APPLICATION OF THYRISTOR-CONTROLLED SERIES COMPENSATORS
TO ENHANCE OSCILLATORY STABILITY AND TRANSMISSION
CAPABILITY OF A LONGITUDINAL POWER SYSTEM

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Abstract: Power transfer capability between the northern area and the central area of the Taiwan power system is severely limited by the fact that the power flows over the two parallel corridors connecting the two areas are rather disproportionate to their thermal limits due to different conductor sizes. Placing series capacitors on the corridor which is lightly loaded seems to be a reasonable means to enhance the overall transfer capability of the parallel corridors without overloading the other corridor which is already close to its thermal limit. A joint research project is conducted by the researchers at National Taiwan University and the engineers at Taiwan Power Company (TPC) in order to examine the feasibility of installing a combination of conventional series capacitors and thyristor-controlled series compensators (TCSCs) at TPC's 345 kV transmission system. Extensive power flow studies are conducted to investigate how the power flows over the two corridors are affected by different locations and capacities of the series capacitors. In addition to steady-state power transfer levels over the two corridors, the eigenvalues for the inter-area oscillation modes are also computed for the system with various compensation plans. A proper compensation plan is determined based on requirements on both steady-state power transfer level and inter-area mode damping. To improve system dynamic performance, a supplementary TCSC damping controller is designed. It is concluded from the results of this work that good damping characteristic can be achieved by coordinated application of the designed TCSC damping controller and the power system stabilizers.

Keywords: thyristor-controlled series compensator, system dynamic performance, power system stability, inter-area oscillations, transmission capability

1. INTRODUCTION

The power system in Taiwan is a longitudinal one with three major areas on the island, namely, North, Center, and South, connected together by a number of 345 kV transmission lines. Since major load centers are located in the north and most generating plants are in the central and southern areas, significant power transfers from central area and southern area to the northern area have been experienced in the past few years [1-3].

Fig. 1 depicts a one-line diagram of the 345 kV transmission system connecting the North and the Center. The surplus power in the central and southern areas is transmitted to the North through two parallel corridors. The thermal limit for each line of corridor II (3660 A) is approximately 1.83 times that of corridor I (2000 A) but the reactances of the two corridors differ not much from each other (0.3698 szflun and 0.3081 Rlkm for corridor I and corridor II, respectively). Thus, it is often observed in daily operation of TPC (Taiwan Power Company) that corridor I is very close to its thermal limit while corridor II is still well below its limit. In the next few years, load in the North is expected to grow steadily but new generating units to be commissioned are all located in the Center and South. As a result, a further in-
crease in the power transfers from the central and southern areas to the northern area is foreseeable and there is a potential risk of overloading corridor I in the future system operation.

To increase the power transfer capability between the Center and the North, TPC initiated the construction of corridor III four years ago. This new corridor, once commissioned, is expected to alleviate the overload problem on corridor I. However, the project will not be completed in the near future due to the difficulty in getting the required right-of-way. It is thus essential for TPC to devise an alternative approach to enhance the overall transmission capability from the Center to the North using the two corridors currently available. As mentioned earlier, the main reason why corridor I is subject to overload while corridor II remains well below its limit is that the reactances of the two corridors are essential the same. Therefore, a reasonable approach to increase the overall transmission level without overloading corridor I would be to reduce the reactance of corridor II by placing series capacitors along the corridor and shift part of the flows over corridor I to corridor II [4-8].

The paper presents results from a joint work by researchers and engineers from National Taiwan University and Taiwan Power Company with the aim to devise a proper combination of conventional and thyristor-controlled series compensators (TCSCs) [9-14] on corridor II such that the transfer level on corridor II is increased while overloading over corridor I is avoided. Section 3 will be devoted to the analysis of the power flows over the two corridors when various combinations of series compensators are installed.

In addition to steady-state power transfer levels over the two parallel corridors, system operators and planners at TPC are most concerned about oscillatory stability of the system before and after the series compensators are installed because there have been several incidents of sustained inter-area oscillations in the past [1-3]. The dampings of the inter-area modes for the system with series compensation will be examined in Section 4. A supplementary TCSC damping controller is designed using frequency response and root locus technique. Effect of TCSC with the designed supplementary damping controller and power system stabilizers (PSS) on inter-area mode damping will also be investigated.

2. SYSTEM DESCRIPTION AND PLANNING OBJECTIVE

2.1 System Description

The system under study is the Taiwan power system in the year 2000. Two representative power flows, one for peak load and the other for off-peak load, are established by system planners at TPC. Table 1 summarizes area generation and load for the two load patterns under study.

