, 20, 21. It is assumed that each PMU measures its bus voltage phasor and all line current phasors on any of the lines connected to the bus. Bus voltage magnitudes (for mode damping level estimation) and bus voltage phase angles (for mode shape estimation) of 11 buses are used as inputs for. By knowing the transmission line network parameters, it is assumed that the neighboring bus voltage phasor can be calculated at each of the buses by eqn. (7) from bus voltage phasor and line current phasor available from the local PMU. Accordingly, phase angle difference between the measured bus voltage phase angle with respect to the respective calculated neighboring bus voltage phase angle at each of the 11 buses are used.

At the substation level, each engine generates its own atomic decomposition modal estimates based on its own local PMU data. Estimation results from each substation are provided in Table I for both inter-area mode (first mode in Table I) and local mode (second mode in Table 1).

There are one inter-area dominant mode in the sample system and many local oscillation mode as studied in this test case. The inter-area mode around 0.486 Hz. To study different damping levels of the two modes, parameters of power system stabilizers of each generator are varied in the test system. Prior to the beginning of the simulation, a small disturbance is created to excite the modes. The disturbance is simulated by varying the speed of generator of random selected bus.
<table>
<thead>
<tr>
<th>Bus No.</th>
<th>First Mode Energy</th>
<th>Freq. (Hz)</th>
<th>Damp. Ratio (%)</th>
<th>Second Mode Energy</th>
<th>Freq. (Hz)</th>
<th>Damp. Ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.84</td>
<td>0.451</td>
<td>2.12</td>
<td>0.451</td>
<td>1.24</td>
<td>0.878</td>
</tr>
<tr>
<td>7</td>
<td>0.45</td>
<td>0.483</td>
<td>3.12</td>
<td>0.497</td>
<td>1.89</td>
<td>1.212</td>
</tr>
<tr>
<td>9</td>
<td>3.04</td>
<td>0.501</td>
<td>0.981</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>2.78</td>
<td>0.495</td>
<td>1.22</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>3.87</td>
<td>0.482</td>
<td>1.21</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>1.23</td>
<td>0.493</td>
<td>2.03</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>1.87</td>
<td>0.464</td>
<td>3.12</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>0.87</td>
<td>0.468</td>
<td>2.14</td>
<td>0.214</td>
<td>1.64</td>
<td>1.258</td>
</tr>
<tr>
<td>20</td>
<td>2.01</td>
<td>0.495</td>
<td>1.89</td>
<td></td>
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</tr>
<tr>
<td>21</td>
<td>0.94</td>
<td>0.485</td>
<td>1.87</td>
<td>0.812</td>
<td>1.62</td>
<td>0.678</td>
</tr>
<tr>
<td>Control Center</td>
<td>0.486</td>
<td>1.675</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In real power systems, oscillation problems may arise from both inter-area modes as well as from local modes which involve one or more generators in a small geographical area. It is important to detect and to locate presence of any poorly damped oscillatory mode whether it is an inter-area mode. In this example, only the result of the dominant mode combination in the control center are shown in Tab. 1. There are too many local modes so they are not listed here.

It can be seen that, the inner node of the system can be used to detect dominant inter-area mode suitably. The dominant mode has an oscillation frequency of 0.486Hz with the damping ratio 1.675.

The local modes are varying in different areas. The combined results are basically the same as the results of the individual buses.

**Conclusions**

The whole structure of oscillation detection contains two levels, namely the substation level and control center level. In the substation level, damped sinusoid model based on atomic decomposition is employed to represent atomic library. Using the power angle trajectory, the modal parameters were identified from the atomic library by atomic decomposition method and atomic decomposition energy entropy was calculated during the identification process. In the control center level, the oscillation detection result of the substations are uploaded and combined to generate overall oscillation frequency and damping ratio by a weighted linear function. Finally, the IEEE Reliability Test System is used to demonstrate the proposed algorithm.

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**References**


