Intelligent Power Oscillation Damping Control with Dynamic Knowledge Inference

R. K. Pandey, Senior Member IEEE
Department of Electrical Engineering
IIT (BHU), Varanasi
India
rpsneh@yahoo.co.in

Deepak Kumar Gupta, Student Member IEEE
Department of Electrical Engineering
IIT (BHU), Varanasi
India
dpkgpt214@gmail.com

Abstract—The paper presents an intelligent power oscillation damping control with dynamic knowledge inference concept. The power oscillation damping in an interconnected large power network requires controllers suitable deployed and regulated with changing system conditions. The combined intelligent control strategy has been proposed for real and reactive power regulation. The Gravitational Search Algorithm (GSA) optimization technique has been used to get the optimal parameters of respective controllers and this has been used in developing knowledge domain with dynamic inference. A Sample six area system has been considered to demonstrate the controlled states with operational shift.

Keywords—Gravitational Search Algorithm (GSA), Integral time multiplied by absolute error (ITAE), Knowledge Inference Mechanism (KIM), Power System Stabilizer (PSS), Static Synchronous Compensator (STATCOM).

I. INTRODUCTION

Damping in the power oscillation is desirable as it not only reduces variation in system states and improves the power quality but also enhances stability limits. As power demand grows rapidly with increase in transmission line length and generators with limited availability of resources, the existing power systems are frequently loaded beyond nominal range. It is known that a supplementary controller (PSS) is normally used to provide damping and improve dynamic performance. However, PSSs may fail to stabilize for larger perturbation, under such situation, FACTS controllers have shown promising results to improve oscillation damping. STATCOM is a regulating device based on a power electronics voltage source converter and can act as either reactive power injection or absorption in the network [1-4]. Many intelligent optimization techniques have been used to design these controllers. Abdel-Magid YL, Abido MA et al used genetic algorithm and tabu search techniques to design power system stabilizers for multi-machine power systems [5-6]. Eslami M et al also reported use of GA and PSO techniques for power oscillation damping [7-8]. Small signal stability model for FACTS devices (UPFC, STATCOM and SSSC etc.) have been reported in [9-10]. PSO technique has been used to tune SVC and PSS [11]. In [12-15], TCSC and UPFC have been designed with intelligent optimization techniques (GA, PSO and Quantum Particle Swarm Optimization) to damp out inter-area oscillation in the system. R. K. Pandey et al. reported UPFC control parameter identification for effective and precise power oscillation damping and the design of multi-stage LQR control strategy, which results in optimal tracking. The design of intelligent weight matrix has been introduced for Q matrix based on the state predominant approach [16-17].

This paper presents further work reported as in [18-19] which gives the concept of controller shifting/sharing as the system operating condition changes with time. Controller shifting concept basically operates within the controller by redesigning the control parameters of respective controller with the change in system operating conditions. Controller sharing concept is realized when local controllers (PSS) reach their maximum capacity and unable to stabilize the system at certain operating conditions. In that case any controller connected nearby in the system (STATCOM) will act as a supplementary controller in addition to the existing one and stabilize entire system quickly. To develop knowledge linked inference mechanism for all controllers connected in the network, a GSA optimization technique has been used. This provides a new control structure and helps in quick regulation with precise damping. However, while realizing such structure in field, this may require additional intelligent soft controllers which may have multi-controller parameters realization in given knowledge domain framework. A sample six area system has been considered with STATCOM connected between area 3 and area 4 and all the generators with PSS of different ratings. Multi-stage LQR control concept is used to design the input control parameters of STATCOM [17].

II. STATE SPACE MODELING OF PSS AND STATCOM

A. Approach for PSS model inclusion

Figure 1 shows the multi machine representation with n number of generators connected in each area. Vt1, Vt2 are the terminal voltage, I1, I2 are the armature current and Y1, Y2 represents loading in respective area. Z represents transmission line.
Armature current and terminal voltage can be represented by:

\[ i_1 = i_{d1} + j_i q_{1}, \quad v_{t1} = v_{d1} + j v_{q1} \]  

\[ v_{d1} + j v_{q1} - j * x_{q1} * (i_{d1} + j_i q_{1}) = v_{d1} + j v_{q1} \]  

Following constant and parameters are introduced for convenience.

