COMPARATIVE STUDY BETWEEN TCSC AND PSS IN DAMPING ELECTRO-MECHANICAL OSCILLATIONS

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Abstract

Investigating the most effective locations of Thyristor Controlled Series Capacitor (TCSC) and its feedback signal, determination of different controllers parameters (TCSC’s Power Oscillation Damper (POD) and Power System Stabilizer (PSS)) to enhance damping capability in multi-machine power system are presented in this paper. Biogeography Based Optimization (BBO) technique is used to get controllers parameters. A comparative damping study was held between separate operation of PSS & TCSC in different cases as well as dual operation of them together. The efficacy of BBO technique in damping local modes of oscillations in multi-machine power systems is confirmed through nonlinear simulation results using Power System Analysis Toolbox (PSAT).

Index TCSC, POD, PSS, Biogeography based optimization, Dual operation.

I. INTRODUCTION

With the increase of electrical power system demand and the need to operate power systems closer to their limits of stability with faster and more flexible manner in the deregulated competitive environment. Moreover, modern power systems can reach stressed conditions more easily than the past. These requirement many cause unstable or poorly damped oscillations that are observed more often in today’s power systems.

The instability problems caused by low frequency inter-area oscillations are therefore becoming significant. Increasing the damping of these modes of oscillation by adequately tuning power system stabilizers (PSSes) or employing FACTS devices based controllers have been the topic of many works.

The PSS is a supplementary control system, which is often applied as part of excitation control system. The basic function of the PSS is to apply a signal to the excitation system, creating electrical torques to the rotor in phase with speed variation that damp out power oscillations.

De Mello et al. in 1969 [1] presented the concepts of synchronous machine stability as affected by excitation control. Their work developed insights into effects of excitation systems and requirement of supplementary stabilizing action for such systems based on the concept of damping and synchronizing torques.

Several approaches have been applied to PSS design problem or to determine parameters for a fixed PSS lead-lag model stated by [2]. These include linear approaches like minimum phase control loop [3], $H_\infty$ [4]. Moreover different optimization techniques were employed to get the controller parameters according to linear approaches [5-7]. But in fact, those approaches depend on improving the damping modes in frequency domain. Such improvement are adequate for small signal stability studies where power systems can be dealt as linear system around an operating point with immutable modes. However, linear approaches don't always reflect the best design in case of transient stability analysis [8], worse they may lead to virtual improvement in damping as will be illustrated in the second section.

Other nonlinear techniques were also introduced, for instance, the fuzzy logic controller [9]. The main disadvantage in fuzzy logic is that the controller design is dependant on the designer experience in choosing the membership function. Trajectory Sensitivity Approach [10] was successfully used, but its application requires a great deal of elaborate mathematical treatment. A successful practice was introduced in [11] to determine parameters of PSS using genetic algorithm based on time domain simulation. In our paper, the last practice will be followed, but with applying another novel technique which is Biogeography-Based Optimization (BBO) with extending the problem horizon by coordinating PSS and TCSC devices to enhance each other in damping electromechanical oscillations.

As for The TCSC, it is a member of FACTS devices family. Its roll in damping electromechanical oscillations has been studied in various papers with several techniques almost the same as PSS techniques discussed above with the same comments. These include pole placement [12], $H_\infty$[13], nonlinear control[14], adaptive control[15,16], and different optimization and artificial intelligence techniques –genetic algorithm[17],particle swarm[18].

The paper is organized as follows: the first section is a general literature review of both PSS and TCSC in improving systems damping properties. The second section exhibit the difference between time domain and frequency domain approaches in choosing adequate fitness function for the optimization technique, as well as, the effectiveness of different locations of TCSC in damping properties. The third section illustrates a comparison between the roles of PSS with...
respect to the role of TCSC in improving system damping properties in strong well meshed system. The forth section, held the same comparison between the same devices in addition to the dual operation of both of them, but in case of contingency case. The fifth section is the conclusions out of this work.

II. INVESTIGATING POD ADJUSTING CRITERIA & TCSC LOCATIONS EFFECTIVENESS

In this section TCSC effectiveness in damping electromechanical oscillations will be checked according to different fitness function approaches (frequency domain-time domain) and at different locations. The changing of TCSC location depends on our interest on a certain mode.

The power system general model equations are stated in (1-3)

\[ \dot{x} = f(x, z, u) \]  
\[ 0 = g(x, z, u) \]  
\[ y = h(x, z, u) \]

Where, \( x \) is a state vector (generators angles, angular speeds, transient voltage, flux; excitation system voltage and AVR output, etc), \( z \) is an algebraic variable vector (bus voltage magnitude, angle, stator currents), \( u \) is an input vector (excitation control reference, mechanical input, TCSC Ref) and \( y \) is an output vector. The choice of output \( y \) variables depends on stabilizing signals such as line power, machine speed, bus voltage magnitude etc.

