Influences on Power System Dynamic Stability/Oscillatory Stability by Large Power Grids Interconnection

Zhu Fang*, Zhao Hong-guang*, Liu Zeng-huang*, Kou Hui-zhen**

ABSTRACT - This paper focuses on the new issues of the low frequency oscillation brought by interconnection of area power grids. The characteristics of the inter-area and the local oscillation modes are discussed. Strategies for improving the dynamic/oscillatory stability of interconnected system and principles of installation of PSS are presented. Also summarized is the experience accumulated from all the projects of forming interconnected systems. PSS has been proved to be the most economical and effective measure to prevent the low frequency oscillation caused by the unstable local modes / the inter-area modes.

Keyword: Interconnected system, dynamic stability, oscillatory stability, Inter-area Mode, Local Mode, low Frequency Oscillation, PSS

1. Introduction—A review on power system oscillatory instability problems in China

During the past 20 years, the installed generation capacity in China has increased from 57,120MW in 1978 to more than 500,000MW in 2005—the world’s second largest. In the last few years, the area grids were interconnected to form large complex power systems.

Before 1980s, in the stage of the provincial power grids and the area power grids the transient stability was the main problem and the oscillatory instability did not show up. The main reason was that conventional excitation systems and the low gain AVR were used. The dynamic performance was underdeveloped.

After 1980s, the fast excitation systems, and the high performance AVR were gradually applied for many generators to enhance transient stability or to replace those deteriorated exciters, the oscillatory instability, i.e., the low frequency oscillation occurred both in the provincial power grids and the area power grids. For example:

In 1983, the Feng-Chang line in Hunan power grid and the Ge-Feng line in Hubei power grid;
In 1984, the interconnected tie line between Guangdong and Hong Kong;
In 1985, the power grid interconnected by Guangdong, Guangxi and Hong Kong power grids;
In 1994, the South China interconnected power system (Guizhou, Guangxi, Guangdong and Hong Kong);
In 1998 and in 2000 the Ertan power plant in Sichuan-Chongqing power grid;

In February and March in 2003, South China-Hong Kong AC/DC transmission system and so on.

The reasons of these low frequency oscillations are as follows:

1. The instruction to implement power system stabilizers (PSS) have not been followed in those critical power plants or PSSs were blocked by volt/Hz limiter
2. No PSS was installed because the studies using false excitation system models or parameters showed that the case was stable.
3. The damping provided by present PSSs cannot satisfy the need of the post-contingency conditions.

In 2001, China started to implement projects to interconnect the area power grids of Northeast-North China, Sichuan Chongqing-Central China, Fujian-East China, and Northeast-North China-Central China-Sichuan Chongqing-Shandong and so on. In these interconnection projects, the oscillatory instability problems have been studied and identified, and corresponding measures have been taken. Studies show that the oscillatory instability has already become the bottleneck for the interconnected power system operation.

2. Inter-area modes and local modes

There are two kinds of oscillation modes in general: one is local mode/ power plant mode, with frequency between 0.5~2.0Hz, another kind oscillation mode is inter-area mode/ tie-line mode, and its frequency is generally between 0.1 ~ 1.0Hz.

Let’s assume that area grid A with N generators is connected with area grid B composed of M generators, the interconnected power system has M+N generators and M+N-1 electro-mechanical modes. Compared with the sum of electro-mechanical modes of the two
separate area grids the interconnected system has one more electro-mechanical mode. For example, the Northeast China power grid has 48 generators and the North China power grid has 52 generators, when the Northeast China and the North China power grids are running separately, they have 98 electro-mechanical modes in all. After the two are interconnected, the power system has 100 generators and 99 electro-mechanical modes. The one newly appeared mode resulted from the two power grids interconnection is the “inter-area oscillation mode”.

2.1 Characteristics of the inter-area mode

A remarkable characteristic of “inter-area oscillation mode” is that its oscillation frequency is the lowest of all electro-mechanical modes. Because the inter-area mode represents two group of generators swing against each other, so the system can be equivalent to a two-machine system with the inertia constants of each group, \( M_1 \) and \( M_2 \). They are the sums of machines of each group. For the swing equation of the relative rotor angle, we can use an equivalent inertia constant of \( M \) which equals to

\[
M = \frac{M_1 M_2}{M_1 + M_2}
\]

The angle speed \( \omega \) of the inter-area mode equals to:

\[
\omega = \sqrt{\frac{K_s \omega_0}{M}}
\]

Where \( K_s \) is the synchronizing torque coefficient. After the power grids are interconnected, the system inertia constant increased, and on the other hand, the synchronizing torque coefficient of the generator group decreased. Therefore, the frequency of the inter-area oscillation mode in the interconnected power system is lower than any frequency of the oscillation mode in the grids before the interconnection.