\[ C11 = C11 + j C21 \]  

\[ R'_{d11} = R - C21 * x_{d11}', \quad R'_{q12} = R - C21 * x_{q12}' \]  

\[ X'_{d11} = X + C11 * x_{q11}', \quad X'_{q21} = X + C11 * x_{q21}' \]  

\[ Z'_{d11} = R'_{d11} * R'_{q12} + X'_{q21} * X'_{d11} \]  

\[ Y_{d1} = (C11 * X'_{d11} - C21 * R'_{q12}) / Z'_{d11} \]  

\[ Y_{q1} = (C11 * R'_{d11} + C21 * X'_{q21}) / Z'_{d11} \]  

Where \( Z = R + j X \) (Trans. Line Reactance) and \( Y = G + j B \) (Load). From Fig. 1 we will have:

\[ i_1 = Y1 * v_{t1} + Z^{-1}(v_{d1} - v_{q1}) \]  

\[ Z * i_1 = [(1 + Z & Y1)] * v_{t1} - v_{q2}, \text{ this can be written as:} \]

\[ \begin{bmatrix} R & -X \end{bmatrix} \begin{bmatrix} i_{d1} \\ i_{q1} \end{bmatrix} = \begin{bmatrix} C11 & -C21 \\ C21 & C11 \end{bmatrix} \begin{bmatrix} v_{d1} \\ v_{q1} \end{bmatrix} - \begin{bmatrix} v_{d1} \\ v_{q1} \end{bmatrix} - \begin{bmatrix} \sin(\delta_m - \delta_m) \\ \cos(\delta_m - \delta_m) \end{bmatrix} \]

\[ \Delta \delta = \delta_m - \delta_m \]  

\[ \begin{bmatrix} \Delta \delta_{d1} \\ \Delta \delta_{q1} \end{bmatrix} = \begin{bmatrix} Y_{d1} \\ Y_{q1} \end{bmatrix} \Delta E_{q1} + \begin{bmatrix} F_{d1} \\ F_{q1} \end{bmatrix} \Delta \delta \]  

Final states equations for one machine can be written as:

\[ M = \Delta \omega = -(K_d \Delta \delta + K_q \Delta E_{q1}) \]  

\[ s \Delta \delta = \omega_0 \Delta \omega \]  

Using above four equations, the state variables vector becomes:

\[ x = [\Delta \omega, \Delta \delta, \Delta E_{q1}, \Delta E_{d1}] \]  

\[ \Delta \omega = (s+T_d K_d) \Delta E_q = K3(-K_d \Delta \delta + \Delta E_{d1}) \]  

\[ \Delta \omega = (s+T_d) \Delta E_{d1} = K_d (u_k - \Delta w) = K_d (u_k - K_d \Delta \delta - K_d \Delta E_{q1}) \]  

Final states space equation combining PSS is:

\[ \Delta X = [A] \Delta X + [B] \Delta U E = [A] \Delta X \]  

Where B is the control matrix, \( \Delta U E \) the supplementary excitation and \( [A] \) is the controlled system matrix. Where:

\[ \Delta X = [\Delta \omega, \Delta \delta, \Delta E_{q1}, \Delta E_{d1}, \Delta X5, \Delta U E]^T \]

**B. Approach for STATCOM model inclusion**

STATCOM connected between area 1 and 2 is shown in figure 3 using Thevenin’s equivalent model. STATCOM is composed of DC-link capacitor, GTO base voltage sources converters, and excitation transformer (ET) connected in shunt. PWM technique has been considered for developing the model of STATCOM. Input control parameters are amplitude modulation ration (\( \Delta m \)) and phase angle (\( \Delta \delta_e \)) for voltage source converter.