It is observed from Table 1 that the deficit power in the northern area (4967 MW and 2768 MW for peak load and off-peak load, respectively) must be supplied from the generators in the central and southern areas through the North-Center 345 kV and 161 kV lines. Since most of the inter-area power flows are transmitted through 345 kV lines, how to increase the power transfer capability of these EHV lines will be of major concern in this work.

2.2 Planning Objective

System planners at TPC recommend that the following requirements be met by the uprated transmission systems:

1. During normal conditions (all lines in service), all 345 kV circuits should be loaded within their thermal limits.
2. During outage conditions (loss of one line), the loadings of all circuits in service should be kept as low as possible, preferably not exceeding their thermal limits.
3. Bus voltage should be between 0.95 pu and 1.05 pu for normal conditions, and between 0.93 pu and 1.07 pu for post-contingency situations.
4. The damping ratios of the inter-area modes must be greater than 0.05.

3. POWER FLOW STUDIES

3.1 The Uncompensated System

To examine the power flows over the two parallel corridors under both normal situation (all lines in service) and outage situation (outage of one line), the seven cases as listed in Table 2 will be considered.

<table>
<thead>
<tr>
<th>TABLE 1 AREA GENERATIONS AND LOADS (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak</td>
</tr>
<tr>
<td>------</td>
</tr>
<tr>
<td>Generation</td>
</tr>
<tr>
<td>Load loss</td>
</tr>
<tr>
<td>Surplus power</td>
</tr>
<tr>
<td>Off-peak</td>
</tr>
<tr>
<td>Generation</td>
</tr>
<tr>
<td>Load loss</td>
</tr>
<tr>
<td>Surplus power</td>
</tr>
</tbody>
</table>

*generations and loads in the eastern area are not included

TABLE 2 SUMMARY OF STUDY CASES

<table>
<thead>
<tr>
<th>Case</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>All lines in service</td>
</tr>
<tr>
<td>1</td>
<td>Outage of one line between LUNTA' and TIENLN</td>
</tr>
<tr>
<td>2</td>
<td>Outage of one line between TIENLN and CHUNLAS</td>
</tr>
<tr>
<td>3</td>
<td>Outage of one line between LUNTA' and OMEI</td>
</tr>
<tr>
<td>4</td>
<td>Outage of one line between LUNTA' and OMEI</td>
</tr>
<tr>
<td>5</td>
<td>Outage of one line between CHUNLAS and OMEI</td>
</tr>
<tr>
<td>6</td>
<td>Outage of one line between OMEI and WUFENG</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TABLE 3 LINE FLOWS (MW) FOR THE UNCOMPENSATED SYSTEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corridor I</td>
</tr>
<tr>
<td>------------</td>
</tr>
<tr>
<td>Case</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>6</td>
</tr>
</tbody>
</table>

*the number in the parenthesis gives percentage of thermal limit
*the flows for bus 1-2 and bus 2-3 are for the two parallel circuits except for an outage of one of the two (cases 1 and 2)
The power flows for peak load situation are given in Table 3. Note that voltage magnitude at bus 5 (OMEI) is also shown because it is the lowest voltage magnitude in this system. It is also noted that the power flows for off-peak load are not shown because in all the study cases (cases 0-6) all lines are loaded within their thermal limits and all bus voltages fall within the specified range. Our later discussions on power flow analysis will be based solely on peak load situation.

Based on the results in Table 3, the following observations are in order.

1. When all lines are in service (case 0), no lines are overloaded and the bus voltage at OMEI is normal. However, the flows over corridors I and II are very disproportionate to their respective thermal ratings; the two lines in corridor I are close to their thermal limits (92% and 83% of thermal limits) while the lines in corridor II are lightly loaded.

2. When one line is out of service (cases 1-6), overloading in one or two lines is observed in each case. In cases 1 and 2 where one line in corridor I is out of service, the other line in corridor I is overloaded (135% and 138% for case 1 and case 2, respectively). Since the loadings of the lines on corridor II are relatively low, it is reasonable to expect that series capacitors installed on corridor II can shift part of corridor I power flow to corridor II and alleviate the overload problem on corridor I effectively.

3. In cases 3 and 4 where a line from a north border bus (LUNTANN or LUNTANS) to OMEI is out of service, the remaining parallel line is overloaded. It is impossible to alleviate the overload problem in the two cases using series capacitors.

4. In cases 5 and 6 where a line from OMEI to CHUNLAS or WUFENG is out of service, the remaining parallel line is not overloaded but the lines in corridor I are overloaded. It is possible to use series capacitors on corridor II to shift part of corridor I power flow to corridor II, but the ability to alleviate overload is rather limited since the reserve capacity of the remaining parallel line in corridor II is not large enough to take the excess power in corridor I.