For instance, when the Northeast-North China power grids run separately, the lowest oscillation frequency of 98 electro-mechanical oscillation modes is about 0.5Hz. After the two power grids are interconnected, the lowest oscillation frequency of electro-mechanical oscillations is about 0.3Hz. The computation analysis also indicated that, the lowest frequency of the “inter-area oscillation mode” is between 0.1Hz ~ 0.2Hz in the interconnected power system composed by the Northeast China, the North China, the Central China (including the Sichuan Chongqing), or in another interconnected power system composed by the North China, the Central China (including the Sichuan Chongqing) and the Shandong power grids. The frequency of the “inter-area oscillation mode” will increase along with the enhancement between various area grids. For example, in the initial period of the South China - Hong Kong interconnected power system, there was only one AC transmission line connecting the West part and the East part, the power transfer was less than 1000MW, and the frequency of the "inter-area oscillation mode" was about 0.3Hz. By the summer of 2003, the whole system inertia constant increased along with the system capacity, and the power transfer between the West part and the East part reached 5000MW. The frequency of the “inter-area oscillation mode” frequency rose to about 0.4Hz, mainly because the main transmission corridor has been strengthened.

2.2 Factors affect the damping of the inter-area mode

The damping of the inter-area mode is affected by many factors; it can be negative, small positive or even strong damping.

2.2.1 The power flow of the tie line

The damping of the “inter-area oscillation mode” in some interconnected power system is affected significantly by the value and the direction of the active power flow of the tie line. In one power flow direction, the damping weakens when the power flow increases, and when the power flow reaches a certain value, the damping becomes negative. However if the active power flow direction reverses, the damping increases while the power flow strengthens under certain conditions.

Table 2.1 shows the computed results of the relations between the damping ratio of the “inter-area mode” and the active power flow between the East China and Fujian power grids. This test is carried out under the heavy power flow condition in 2003, and no PSS is in service. Table 2.1 shows, as the active power flows from Fujian to East China, along with the power flow increases, the damping weakens, and at the power flow of 700MW, the damping ratio is 0.0046, however as long as the power flows from East China to Fujian, the "inter-area oscillation mode" is well damped, and at the active power flow of 900MW, the damping ratio is 0.3268, which is a strong damping.

<table>
<thead>
<tr>
<th>Transmission active-power (MW)</th>
<th>East China to Fujian 900MW</th>
<th>Fujian to East China 0MW</th>
<th>Fujian to East China 600MW</th>
<th>Fujian to East China 700MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Damping ratio (without PSS)</td>
<td>0.3268</td>
<td>0.1300</td>
<td>0.0166</td>
<td>0.0046</td>
</tr>
</tbody>
</table>
However, it is observed that in some interconnected systems, the damping of the “inter-area mode” is not affected significantly by the value and the direction of the tie line active-power flow, but by the interior network structure and the power flow patterns inside each area power grid. The Northeast-North China power grid serves as a good example.

Table 2.2 shows the damping ratios of the “inter-area modes” are all negative and almost the same value for different levels and directions of the tie line power flow. This is true for a special load flow pattern inside the Northeast power grid of 2001 and no PSS in service.

<table>
<thead>
<tr>
<th>Transmission active-power (MW)</th>
<th>Northeast to North China 769MW</th>
<th>0MW transfer</th>
<th>North China to Northeast 729</th>
</tr>
</thead>
<tbody>
<tr>
<td>Damping ratio (without PSS)</td>
<td>-0.1230</td>
<td>-0.1254</td>
<td>-0.1210</td>
</tr>
</tbody>
</table>

* the load flow pattern inside Northeast China power grid of 2001

2.2.2 Network structure and power flow pattern inside each area power grids

Table 2.3 shows that the damping ratios of the “inter-area modes” are positive and greater than 0.08 for different value and direction of the tie line power flow under another load flow pattern inside the Northeast area grid. Comparing between Table 2.3 with Table 2.2, it is concluded that the power flow pattern inside the Northeast China power grid has significant impacts on the damping of the “inter-area mode” for Northeast - North China interconnected power system.