After linearizing (1-3) around an initial operating point \((x_0, z_0, u_0)\) and eliminating the \( z \) variables, the system can be expressed with (4,5) which are the general state space equations:

\[ \dot{x} = Ax + Bu \]  
\[ y = Cx + Du \]

Where:

\[ A = \frac{\partial f}{\partial x} - \frac{\partial f}{\partial z} \left( \frac{\partial g}{\partial z} \right)^{-1} \frac{\partial g}{\partial x} \]  
\[ B = \frac{\partial f}{\partial u} - \frac{\partial f}{\partial z} \left( \frac{\partial g}{\partial z} \right)^{-1} \frac{\partial g}{\partial u} \]  
\[ C = \frac{\partial h}{\partial x} - \frac{\partial h}{\partial z} \left( \frac{\partial g}{\partial z} \right)^{-1} \frac{\partial g}{\partial x} \]  
\[ D = \frac{\partial h}{\partial u} - \frac{\partial h}{\partial z} \left( \frac{\partial g}{\partial z} \right)^{-1} \frac{\partial g}{\partial u} \]

From matrix \( A \), the system modes can be calculated. Then, the electromechanical modes of interest can be captured using participation factor method [19]. Once the electromechanical modes are obtained, TCSC and feedback signal effective locations according to a certain mode of interest are determined by singular value decomposition method stated in [20].

To test the effectiveness and applicability of the proposed approaches, the WSCC 9-bus 3-machines system [21], shown in Fig.1, is used. This system-after linearization- has two electromechanical modes related to generators, angular velocities by participation factors as shown in table (1). The parameters of POD shown in Fig.2 were adjusted using BBO technique illustrated in appendix (A).

Our first, target is to investigate different fitness functions approaches in adjusting the POD parameters, then investigating the effectiveness of different combination of TCSC and feedback locations.

A. Fitness function investigation

At this section, TCSC and its feedback signal are investigated at lines (6-9) and (6-4) respectively. This is the best compromising effective combination which has moderate effectiveness on the electromechanical modes simultaneously according to controllability and observability calculations stated in [20]. The POD parameters range was taken as shown in table2. The washout time constant \( (T_w) \) isn't a critical parameter and it can be chosen in range of \((0.5-20)\). In our case it was taken as 1.5. The fitness function for optimizing those parameters can be based on freq-domain or time domain approaches. The former is widely used in literature [5, 6] because it needs short time for calculation. The latter is used also, but with less intense [11].

![Fig. 1: WSCC 9-bus system](image)

Table 1: Electro-mechanical modes and participation factors of different generators

<table>
<thead>
<tr>
<th>Electromechanical mode</th>
<th>Participation Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real</td>
<td>Imag</td>
</tr>
<tr>
<td>-0.698</td>
<td>± 13.084</td>
</tr>
<tr>
<td>-0.161</td>
<td>± 8.678</td>
</tr>
</tbody>
</table>
The fitness function according to Freq. domain approach aims to increase the damping ratios for the electromechanical modes. It can be stated as (6):

\[
\text{Minimize } (J), \quad J = -\sigma_1 - \sigma_2
\]  
\[\sigma_1, \sigma_2 \text{ are damping ratios according to electromechanical oscillations.}\]

On the other hand, the time domain approach aims to minimize the angular velocity deviations of different generators after disturbance. It can be stated as follows:

\[
\text{Minimize } (J), \quad J = \sum_{k=1}^{n} \int_{t=0}^{t_{\text{sim}}} |\omega_k| \, dt
\]

Where \( n \) : number of system generators (three in our case).

After applying both approaches, the obtained controller parameters are shown in table B.1 Damping ratios of both electro-mechanical modes are shown in table 3. From that table, the modes in case of freq-domain approach have highly damping ratios rather than those of time domain.

To guarantee the calculated modes results, time domain simulation was held for 3-phase short circuit at bus 7 lasted for 6-cycles. Generators angles deviations are shown in Figs. (3, 4).

Although table 3 shows high damping ratios for both modes in case of Freq-domain approach, simulation results don't jibe with such high damping ratios. That's due to the nonlinearity of the system which leads to modes changing during and after simulation time. Table 4 illustrates modes after 10 Sec. of time domain simulation. Because of that deluding behavior of system optimized based on Freq-domain, all of our optimization fitness function, from now and upon, will depend on time-domain approach only as (7).