The linearized equations of two area power system are [10]:

\[ \Delta \delta = \omega_0 \Delta \omega \]  

\[ \Delta \omega = -D \Delta \omega + \Delta \omega_m \]  

Where:

\[ M = \Delta \omega = -(K_d \Delta \delta + K_q \Delta E_{q1}) \]  

\[ s \Delta \delta = \omega_0 \Delta \omega \]
\[
\Delta E_\mu = -\frac{\Delta E_\nu - (X_\nu - X'_\nu) \Delta J_\nu + \Delta E_\mu}{T_{\nu}\alpha}
\]

\[
\Delta E_\nu = \frac{-\Delta E_\mu + K_n (-\Delta V_j)}{T_n}
\]

The complete state space model of two area power system installed with STATCOM can be obtained as following:

\[
\Delta x = A\Delta x + B\Delta u
\]

\[
\Delta x = \left[ \Delta \delta, \Delta \omega, \Delta \omega, \Delta E_{1q}, \Delta E_{2q}, \Delta E_{1d}, \Delta E_{2d}, \Delta V_q \right]^T
\]

\[
\Delta u = \left[ \Delta m_i, \Delta \delta_i \right]^T
\]

III. Gravitational Search Algorithm (GSA)

GSA is a newly developed intelligent search technique based on the gravitational law and interaction of masses. In GSA, agents are collection of masses and considered as the object (candidate solutions) with their performance measured by their masses. All objects/agents attract each other by the gravity force resulting in a global movement of all objects towards the objects with heavier masses [20].

Consider a system with \( N \) number of objects with \( d \)-dimensions, then position of each agent \( i \) is defined as:

\[
X_i = (X_i^1, ..., X_i^d, ..., X_i^n)
\]

The force acting on mass ‘i’ due to mass ‘j’ is:

\[
F_{ij} = G(t) \frac{M_{pi}M_{pj}(t)}{R_{ij}(t) + \varepsilon}(X_j^d(t) - X_i^d(t))
\]

Where, \( G(t) \) is the gravitational constant, \( M_{pj} \) is the active gravitational mass of \( j \) agent and \( M_{pi} \) is the passive gravitational mass related to agent \( i \). \( \varepsilon \) is small constant.

Total force acts on a single agent \( i \) and acceleration in a dimension \( d \) from other agents is:

\[
F_{ij}^d(t) = \sum_{j=1, j \neq i}^N \text{rand}_j F_{ij}^d(t), \quad a_i^d(t) = \frac{F_i^d(t)}{M_i(t)}
\]

where, \( M_i(t) \) is the inertial mass of \( i \)th agent.

Velocity of agent is updated by:

\[
v_i^d(t + 1) = \text{rand}_i * v_i^d(t) + \alpha_i^d(t)
\]

\[
x_i^d(t + 1) = x_i^d(t) + v_i^d(t + 1)
\]

And the masses of each agent are updated by:

\[
m_i(t) = \frac{\text{fit}(t) - \text{worst}(t)}{\text{best}(t) - \text{worst}(t)}, \quad M_i(t) = \frac{m_i(t)}{\sum_{j=1}^N m_j(t)}
\]

Here \( \text{best}(t) \) and \( \text{worst}(t) \) both are depend upon objective problem (i.e., maximization or minimization).

IV. Knowledge Inference Mechanism (KIM)

Knowledge inference mechanism can be defined as the set of rules for designing the controller’s parameters at operational shift in the network condition. With the change in the perturbation in the network, oscillation in the states variables will increase and may violates form the desired limits or may sustain for the longer time which finally will affect the stability of the system. Damping of these oscillations depends upon the setting of controller parameters and if the design of controller is not proper then it will not only degrade the system performance but also aggravate the adverse dynamic conditions. Knowledge domain is the set of tuned controller parameters at different operating condition which is developed and stored in off-line conditions. It includes the range of tuned control parameters in which systems state variables are within their limits. Development of this knowledge domain can be done by any heuristic optimization technique with any objective function, which should be related to the damping in the system. In this paper GSA optimization technique is considered and ITAE is taken as objective function [18-19].

The objective function which is used to generate Knowledge Domain by the use of gravitational search algorithm is ITAE (minimization problem).

\[
J(t) = ITAE = \int_0^T |e(t)| dt
\]

Where \( e(t) \) is the error of the state variables from their desired values. GSA is used to tune the control parameters for the PSS and STATCOM for many system operating conditions off-line. All the tuned parameters are stored in their respective knowledge domain.