5. The voltage at OMEI is lower than 0.95 pu at each outage case. The voltage is even lower than 0.93 pu in case 6.

In summary, the series capacitors are expected to make power flows over corridors I and II more proportionate to their respective thermal limits under normal situations and alleviate line overloading in some line outage cases.

3.2 The Compensated System under Normal Situation

Various sites and capacities for the series capacitors on corridor II have been examined in order to shift powers from corridor I to corridor II. The following three alternatives have been found to be effective for power transfer:

- plan 1: 50% compensation on the line between OMEI (bus 5) and CHUNLAS (bus 3)
- plan 2: 50% compensation on the line between OMEI (bus 5) and WUFENG (bus 6)
- plan 3: 45% compensation on the line between OMEI (bus 5) and CHUNLAS (bus 3)
- 35% compensation on the line between OMEI (bus 5) and WUFENG (bus 6)

Note that the series compensation level in each compensation plan has been determined in order to reach roughly balanced flows on the lines in corridors I and corridor II. Details are not given due to limited space. The power flows for the system with various compensation plans are summarized in Table 4. All lines are assumed to be in service.

From the results in Table 4, the following observations can be made.

1. In plans 1 and 2, only one line on corridor II (OMEI-CHUNLAS or OMEI-WUFENG) is compensated. The loading on corridor I has been reduced to a great extent while the power flow on the compensated line has been increased. Since the power flow of the line on corridor II parallel to the compensated line is reduced, the power flows are not balanced between the lines on corridor II.

2. To have more balanced flows over the lines on corridor II, a compensation plan with two lines compensated such as plan 3 can be employed. In this case, the line flows over lines 5-3 and 5-6 are rather balanced. It is noted that the heavy load over line 4-5 (84%) in plan 3 will be relieved by a new parallel line to be commissioned next year.

3. If it is decided to use a single capacitor based on economic considerations, plan 1 is superior to plan 2 since the compensated line in plan 1 (OMEI-CHUNLAS) is loaded to 87% of its thermal limit while that in plan 2 (OMEI-WUFENG) is loaded to 96% of its limit.

3.3 The Compensated System under Outage Situation

Extensive studies have been made to investigate the effect of different compensation plans on the power flows over corridor I and corridor II when a line is out of service. The required compensation ratio for each of the six line outage cases may be different from that for the normal case. For example, to avoid overloading on the remaining line of corridor I, the compensation ratios in plan 3 must be increased to 50% in case 1 and case 2. On the other hand, the compensation ratios in case 5 and case 6 must not exceed 20% to avoid overloading on the compensated line. In summary, the compensation ratios which have been designed based on normal system conditions must be adjusted under line outage conditions.

<table>
<thead>
<tr>
<th>Bus no.</th>
<th>Corridor I</th>
<th>Corridor II</th>
<th>Voltage at bus 5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>1834</td>
<td>1611</td>
<td>1281</td>
</tr>
<tr>
<td></td>
<td>(78)</td>
<td>(67)</td>
<td>(62)</td>
</tr>
<tr>
<td></td>
<td>2116</td>
<td>1970</td>
<td>1099</td>
</tr>
<tr>
<td></td>
<td>(92)</td>
<td>(83)</td>
<td>(54)</td>
</tr>
<tr>
<td></td>
<td>1889</td>
<td>1757</td>
<td>1246</td>
</tr>
<tr>
<td></td>
<td>(80)</td>
<td>(72)</td>
<td>(69)</td>
</tr>
<tr>
<td></td>
<td>1770</td>
<td>1578</td>
<td>1323</td>
</tr>
<tr>
<td></td>
<td>(75)</td>
<td>(66)</td>
<td>(63)</td>
</tr>
</tbody>
</table>

*The number in the parenthesis gives percentage of thermal limit
5.4 Applications of Thyristor-Controlled Series Compensator

The need of different compensation ratios under different operating conditions can be achieved by the combination use of fixed series capacitors, mechanically-switched capacitors, and thyristor-controlled series capacitors [8-10]. Note that both mechanically-switched capacitors and thyristor-controlled series capacitors can be used to balance the line loadings between corridor I to II under different operating conditions. However, TCSC can be used to control the line compensation ratio over a continuous range. In addition, TCSC can improve system dynamic performance, which has been of concern by the operators and planners at TPC, through the use of supplementary damping controller [10,11,14]. The TCSC can also contribute to the mitigation of subsynchronous resonance (SSR) oscillations [12-14]. The effect of TCSC and its supplementary controller on the SSR of TPC's transmission system is currently being examined by a group of engineers at TPC but detailed SSR study is beyond the scope of this paper.

