ABSTRACT

In this paper, the application of the Prony method for the estimation of dominant inter-area oscillations modes in large power systems is presented. The main goal of this paper is to compare the dominant oscillations modes extracted by the Prony method with those obtained by Eigen-value analysis. In order to achieve that, two testing systems have been designed. The first system is a multi-machine system consisting of 22 buses and 10 generators, and the second testing system is built on the same topology but with an integrated Fixed Speed Wind Farm (FSWF). In addition, the impact of the FSWF on inter-area oscillation modes will be discussed in this paper.

INTRODUCTION

With the recent increases in the number of renewable energy sources in electrical power systems, electricity power regulators now insist that these previously isolated power networks become connected to the main network to form a larger power grids. This will result in long distant power transfers between adjacent power grids. Such power transfers carry the potential risk of low frequency inter-area oscillations in a large power system. Thus, it is critically important to develop reliable and robust methods for monitoring and mitigating potentially dangerous not damped oscillations.

To reduce this risk, the identification of the characteristics of the inter-area oscillations, including damping factors and frequency, is an important step before the system operator can apply corrective measures. A conventional method of the identification of oscillation modes is Eigen-value analysis. With the help of Eigen-values, eigenvectors and participation factors, the system dynamic behaviours can be clearly predicted.

The Prony method [1] has been well known for about twenty years; it is capable of extracting the oscillation modes from given signals, such as oscillating frequencies or active powers. Some power companies have utilized the Prony method for the real-time monitoring of power system oscillations in conjunction with new technologies, such as Phasor Measurement Units (PMU).

The aim of this research is to compare the oscillation modes obtained from the Eigen-value analysis and Prony method. This will help to provide reliable parameters of power system oscillations for a real-time Wide Area Monitoring Protection and Control (WAMPAC).

COMPUTER SIMULATIONS

1) Multi-machine test system

In this part, a test system with 10 synchronous machines, represented in Fig. 1, was analyzed. From the topology of the power system, two areas (A and B) connected over the tie-lines can be easily identified. Under steady-state conditions, approximately 500 MW of active power was transferred over two 1000 km inter-tie lines.

Under steady-state conditions, the dominant inter-area oscillation modes $\lambda_{73}$ and $\lambda_{74}$ are calculated by Eigen-value analysis and presented in Tab. 1. Note that the total number of oscillation modes was 149.

<table>
<thead>
<tr>
<th>Name</th>
<th>Real part</th>
<th>Imaginary part</th>
<th>Period (s)</th>
<th>Frequency (Hz)</th>
<th>Damping</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_{73}$</td>
<td>-0.11701</td>
<td>4.719537</td>
<td>1.331314</td>
<td>0.751138</td>
<td>0.11701</td>
</tr>
<tr>
<td>$\lambda_{74}$</td>
<td>-0.11701</td>
<td>-4.71954</td>
<td>1.331314</td>
<td>0.751138</td>
<td>0.11701</td>
</tr>
</tbody>
</table>

In order to initialize the inter-area oscillations, a single phase short circuit fault was stimulated on one of the inter-tie lines, lasting from 2-2.1 s. Consequently, the generators in the two areas started to oscillate against each other [2].

Under the above described temporary short circuit, the active power flow over the sound inter-tie line was analyzed using the Prony method. The unknown frequency and damping of the power oscillations estimated by using Prony method are presented in Figs. 2 and 3, which also present the comparisons of the inter-
area oscillation modes obtained from Eigen-value analysis and the Prony method in the time domain. Tab. 2 presents the comparisons of inter-area oscillation modes obtained using Eigen-value analysis and the mean value of the results from the Prony method.

In this case, the sampling frequency of the active power measurements is 1250 Hz. The window size of the active power signal processing using the Prony method is 1.0 s, and the interval between the processing windows is 0.2 s.

Fig. 2. Comparisons of damping factors obtained from Eigen-value analysis and the Prony method in a multi-machine system.

![Fig. 2](image)

![Fig. 3](image)

Tab. 2: Comparison of results obtained

<table>
<thead>
<tr>
<th></th>
<th>Oscillation damping (%)</th>
<th>Oscillation frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eigen value analysis</td>
<td>0.11701</td>
<td>0.7511</td>
</tr>
<tr>
<td>The Prony method (mean value by sliding windows)</td>
<td>0.1192</td>
<td>0.770</td>
</tr>
<tr>
<td>Error (%)</td>
<td>1.79</td>
<td>2.5</td>
</tr>
</tbody>
</table>

In Fig. 4, the original oscillating active power on the tie-line and the signal obtained after the reconstruction based on the parameters obtained over the Prony method, are presented.

![Fig. 4](image)

From the demonstrations above, it is concluded that, in multi-synchronous machine systems, oscillation modes obtained by using the Prony method are very close to those obtained using the classical Eigen-value analysis. The small discrepancies between the values are acceptable and the results obtained can be used as reliable instability indicators.

2) Multi-machine test systems with FSWF

Case 1

In this case, a Fixed Speed Wind Farm (FSWF) is connected to the bus M, where the synchronous generator G_4 is located. The FSWF supplied 25 MW to the system and consumed 10 MVAr from the system. The G_4 balanced the active and reactive power in the system when the loads remained constant.