A. Knowledge Retrieval with Inference Mechanism and Controllers realization

Change in the system operating condition is linked with the percentage change in the system state variables response and as the dynamical operational shift occurs, corresponding change in the behavior of the system is measured. Values of controllers parameters stored in the knowledge domain are linked with the respective operational change in the network. With the detection of percentage change in the behavior of the system, returning of controller take place with the help of knowledge inference mechanism with some switching delay and stabilize the system as quickly as possible. (Figure. 5)
B. Complete Regulation of the System

Complete system regulation has to be checked after retuning the controller’s parameters and modulating the power flow in the network. There might be some operating condition where all the controllers connected in the network will not perform satisfactory, in that case isolation of that particular region from the system completely will serve as a final control action (may be load shedding or SPS operation) and prevent major collapse in the system.

V. Case Study and Results

Two cases have been considered to demonstrate the effectiveness of controller sharing and shifting concept with GSA driven knowledge inference mechanism. First case represents the retuning of PSS controllers parameters (controller shifting) as the system operating condition changes with time and retuned parameters damp out the oscillation more as compared to the previous tuned values. Second case represents the effectiveness of the STATCOM connected in the network when PSS fails to stabilize the network at certain system operating condition. PSS with STATCOM together modulated the power flow in the network as desired and brings the system stable. Six Area Systems have been considered with STATCOM connected between area 3 and area 4 and PSS to all the areas. Time constants (T1 and T2) of lead-lag compensation block are used as the control parameters for PSS and amplitude modulation ratio \( m_o \) and phase angle \( \delta_o \) as the control parameters for STATCOM.

Table 1 shows the comparison between system responses in terms of overshoot/undershoot and settling time for tuning of controller with GSA driven knowledge domain inference mechanism concept and without this concept. Figure 7 shows the system states variables response with GSA driven KIM based retuned PSS parameters for change in operating condition which enhance the oscillation damping in the system and stabilize the network. Figure 8 shows some operating condition where PSS only not able to stabilize the system, in that case STATCOM acts as supplementary controller in addition to the existing PSS controller and stabilize the system as quickly as possible (shown in Figure 9). The results demonstrate that over-shoot/under-shoot and settling time of the system state variables are greatly reduced by applying the proposed concept for tuning of controllers.

Load in Area 3 (\( Y_3 = G_3 + jB_3 \)); where \( G_3 = 1.6615 \); \( B_3 = 1.9029 \);

Case I- \( L3(1) = 1.6 * Y_3 \) at time \( t1 \) and \( L3(2) = 0.8 * Y_3 \) at \( t2 \); where \( t1 = 0 \) sec and \( t2 = 1.5 \) sec

Figure 4 Control Structure for Knowledge Domain Mapping

Figure 5 Flow chart for controller realization in dynamical mode

Figure 6 Six Area System with STATCOM between Area 3 and 4

Figure 7 System states variables response with GSA driven KIM based retuned PSS parameters for change in operating condition which enhance the oscillation damping in the system and stabilize the network.

Figure 8 Some operating condition where PSS only not able to stabilize the system, in that case STATCOM acts as supplementary controller in addition to the existing PSS controller and stabilize the system as quickly as possible.
Case II = L3(3) = 1.7*Y3 (1- PSS only / 2- STATCOM supplements PSS)

Figure 7 Perturbation response of system states for Case I for Six Area System (Area 3)
TABLE I. COMPARISON OF SYSTEM RESPONSE WITH ALL CASES FOR SIX AREA SYSTEM (AREA 3)