<table>
<thead>
<tr>
<th>Transmission active-power (MW)</th>
<th>Northeast to North China 900MW</th>
<th>Northeast to North China 600MW</th>
<th>Northeast to North China 0MW</th>
<th>North China to Northeast 300MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Damping ratio (without PSS)</td>
<td>0.1163</td>
<td>0.281</td>
<td>0.0846</td>
<td>0.1344</td>
</tr>
</tbody>
</table>

* The load flow pattern inside Northeast China power grid of 2001

2.2.3 Negative damping produced by AVR

It is well recognized that the negative damping of the “local mode” is produced by the AVR in heavy loading conditions.

Our studies shown in Table 2.4 demonstrated that the negative damping of the inter-area mode is also produced by AVR.

<table>
<thead>
<tr>
<th>No.</th>
<th>tie line power transfer</th>
<th>Without AVR</th>
<th>With AVR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Northeast to North China 769MW in 2001</td>
<td>0.2798</td>
<td>-0.1230</td>
</tr>
<tr>
<td>2</td>
<td>Northeast to North China 0MW in 2001</td>
<td>0.3691</td>
<td>-0.1254</td>
</tr>
<tr>
<td>3</td>
<td>North China to Northeast 729MW in 2001</td>
<td>0.4333</td>
<td>-0.1210</td>
</tr>
</tbody>
</table>

As Table 2.4 shows, Without AVR, the damping ratios of the “inter-area modes” for different tie line power transfer and flow directions are positive; however, the damping ratios become negative with AVR in service.

2.3 Impact of interconnection of the original area grids on the local modes

As mentioned above, there are N+M-1 electro-mechanical modes in the interconnected system composed of area grids of A and B where N and M are the numbers of the generators of A and B respectively. Besides the newly appeared “inter-area mode”, there are N+M-2 electro-mechanical modes. Among them, it is very interesting to observe that those undamped and poorly damped local modes of the interconnected system keep as almost the same as the local modes of the original area grids. For example, Table 2.5 shows all the modes with damping ratios less than 0.02 when Fujian power grid and the East China power grid run separately. In Table 2.6 there are five modes with damping ratios less than 0.02 for the Fujian-East China interconnected power system. The one with frequency of 0.506 Hz and damping ratio of −0.0859 is the new inter-area mode. Comparing the rest four modes in Table 2.6 with the modes in Table 2.5, it is evident that they are very close.

<table>
<thead>
<tr>
<th>No.</th>
<th>( \alpha )</th>
<th>( \omega )</th>
<th>( f )</th>
<th>( \zeta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.3427</td>
<td>4.107</td>
<td>0.654</td>
<td>-0.0832</td>
</tr>
<tr>
<td>2</td>
<td>-0.0443</td>
<td>7.251</td>
<td>1.154</td>
<td>0.0061</td>
</tr>
<tr>
<td>3</td>
<td>-0.0688</td>
<td>10.705</td>
<td>1.704</td>
<td>0.0064</td>
</tr>
<tr>
<td>4</td>
<td>-0.0795</td>
<td>5.526</td>
<td>0.879</td>
<td>0.0144</td>
</tr>
</tbody>
</table>
Table 2.6 Electro-mechanical modes with damping ratio less than 0.02 for Fujian - East China interconnected power system

<table>
<thead>
<tr>
<th>No</th>
<th>α</th>
<th>ω</th>
<th>f</th>
<th>ζ</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.2741</td>
<td>3.181</td>
<td>0.506</td>
<td>-0.0859</td>
</tr>
<tr>
<td>2</td>
<td>0.2463</td>
<td>4.183</td>
<td>0.666</td>
<td>-0.0588</td>
</tr>
<tr>
<td>3</td>
<td>-0.0407</td>
<td>7.246</td>
<td>1.153</td>
<td>0.0056</td>
</tr>
<tr>
<td>4</td>
<td>-0.0718</td>
<td>10.707</td>
<td>1.703</td>
<td>0.0067</td>
</tr>
<tr>
<td>5</td>
<td>-0.0716</td>
<td>5.675</td>
<td>0.903</td>
<td>0.0126</td>
</tr>
</tbody>
</table>

The above mentioned property of those undamped and poorly damped local modes may lead to reduce the work in the analysis of system stability. However more investigations are needed to identify the criterion for the existence of such property. One of the criteria lays on the weakness of the tie line connection between those area grids. This conclusion has been demonstrated by the studies of the Northeast-North China interconnected power system. Table 2.7 shows the electro-mechanical modes with damping ratios less than 0.02 or close to 0.02 before Northeast and North China power grids were interconnected. Table 2.8 shows the electro-mechanical modes with damping ratios less than 0.02 after Northeast and North China power grids were interconnected (0MW power flow). Before the interconnection, it has 11 oscillation modes with poor damping ratios, and 4 of them are negative. After the interconnection shown in Table 2.8, it has 12 oscillation modes with damping ratios less than 0.02, and 5 of them are negative. In Table 2.8 the one with frequency of 0.298 Hz (the lowest in this system) and the damping ratio of -0.1254 is the newly appeared inter-area mode, comparing the rest of 11 local modes in Table 2.8 with the modes in Table 2.7, it is evident that they are very close.