4. INTER-AREA OSCILLATIONS

4.1 The Uncompensated System

Taiwan power system is longitudinal in nature and hence several incidents of poorly-damped inter-area oscillations have been reported in the past [1-3]. The dominant oscillation mode is an inter-area mode with a frequency between 0.8 Hz and 0.9 Hz. The generators in the northern area and central area usually form a group which oscillates with another group of generators in the south. The mode has been observed on a system-wide Dynamic Performance Monitoring System [3] and verified by time domain simulations and eigenvalue-eigenvector analysis [1-2]. In order to improve the damping characteristic of this inter-area mode oscillation, eight accelerating power type power system stabilizers (PSS) have been installed at generating plants which play an important role in the mode.

In this work, the eigenvalues (oscillation frequencies and damping ratios) in the frequency range between 0.1 Hz and 1.5 Hz and the associated eigenvectors (mode shapes) are computed by PEALS program of Small Signal Stability Package (SSSP) [13]. The computed frequency and damping ratio of the inter-area oscillation mode without and with PSS for the uncompensated base case system (Table 1) are listed in Table 5. It is noted that the PSS parameters currently employed by TPC are used in this study.

It is observed from Table 5 that the damping ratios of the inter-area mode for the uncompensated system under peak load and off-peak load conditions can be improved from 0.051 to 0.1714 and from 0.025 to 0.0599, respectively, by the application of the eight stabilizers. It is noted that the damping ratio for the off-peak load case is rather close to the lowest acceptable level of 0.05 as described in Section 2.2.

4.2 The System with Conventional Series Capacitors

To examine the effect of fixed series compensation (SC) on the damping characteristic of the inter-area mode, the damping ratios of the inter-area mode after the series capacitors are installed are listed in Table 5 (fixed series compensated system). Only the results for plan 3 are listed due to limited space. It should be pointed out that in the PSS tuning process the phase characteristics of the generating units before and after the series capacitors are installed must be compared. In the present case, no significant difference is observed for the phase characteristics when the series capacitors are installed. Therefore, the PSS parameters are not redesigned. It is observed that, for the case without PSS, the damping ratio of the inter-area mode changes slightly from 0.0510 to 0.0466 and from 0.0250 to 0.0254 for peak load and off-peak load, respectively, when the capacitors are installed. On the other hand, the damping characteristic for the system with series capacitors is worse than that without series capacitors for the case with PSS (the damping ratios decrease from 0.1714 to 0.1557 and from 0.0599 to 0.0551 for peak load and off-peak load, respectively).

4.3 Applications of Thyristor Controlled Series Compensators

As mentioned before, TCSC is capable of providing positive damping effect to the inter-area mode in addition to providing flexible control of power flows. To examine the effectiveness of TCSC damping effect, an additional 5% compensation, which is modulated by the supplementary controller, is provided by TCSC in each of the two lines (OMEI-CHUNLAS and OMEI-WUFENG). The block diagram of the TCSC model for stability studies is shown in Fig. 2.

The TCSC supplementary controller is a lead-lag compensator with a washout function. In the present work, either bus voltage at OMEI or the real power at the TCSC location is taken as the input of TCSC. Note that other damping signals, such as synthesized remote area bus voltages and angular difference [16], can also be used. The washout time constant

![Fig. 2 Block diagram of TCSC with supplementary damping controller](image-url)
$T_w$ is chosen to be 3.0 seconds. It is our purpose to determine proper values of $K, T_1, T_2, T_3,$ and $T_4$ in order to improve the damping for the dominant inter-area oscillation mode while maintaining the damping performance for other well-damped modes. In this paper, root locus and bode plot techniques are employed for the tuning of the controller constants. The lead-lag time constants are first determined by phase margin test. By examining the frequency responses of the open-loop system when a small disturbance is applied to the reactance setpoint $X_{set}$ of TCSC, several sets of time constants can be chosen to extend the phase margin of the open-loop system. As an example, Fig. 3 shows the phase characteristic of the open-loop system and the compensated system (before the feedback loop is closed) under off-peak load conditions with the negative value of OMEI voltage magnitude as its feedback signal. Root loci for various combinations of lead-lag time constants have been plotted with the controller gain $K$ as the parameter. Note that the controller gain $K$ is defined as per unit TCSC reactance divided by per unit bus voltage (or line power), which has been computed using a base of 345 kV and 100 MVA. Figs. 4, 5, and 6 show three typical plots for different values of lead-lag time constants under off-peak load conditions. It is noted that the poorly-damped mode, namely, mode A, in Figs. 4 to 6 is the dominant mode of major concern. Another mode, which is well-damped before the addition of the TCSC damping controller, namely, mode B, is also shown in Figs. 4-6 because this mode is sensitive to controller parameter variations. From the mode shape, it is observed that mode B is an inter-area mode in which the generators in the central area oscillate against the generators in the north and south. The following observations can be made from the root loci in Figs. 4-6:

1. The damping of mode A will be improved as the TCSC controller gain is increased for the system without or with PSS.
2. As shown in Figs. 4(b) and 6(b), TCSC controller tends to provide negative damping effect to mode B when the PSS is present. In the root loci of Fig. 5(b), similar observation is made except for the case of small TCSC gain where the damping for mode B improves slightly with increasing TCSC gain. Thus, it is essential to have a proper value of TCSC gain such that the damping of mode A is improved and the damping of mode B remains satisfactory (having a damping ratio greater than 0.05).
3. Based on the root loci in Figs. 4-6, a set of proper parameters can be chosen for off-peak load condition as shown in the second row of Table 6. Bus voltage at OMEI has been employed as the input to the TCSC supplementary damping controller. The same procedure can be followed to determine the TCSC parameters for the case of peak load condition and line power input. The results are summarized in Table 6.

With the TCSC controller parameters as described in Table 6 at hand, one can proceed to compute the frequency and damping ratio for the system with TCSC damping controller. The results are shown in Table 5. It can be observed from Table 5 that the TCSC damping controller can contribute positive damping to the inter-area oscillation mode (mode A).

<table>
<thead>
<tr>
<th>Feedback signal</th>
<th>$T_1$</th>
<th>$T_2$</th>
<th>$T_3$</th>
<th>$T_4$</th>
<th>$K$</th>
</tr>
</thead>
<tbody>
<tr>
<td>OMEI bus voltage</td>
<td>Peak</td>
<td>0.2</td>
<td>0.015</td>
<td>0.2</td>
<td>0.014</td>
</tr>
<tr>
<td>Line power</td>
<td>Off-peak</td>
<td>0.198</td>
<td>1.59</td>
<td>0.198</td>
<td>1.55</td>
</tr>
</tbody>
</table>

For the system without PSS and with TCSC voltage feedback controller, the damping ratio of this mode is improved from 0.0510 to 0.1303 and from 0.0250 to 0.1003 for peak load case and off-peak load case, respectively. For the same system but with TCSC line power feedback controller, the damping ratio is improved from 0.0510 to 0.0733 and from 0.0250 to 0.0316 for peak load case and off-peak load case.
respectively. It seems that the bus voltage at OMEI is a better choice for TCSC supplementary controller input signal than the line power as far as the damping of inter-area mode is concerned. In addition, TCSC supplementary damping controller (with bus voltage input) alone provides nearly the same damping effect as the PSS. Of course, a combination of TCSC damping controller and PSS gives the best damping performance among all the cases studied.

In order to demonstrate the effectiveness of the TCSC damping controller, the dynamic response curves of generator speed following a 3-cycle three-phase bus ground fault at LUNTAN for off-peak load condition are simulated using ETMSP (Extended Transient-Midterm Stability Program) and the results are given in Fig. 7. It can be seen from Fig. 7 that the damping of the low frequency oscillation mode can be significantly improved by the TCSC damping controller. Again, a combination of PSS and TCSC damping controller gives the best performance.

It is worth noting that, although the TCSC damping controller has been designed under normal condition (all lines in service), it provides good damping effect even when there is a line outage in the system. The results for line outage conditions are not presented due to limited space.

5. CONCLUSIONS

A combination of conventional capacitors and thyristor-controlled series compensators has been planned on the 345 kV transmission system of Taiwan Power Company. The effect of various series compensation plans on the redistribution of the power flows over the two parallel corridors connecting the northern area and the central area is first investigated. Then the damping characteristic of the inter-area mode of major concern to system operators and planners is studied for the system without series compensation and for the system with combination of conventional series capacitors and TCSCs. A supplementary TCSC damping controller is des-
igned in order to improve the damping of the inter-area mode. Coordinated application of PSS and TCSC is also investigated. It is concluded from the results of this work that the combination of capacitors and TCSCs is effective in controlling the power flows over the two parallel corridors and thereby enhancing the overall transmission capability without overloadimg any circuit. It is also found that the damping of the inter-area mode can be significantly improved by the proposed TCSC damping controller.

Future works will be devoted to the evaluation of TCSC’s effect on subsynchronous resonance.

6. ACKNOWLEDGMENTS

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7. REFERENCES


8. BIOGRAPHIES

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