Classical Eigen-value analysis was carried out under steady-state conditions. The inter-area oscillation modes of the synchronous generators are presented in the Tab. 3. In this case, there were 331 Eigen-values in the system, due to the integration of the FWSF.

Table 3: inter-area oscillation modes for the system from.

<table>
<thead>
<tr>
<th>Name</th>
<th>Real part (λ)</th>
<th>Imaginary part</th>
<th>Period (s)</th>
<th>Frequency (Hz)</th>
<th>Damping</th>
</tr>
</thead>
<tbody>
<tr>
<td>λ_185</td>
<td>-0.1046032</td>
<td>4.833925</td>
<td>1.2998</td>
<td>0.7693431</td>
<td>0.1046032</td>
</tr>
<tr>
<td>λ_186</td>
<td>-0.1046032</td>
<td>-4.833925</td>
<td>1.2998</td>
<td>0.7693431</td>
<td>0.1046032</td>
</tr>
</tbody>
</table>

In this case, the same single phase short circuit fault was simulated on the interconnecting inter-tie line, lasting from 2-2.1 s. Again, the oscillating active power was processed using the Prony method.

Figs. 5 and 6 present comparisons of the inter-area oscillation modes of synchronous generators obtained from Eigen-value analysis and from the Prony method in the time domain. The difference between oscillations modes of those two methods is not negligible. However, the reconstructed signal produced by the Prony method is very close to the original signal, as represented in Fig. 7.
An explanation for the differences in the oscillation modes obtained from Eigen-value analysis and the Prony method is that Eigen-values \( \lambda_{185} \) and \( \lambda_{186} \) represent the inter-area oscillations of the synchronous generators in the system only. But due to the integration of a wind farm, the inter-area oscillations between area A and area B were also influenced by the oscillation modes of the wind farm, as illustrated in Fig 8. Tab. 4 presents the oscillation modes (\( \lambda_{207} \) and \( \lambda_{208} \)) of the FSWF oscillating against the rest of the system after a large disturbance.

It is obvious that the damping of the inter-area oscillation modes obtained by the Prony method is around 0.151, which is less than 0.7596, as found in \( \lambda_{207} \) and \( \lambda_{208} \), and larger than 0.1046, as found in \( \lambda_{185} \) and \( \lambda_{186} \). In addition, the frequency of the inter-area oscillation modes produced by the Prony method is 0.785Hz, which is larger than 0.77Hz, as found in \( \lambda_{185} \) and \( \lambda_{186} \), and lower than 0.7940, as found in \( \lambda_{207} \) and \( \lambda_{208} \).

Therefore, from the information above, it can be concluded that, in a large power system with fixed speed wind farms, it is acceptable to use the Prony method to extract the inter-area oscillations modes from the oscillating active power in the tie-line. Those estimated oscillation modes were conformed by Eigen-value analysis.

**Table 4: The oscillation modes of the FSWF for the system.**

<table>
<thead>
<tr>
<th>Name</th>
<th>Real part</th>
<th>Imaginary part</th>
<th>Period (s)</th>
<th>Frequency (Hz)</th>
<th>Damping</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \lambda_{207} )</td>
<td>-0.7596276</td>
<td>-4.988667</td>
<td>1.259492</td>
<td>0.7939711</td>
<td>0.7596276</td>
</tr>
<tr>
<td>( \lambda_{208} )</td>
<td>-0.7596276</td>
<td>4.988667</td>
<td>1.259492</td>
<td>0.7939711</td>
<td>0.7596276</td>
</tr>
</tbody>
</table>

In this case, the FSWF increased its active power output to 50MW, and absorbed 20MVAr reactive power from the network. Consequently, the generator four (\( G_{4} \)) changed its output as the loads remained constant. As before, the oscillating active power on the tie-line was processed using the Prony method. Fig. 9 presents the inter-area oscillation modes estimated by the Prony method.
method.

Fig. 9. Inter oscillation modes in a large system with a FSWF (50MW) estimated by the Prony method.

From the results of the last cases, by using the Prony method, the general damping of the inter-area oscillations was improved due to the integration of the FSWF, and the inter-area oscillation frequency was decreased, as shown in Figs 10 and 11. Fig 12 also presents the damping ratios of the inter-area oscillations from the Prony method. It is obvious that, with the integration of the FSWF, the damping ratios of the inter-area oscillations were increased significantly. Note that damping ratio is a useful measure of the damping, as defined [3]:

$$\zeta = \frac{-\sigma}{\sqrt{\sigma^2 + \omega^2}}$$

where the $$\lambda = -\sigma \pm j\omega$$ is the oscillation mode.

Fig. 10. Comparisons of general inter-area oscillation dampings using the Prony method in a large system with different FSWF outputs.

CONCLUSIONS

In this paper a practical technique for the on-line identification of oscillation modes in large interconnected power systems is presented. It was concluded that the results obtained using the Prony method correspond to the results obtained using classical Eigen-value analysis.

Fig. 11. Comparisons of general inter-area oscillation frequencies using the Prony method in a large system with different FSWF outputs.

It was also concluded that for practical analysis the oscillating active power can be efficiently used as an input to the Prony estimator. Based on the results obtained, it is possible to design an efficient early instability predictor.

In addition, the paper has also concluded that, because of the integration of the FSWF, the damping ratios of the inter-area oscillations have been improved significantly.

REFERENCES