<table>
<thead>
<tr>
<th>System</th>
<th>State</th>
<th>Overshoot</th>
<th>Settling time</th>
<th>Eigenvalues</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case I (Previously tuned PSS)</td>
<td>$\Delta \omega 3$</td>
<td>0.05</td>
<td>6.10</td>
<td>$-3.0591+14.3573i$</td>
</tr>
<tr>
<td></td>
<td>$\Delta \omega 3$</td>
<td>-6.0</td>
<td>6.50</td>
<td>$-3.0591-14.3573i$</td>
</tr>
<tr>
<td></td>
<td>$\Delta Eq 3$</td>
<td>3.1</td>
<td>6.60</td>
<td>$-12.9564$</td>
</tr>
<tr>
<td></td>
<td>$\Delta Eq 3$</td>
<td>75.0</td>
<td>6.20</td>
<td>$-0.7330 + 3.0407i$</td>
</tr>
<tr>
<td></td>
<td>$\Delta Eq 3$</td>
<td>0.05</td>
<td>6.10</td>
<td>$-0.7330 - 3.0407i$</td>
</tr>
<tr>
<td></td>
<td>$\Delta UE 3$</td>
<td>2.40</td>
<td>6.50</td>
<td>$-0.1227$</td>
</tr>
<tr>
<td>Case I (Retuned PSS with KIM)</td>
<td>$\Delta \omega 3$</td>
<td>0.035</td>
<td>2.60</td>
<td>$-5.3379+11.8651i$</td>
</tr>
<tr>
<td></td>
<td>$\Delta \omega 3$</td>
<td>-4.0</td>
<td>2.50</td>
<td>$-5.3379-11.8651i$</td>
</tr>
<tr>
<td></td>
<td>$\Delta Eq 3$</td>
<td>1.80</td>
<td>2.70</td>
<td>$-2.8189 + 4.9954i$</td>
</tr>
<tr>
<td></td>
<td>$\Delta Eq 3$</td>
<td>50.0</td>
<td>2.80</td>
<td>$-2.8189 - 4.9954i$</td>
</tr>
<tr>
<td></td>
<td>$\Delta Eq 3$</td>
<td>0.035</td>
<td>2.60</td>
<td>$-2.7471$</td>
</tr>
<tr>
<td></td>
<td>$\Delta UE 3$</td>
<td>1.0</td>
<td>2.50</td>
<td>$-0.1245$</td>
</tr>
<tr>
<td>Case II PSS Fails to Stabilize even with GSA Driven KIM</td>
<td>$\Delta \omega 3$</td>
<td>---</td>
<td>---</td>
<td>$-15.0770$</td>
</tr>
<tr>
<td></td>
<td>$\Delta \omega 3$</td>
<td>---</td>
<td>---</td>
<td>$0.2115 + 8.9028i$</td>
</tr>
<tr>
<td></td>
<td>$\Delta Eq 3$</td>
<td>---</td>
<td>---</td>
<td>$0.2115 - 8.9028i$</td>
</tr>
<tr>
<td></td>
<td>$\Delta Eq 3$</td>
<td>---</td>
<td>---</td>
<td>$-2.4103 + 0.8128i$</td>
</tr>
<tr>
<td></td>
<td>$\Delta Eq 3$</td>
<td>---</td>
<td>---</td>
<td>$-2.4103 - 0.8128i$</td>
</tr>
<tr>
<td></td>
<td>$\Delta UE 3$</td>
<td>---</td>
<td>---</td>
<td>$-0.1256$</td>
</tr>
<tr>
<td>Case II STATCOM as supplementary controller with PSS</td>
<td>$\Delta \omega 3$</td>
<td>-0.08</td>
<td>5.0</td>
<td>$-5787.400$</td>
</tr>
<tr>
<td></td>
<td>$\Delta \omega 3$</td>
<td>3.90</td>
<td>8.0</td>
<td>$-0199.800$</td>
</tr>
<tr>
<td></td>
<td>$\Delta Eq 3$</td>
<td>-0.20</td>
<td>17.0</td>
<td>$-0.900 + 7.8000i$</td>
</tr>
<tr>
<td></td>
<td>$\Delta Eq 3$</td>
<td>-1.20</td>
<td>5.0</td>
<td>$-0.900- 7.8000i$</td>
</tr>
<tr>
<td></td>
<td>$\Delta Eq 3$</td>
<td>-0.10</td>
<td>12.0</td>
<td>$-2.200 + 6.0000i$</td>
</tr>
<tr>
<td></td>
<td>$\Delta Eq 3$</td>
<td>-0.46</td>
<td>8.0</td>
<td>$-2.200 - 6.0000i$</td>
</tr>
</tbody>
</table>

VI. CONCLUSION

This paper presents an intelligent power oscillation damping control utilizing dynamical knowledge domain linked inference mechanism. The concept of controller sharing and shifting, to damp oscillations with dynamical change in operating condition, has been demonstrated. GSA has been used to develop the knowledge inference mechanism for controllers. The proposed controller shifting concept demonstrates that range of PSS at different operating condition is inadequate and change in operational shift will increase oscillations further, thus by retuning of PSS parameters the oscillations are quickly damped. The controller sharing concept demonstrates an effective role of STATCOM switching which is suitably connected in system at certain operating condition where PSS fails to stabilize. It is noticed that PSS with STATCOM enhances power modulation as desired, and thus stabilize the unstable system. The simulation results demonstrate that the over-shoot/ under-shoot along with settling time of the system state variables are greatly reduced.
VII. APPENDIX