Table 2.7 The local modes with poor damping ratios for the Northeast grid and the North China grid running separately

<table>
<thead>
<tr>
<th>No</th>
<th>α</th>
<th>ω</th>
<th>f</th>
<th>ζ</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.2993</td>
<td>7.557</td>
<td>1.207</td>
<td>-0.0396</td>
</tr>
<tr>
<td>2</td>
<td>0.1748</td>
<td>7.263</td>
<td>1.156</td>
<td>-0.0241</td>
</tr>
<tr>
<td>3</td>
<td>0.0748</td>
<td>6.242</td>
<td>0.993</td>
<td>-0.0120</td>
</tr>
<tr>
<td>4</td>
<td>0.0811</td>
<td>7.823</td>
<td>1.245</td>
<td>-0.0104</td>
</tr>
<tr>
<td>5</td>
<td>-0.0246</td>
<td>8.070</td>
<td>1.284</td>
<td>0.0031</td>
</tr>
<tr>
<td>6</td>
<td>-0.0301</td>
<td>8.509</td>
<td>1.354</td>
<td>0.0035</td>
</tr>
<tr>
<td>7</td>
<td>-0.1005</td>
<td>7.672</td>
<td>1.221</td>
<td>0.0131</td>
</tr>
<tr>
<td>8</td>
<td>-0.1190</td>
<td>7.961</td>
<td>1.267</td>
<td>0.0149</td>
</tr>
<tr>
<td>9</td>
<td>-0.1413</td>
<td>8.129</td>
<td>1.298</td>
<td>0.0174</td>
</tr>
<tr>
<td>10</td>
<td>-0.2695</td>
<td>14.575</td>
<td>2.319</td>
<td>0.0185</td>
</tr>
<tr>
<td>11</td>
<td>-0.1083</td>
<td>5.234</td>
<td>0.833</td>
<td>0.0207</td>
</tr>
</tbody>
</table>

3. The strategy to improve small disturbance stability of the interconnected power system

To improve small disturbance stability of interconnected power systems, both “local modes” and “inter-area modes” should be enhanced, especially the “inter-area modes”.

3.1 Using PSS to improve system damping

The most economical and effective measure to enhance the damping of “local modes” and ”inter-area modes”, is to dispose PSS on generators having strong association with the “local modes” and the “inter-area modes”. It is already widely used in the grids of domestic and overseas [1]. The PSS’s ability in improving stability should be fully utilized before other kind of measures being explored.

3.1.1 Disposing power system stabilizer can eliminate the negative damping

High gain and high speed excitation control of generator has a vital role to enhance static stability and transient stability in the power system [2]. However it may also provide some negative damping in certain conditions if PSS doesn’t apply or PSS is not tuned properly. As long as PSS is applied and tuned in such a way that the positive damping PSS provided is greater than the negative damping, both system small and large disturbance stability can be significantly improved without introducing low frequency oscillations.[3].

3.1.2 High availability and reliability

PSS and AVR are constituents of excitation control system; and they have the same availability. AVR and
PSS based microcomputer has even higher reliability than the exciter.

3.1.3 Sound adaptability to different operating conditions

PSS can be tuned to provide suitable phase compensation for a wide frequency band width. Thus, it can provide positive damping for those electromechanical modes which have strong association with that machine in all possible operating conditions. While other additive controls (for example linear optimizer excitation control, non-linear optimizer excitation control) cannot achieve at present.

3.1.4 Principle of PSS application in the interconnected power system

Besides its low oscillation frequency, another characteristic of the "inter-area mode" which resulted from the interconnection of area grids is that many generators have strong association with this mode. Therefore, it is not appropriate to dispose PSS only at just one generator or a few ones; PSS should be installed in every generator which associates with this mode. How many units and which unit should be chosen to install PSS depends on individual interconnected power system.