### Table 2: POD Parameters Limits

<table>
<thead>
<tr>
<th>Parameter</th>
<th>K</th>
<th>T1</th>
<th>T2</th>
<th>T3</th>
<th>T4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min-limit</td>
<td>-3.6</td>
<td>-2.2</td>
<td>0.2</td>
<td>-2.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Max-limit</td>
<td>3.6</td>
<td>2.2</td>
<td>2.2</td>
<td>2.2</td>
<td>2.2</td>
</tr>
</tbody>
</table>

### Table 3: Electro-mechanical modes and damping ratios according Freq/Time-domain App

<table>
<thead>
<tr>
<th>Mode</th>
<th>Damping ratio</th>
<th>Mode</th>
<th>Damping ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>-2.97 ± 11.97J</td>
<td>0.24</td>
<td>-2.77 ± 13.24J</td>
<td>0.058</td>
</tr>
<tr>
<td>-0.97 ± 8.92J</td>
<td>0.108</td>
<td>-0.34 ± 8.92J</td>
<td>0.038</td>
</tr>
</tbody>
</table>

### Table 4: Electro-mechanical modes and damping ratios according Freq/Time-domain App. after 10 Sec. of simulation

<table>
<thead>
<tr>
<th>Mode</th>
<th>Damping ratio</th>
<th>Mode</th>
<th>Damping ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.52 ± 13.07J</td>
<td>0.037</td>
<td>-0.796 ± 13.21J</td>
<td>0.06</td>
</tr>
<tr>
<td>0.13 ± 8.66J</td>
<td>Unstable</td>
<td>-0.39 ± 8.47J</td>
<td>0.045</td>
</tr>
</tbody>
</table>

### B. Reinvestigation of TCSC and its feedback locations
At this moment, the performance of TCSC up till now is poor in damping oscillations even in case of time-domain approach. As a result, TCSC and feedback signal combination were investigated again, where TCSC placed at line (5-7) and feedback signal was taken from the same line. This combination provides greater effectiveness on mode 2 rather than mode 1 which is well damped by nature. The controller's parameters are set in table B.2. Figs. (5, 6) show the damping performance of the new combination alternative compared to the previous one under three phase, 6-cycle fault at bus 7.

III. PSS PLACEMENT & PARAMETERS ADJUSTMENT

In this section, the damping problem will be remedied by using PSS. The model of PSS with static exciter model is shown in Fig.7. Locating PSSes is much easier than finding the effective locations of TCSC and its feedback signal, it depends simply on participation factor principle [22]. From table (1), to stabilize both electro-mechanical modes, a PSS will be placed at Gen.3 for mode 1 and another at Gen.2 for mode 2. The washout time constants of both PSS are not critical to choose and they were taken as 1.5. To reduce the number of adjusted parameters, $T_2$ and $T_4$ were taken as 0.07 for both stabilizers. The remaining six parameters ($K$, $T_1$, and $T_3$ for both stabilizers) were determined using BBO technique.

![Fig. 6: Gen 3 rotor angle deviation after fault](image)

The limits of PSS's parameters were taken as stated in [23]. Table B.3 shows the parameters values after applying BBO technique. Figs. (8-9) illustrate the damping performance of the individual operation of PSSes and TCSC after applying three phase, 6-cycle fault at bus 7.

It can be concluded from these figures that the performance of PSSes in damping electro-mechanical oscillation is superior than that concerned to using POD. However, it must be stated that during the previous comparison the system was tested under fault without disconnecting any transmission circuit. In other words, the system was well meshed. In the following section, the system performance with each controller will be compared, but under another scenario of faults.

IV. DUAL OPERATION OF PSS AND TCSC

In this section, a comparison was held between PSSes and TCSC based POD at heavily loading contingency case. This condition can be obtained by constant power factor non-uniform load increase as shown in table 5 to stress Line (5-7) which is considered as a double circuit line.
After a 3-phase short circuit fault near bus 7, one circuit from line (5-7) was disconnected after 6-cycles to clear that fault.

PSSes parameters were remained the same as stated in table B.3. Where POD of TCSC was designed at this situation to work in harmony with PSS to enhance system damping. TCSC was investigated at line (5-7), feedback signal from line (2-7). This combination has high effectiveness on both the electromechanical modes at this contingency case. POD parameters are shown in table B.4. Figs (10, 11) show different controllers performance, as well as, the performance of dual operation of them.