All the constant K1 to K6 given in equation (16)-(19) can be calculated by following equations:

\[ K_{1l} = \begin{bmatrix} 0 & F_{dl} & F_{qil} \end{bmatrix} \begin{bmatrix} (x_{qil} - x_{dil}) \end{bmatrix} \]

\[ K_{2l} = \begin{bmatrix} i_{qil} \end{bmatrix} + \begin{bmatrix} Y_{dil} & Y_{qil} \end{bmatrix} \begin{bmatrix} (e_{qil} + (x_{qil} - x_{dil}'))*i_{dil} \end{bmatrix} \]

\[ K_{3l} = 1/[(1 + (x_{dil} - x_{dil}'))*Y_{dil}] \]

\[ K_{5l} = \begin{bmatrix} 0 & F_{dil} & F_{qil} \end{bmatrix} \begin{bmatrix} (x_{dil} - x_{qil})' \end{bmatrix} \]

\[ K_{6l} = \begin{bmatrix} (v_{qil}/v_{dil}) \end{bmatrix} + \begin{bmatrix} Y_{dil} & Y_{qil} \end{bmatrix} \begin{bmatrix} (x_{dil} - x_{qil})' \end{bmatrix} \]

In the above constants (K1 to K6), i represent the i\textsuperscript{th} generator and 1 is for area 1 and is extended for multi area multi generator system.

Data of Generator [21]:

**Area 1 with PSS1 (G1):**
- Generator 1 (100 MW): M1=16.64 MJ/MVA; T1d0=5.6 sec; X1d=1.192; X1q=1.192; X1d1=0.1269; E1q1=1.0 p.u.
- Excitation System 1: K1a=18.5; T1a=0.2 sec;
- Generator 1 (100 MW): M1=16.64 MJ/MVA; T1d0=5.6 sec; X1d=1.192; X1q=1.192; X1d1=0.1269; E1q1=1.0 p.u.
- Transformer:
  - Area 3 and Area 4 connected with STATCOM:
    - X6d=1.54; X6q=1.49; X6d1=0.1060; E6q1=1.0 p.u.

**Area 2 with PSS2 (G2):**
- Generator 2 (184 MW): M2=27.94 MJ/MVA; T2d0=3.3 sec; X2d=0.4993; X2q=0.4849; X2d1=0.0789; E2q1=1.0 p.u.
- Excitation System 2: K2a=18.5; T2a=0.2 sec;
- Area 2 with PSS3 (G3): Generator 3 (135 MW): M3=6.52 MJ/MVA; T3d0=3.5 sec; X3d=0.8667; X3q=0.5207; X3d1=0.2467; E3q1=1.0 p.u.
- Excitation System 3: K3a=40; T3a=0.060 sec;
- Area 3 with PSS4 (G4): Generator 4 (100 MW): M4=16.64 MJ/MVA; T4d0=5.6 sec; X4d=1.192; X4q=1.192; X4d1=0.1269; E4q1=1.0 p.u.
- Excitation System 4: K4a=18.5; T4a=0.2 sec;
- Generator 5 (135 MW): M5=6.52 MJ/MVA; T5d0=3.5 sec; X5d=0.8667; X5q=0.5207; X5d1=0.2467; E5q1=1.0 p.u.
- Excitation System 5: K5a=40; T5a=0.060 sec;
- Generator 6 (140 MW): M6=16.1 MJ/MVA; T6d0=7.9 sec; X6d=1.54; X6q=1.49; X6d1=0.1060; E6q1=1.0 p.u.
- Excitation System 6: K6a=45; T6a=0.060 sec;

**Area 3 and Area 4 connected with STATCOM:**
- Transformer: X\text{m}=0.03;
- Transmission line: X\text{c}=0.3;
- Operating conditions: V\text{m}=1.0 p.u.; \delta=40 degree;
- DC Link Capacitor: C\text{dc}=0.0005; V\text{dc}=1.0 p.u.

**Gravitational Search Algorithm Parameters:**
- No. of Populations: 70
- No. of Iteration: 15
- G0 (Gravitational constant)=100; \alpha=20

REFERENCES