3.2 Other measures for improving small disturbance stability

In addition to the generation excitation control for improving stability, other measures should be further explored such as:

- DC transmission modulation: DC transmission modulation and coordination with the excitation control can be very effective for stability improvement. However the DC transmission system may frequently have single pole or the double-pole blocking, so we cannot merely depend upon this measure to solve “inter-area mode” negative damping or poor damping problems and it should be treated as an important and effective supplementary measure to PSS.
- Thyristor Controlled Series Compensation (TCSC) on the transmission line is also an effective measure to enhance the power system stability. Since its cost is high, TCSC should be used after the ability of excitation control being fully explored. Consideration should also be given to the impact of the outage of TCSC on system reliability as n-1 criteria.
- Static Var Compensation (SVC) is the best way to compensate flick voltage disturbance in the distribute network. Using it for prevention of area mode oscillation is not as effective as DC transmission modulation, and TCSC.

4. Example of application of PSS in China’s interconnected power system

With the formation, the development and the expansion of the interconnected power systems in China, PSSs have been widely applied as a main measure to prevent low frequency oscillation.

- Interconnected power system of Guangdong and Hong Kong

After Guangdong and Hong Kong power grids were interconnected in 1984, low frequency oscillations occurred many times. According to the results of analysis, the AVR negative damping of Castle Peak power plant of Hong Kong- Kowloon is the main source of the low frequency oscillation in the interconnected power system. After disposing PSS on that plant the low frequency oscillation disappeared. [5].

- Interconnected power system of Sichuan Chongqing and Central China

Sichuan Chongqing and Central China power grids were interconnected at the beginning of 2002 through a
500kV transmission line, namely Wanlong line. The studies indicated that the interconnected power system has a frequency of about 0.3Hz “inter-area mode”, its damping ratio is -0.117. The analysis results indicated that it is the “inter-area” oscillation between the generator group of Sichuan Chongqing power grid and the generator group of the Northeast China power grid (Fig 4-1). After disposing PSS in Ertan, Tongjiezi, Baozhusi, Geheyan, Fentan, Wuqiangxi, Gezhou Dam generators and so on, a field test was carried out which demonstrated that the damping ratio increases to 0.045 when Sichuan Chongqing delivered 600MW active power to Central China [6].

- Interconnected power system of the Northeast and North China

After the Northeast and the North China power grids interconnected, it has an “inter-area mode” with frequency about 0.3Hz. This is the oscillation between the generator group of the Northeast power grid and the generator group of the North China power grid. When the Northeast China power grid runs on special pattern of load flow, the damping is negative and system becomes unstable. After installing PSS on generators of Yimen, Fuer, Baishan, Xibaipo, Muer, Shuangliao, Shuangyashan plants and so on, the damping of this “inter-area mode” turns out to be positive, system becomes stable [7].

- Interconnected power system of the North China and Central China

After the North China and Central China power grids were interconnected, it has an “inter-area mode” with frequency of about 0.15Hz. This is the oscillation between the generators group of the Northeast-North China power grid and the generator group of the Sichuan Chongqing-Central China power grid (Fig.4-2), and the eigenvalue is -0.007893±j0.816952 representing very poor damping. After disposing PSS on many of generators associating with this mode in the Northeast China, North China, Central China and Sichuan Chongqing, the damping of the “inter-area mode” becomes well damped [8].

5. Conclusions

(1) The newly appeared inter-area mode, after those area grids were jointed together to form the interconnected system is the primary focus to assess interconnected power system oscillatory stability. The damping of the “inter-area mode” varies from negative to positive depending on the value and direction of the active power flow of the tie lines. It also depends on the load flow pattern inside the area power grids that compose the interconnected system.

(2) AVR is the main source of poorly damped/undamped low frequency oscillations under stressed operating conditions. Therefore the models and its parameters of the excitation control system should be as accurate as possible and obtained from field tests.

(3) It is observed in our studies that after the area grids were interconnected, the poor damped local modes of the original area grids keep almost unchanged. This phenomenon needs to probe further.

(4) Strategies to enhance system stability and principles for installation PSS have been proposed in this paper.

(5) During the past ten years, all the projects of the interconnection of different area grids in China have been successfully accomplished. From early stage planning, analysis and identify stability bottlenecks to coordinate design, commissioning PSS to eliminate the bottlenecks, CEPRI and NEPDCC have accumulated tremendous experience. It is also demonstrated that PSS is an effective measure to assure stable operation for such a geographically stretched complex interconnected power system.

Acknowledgment

Authors would like to thank Prof. Chu Liu for his advice and work in editing this paper.

References