![Fig. 8: Gen 2 rotor angle deviation after fault](image1)

![Fig. 9: Gen 3 rotor angle deviation after fault](image2)

![Fig. 10: Gen 2 rotor angle deviation after fault](image3)

![Fig. 11: Gen 3 rotor angle deviation after fault](image4)

It's clear that the performance of TCSC POD is competitive to the performance of PSS at this case of weak system. In other words, TCSC performance is more effective in weak systems, unlike in the well meshed system. Moreover, the optimization technique succeeded to establish a harmony in performance between both controllers (PSSes and POD) without adverse attacking (destabilizing action).

V. CONCLUSION

a. Time domain results are more reliable than freq-domain results when both are chosen as fitness functions. The freq-domain may lead to a deluding performance because of system nonlinearity.

b. TCSC controller shows a low damping performance compared with that of PSS in well meshed system.

c. TCSC controller shows a competitive damping performance with that of PSS at weak systems which is illustrated in case of disconnection of one circuit of heavily loaded line. Here is the bright side, as the TCSC is always installed to
increase power transfer capability in weak lines. As a result, supplying a TCSC with POD will be just a by product can be gained with no extra charges. Moreover, it has a significant damping action in case of dual operation with the PSS.

APPENDIX (A)

Biogeography-Based Optimization (BBO)[24]

BBO is a novel biological optimization technique which simulates the biogeography of nearby islands and how they interact with each others. Each island has high suitability index (HSI) which determine the number of species (S_i) will be able to live there. Islands can exchange features with each others by immigration of different species.

Islands with high HSI have the right to export more species (high μ_i) to nearby islands, but it can receive low numbers of guest species (low λ_i†), because it's overcrowded. On contrary, Islands with low HSI can export small number of species (low μ_i) to nearby islands, but they can receive large number of guest species (high λ_i), because it's almost empty. Islands, here, represent solutions. With this analogy, a solution which has high HSI will have the right to export its powerful genes to modify the other solutions around. On contrary, solutions with low HSI will be objected to receive those powerful only genes to be modified. The complete flow chart of BBO technique is shown in Fig.A.1.

BBO has proved high ability to escape from suboptimum solutions over well-known optimization techniques [24]. For instance, Fig.A.2 shows best generation solution for BBO and genetic algorithm to get the TCSC POD parameters for maximizing the modes damping ratios according to (6). Number of generations=100, 20 individual/generation with .005 mutation probability. To make the comparison fairer, both techniques started from the same initial solutions.

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*μ_i*: is the exporting factor which determines the ability of a certain solution to modify the others.

†λ_i*: is the importing factor which determines the probability of certain solution to be modified.
Fig. A.2: GA, BBO Minimum cost throughout iterations

APPENDIX (B)

Table B. 1: POD parameters where TCSC at feedback signal at lines (6-9) and (4-6), respectively

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
<td>0.067</td>
<td>-0.848</td>
</tr>
<tr>
<td>T1</td>
<td>0.56</td>
<td>1.012</td>
</tr>
<tr>
<td>T2</td>
<td>0.161</td>
<td>0.348</td>
</tr>
<tr>
<td>T3</td>
<td>0.56</td>
<td>-0.085</td>
</tr>
<tr>
<td>T4</td>
<td>0.161</td>
<td>1.724</td>
</tr>
</tbody>
</table>

Table B. 2: POD parameters where TCSC and feedback signal From line (5-7)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>K</th>
<th>T1</th>
<th>T2</th>
<th>T3</th>
<th>T4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.29</td>
<td>0.029</td>
<td>1.066</td>
<td>-0.995</td>
<td>0.256</td>
</tr>
</tbody>
</table>

Table B. 3: PSS parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>K</th>
<th>T1</th>
<th>T2</th>
<th>T3</th>
<th>T4</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSS @ gen2</td>
<td>3</td>
<td>2.2</td>
<td>0.07</td>
<td>0.014</td>
<td>0.007</td>
</tr>
<tr>
<td>PSS @ gen3</td>
<td>1.22</td>
<td>1.59</td>
<td>0.07</td>
<td>0.034</td>
<td>0.007</td>
</tr>
</tbody>
</table>

Table B. 4: POD parameters where TCSC at feedback signal at lines (5-7) and (2-7), respectively

<table>
<thead>
<tr>
<th>Parameters</th>
<th>K</th>
<th>T1</th>
<th>T2</th>
<th>T3</th>
<th>T4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-0.945</td>
<td>-0.028</td>
<td>0.379</td>
<td>0.957</td>
<td>0.324</td>
</tr>
</tbody>
</table>

REFERENCES

[24] Dan Simon team, Cleveland State University "Biogeography-Based Optimization," unpublished

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