Simultaneous Tuning of Multi-Band Power System Stabilizer and Various IPFC-based Damping Controllers: An Effective method for Mitigation of Low frequency Oscillations

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Abstract

In this paper, coordinated tuning of three band power system stabilizer (PSS3B) with interline power flow controller (IPFC) in single machine infinite bus power system is proposed. From the dynamic model of the power system equipped with IPFC, linear Phillips-Heffron model is established. The damping controllers considering the various control signals of the IPFC designed based on linearized model. Optimal tuning of the controllers formulated as an optimization problem and solved using krill herd optimization algorithm. The eigenvalues analysis and response of the system to step change in mechanical torque used to demonstrate the effectiveness of the proposed method. Studies reveal that the most effective input signal of IPFC utilized for damping the low frequency oscillation coordinated with PSS3B is found to be the input signal $m_2$, providing robust performance under different operation conditions.

Keywords: PSS3B, IPFC, Krill Herd

1. Introduction

The phenomenon that is very important and a real concern in the power industry is the stability of electromechanical oscillation, i.e., the low frequency oscillations having an oscillation frequency in the range of 0.2 Hz to 2 Hz. These oscillations limit the maximum amount of power that can be transferred over the transmission lines and sometimes may have disastrous consequences to the interconnected power systems stability, leading to partial or total black-outs. Therefore, equipment and procedures to damp these oscillations are required for safe operation of power systems and allow existent transmission networks to be used better. The traditional approaches to damp the power system oscillation are by adding a power system stabilizer (PSS) in the excitation system of the generators [1]-[3]. In These years using of FACTS devices and PSS has extended to improve stability. Considering that the PSS is one of important equipment to damp the mechanical oscillation of generators. Although PSS can relieve the mechanical oscillation of generators however there are some unstable inter-area modes that we can not dispel them without using FACTS devices, so PSS and FACTS devices have been used to enhance the damping [4]-[6]. FACTS devices are playing an increasing and major role in the operation and control of competitive power systems. However, uncoordinated local control of FACTS devices and PSSs may cause instability interactions. To improve overall system performance, many researches were
made on the coordination between PSSs and FACTS POD controllers [7]-[11]. Some of these methods are based on the complex nonlinear simulation [7], [8], while the others are based on the linearized power system model. Using bio-inspired optimization algorithms for many power system control applications shows that these algorithms have very effective performance and they can find near optimal solutions. So, in this paper a new bio-based swarm intelligence algorithm, called Krill Herd (KH) is proposed for optimal tuning of the PSS3B and IPFC POD controller gains to stabilize a synchronous machine connected to an infinite bus power system. The KH algorithm is based on the description of the herding of the krill agents in response to specific biological and environmental processes. The objective function of each krill individual is defined as its distances from food and highest density of the agent [12]. In this paper firstly power system under study linearized and Phillips-Heffron model of the power system equipped with IPFC established. Then by eigenvalues analysis less damped or unstable modes specified. In the second stage PSS3B designed in multiple operating points for power system under study and then by calculation of eigenvalues the improvement of the system stability is shown. Analysis of the eigenvalues show that there are some modes that PSS3B cannot damp them well. In the third stage, PSS3B coordinated with POD controller for all four input signals of the IPFC,  \( m_1 \),  \( \delta_1 \),  \( m_2 \), and  \( \delta_2 \) separately tuned. Then eigenvalues analysis shows that POD controller for input signal of  \( m_2 \) for IPFC coordinated with PSS3B have the best performance in power system stability. Also, response of the system to step change in input mechanical torque proves the results of the eigenvalues analysis.

2. PSS3B Model

The model of three band power system stabilizer (PSS3B) shown in Figure 1 has dual inputs of electrical power deviation and rotor angular frequency deviation. The signals are used to derive an equivalent mechanical power signal. The time constants  \( T_1 \) and  \( T_2 \) represent the transducer time constants, and  \( T_{w1} \) and  \( T_{w2} \) represents the washout time constants [13].

\[
\begin{align*}
\Delta \omega & \rightarrow \frac{1}{1 + sT_1} \rightarrow \frac{sT_{w1}}{1 + sT_{w1}} \rightarrow K_2 \rightarrow \sum \rightarrow K_1 \rightarrow \frac{sT_{1w} + 1}{sT_{1w} + 1} \rightarrow U_{PSS} \\
\Delta P_e & \rightarrow \frac{1}{1 + sT_2} \rightarrow \frac{sT_{w2}}{1 + sT_{w2}} \rightarrow K_3
\end{align*}
\]

Figure 1: Structure of PSS3B

3. IPFC POD controller

The damping controller is designed to contribute a positive damping torque in phase with the speed deviation to the electromechanical oscillation loop of the generator. The structure of the IPFC based damping controller shown in Figure 2.

\[
\begin{align*}
\Delta \omega & \rightarrow K_{dc} \rightarrow \frac{sT_w}{1 + sT_w} \rightarrow \frac{1 + sT_3}{1 + sT_4} \rightarrow 1 + sT_3 \rightarrow 1 + sT_4 \rightarrow \Delta U
\end{align*}
\]

Figure 2: Structure of IPFC based POD controller
In the Figures 1 and 2 $T_{w1}$, $T_{w2}$ and $T_{w}$ are chosen 10. Also, for simplifying optimization problem value of $T_{2n}$, $T_{2d}$, $T_{1d}$ and $T_{2d}$ specified as 0.02, 0.03, 0.01 and 0.01 respectively. So, in optimization problem we have to find eight parameters $T_1$, $T_2$, $K_1$, $K_2$, $K_3$, $K_{dc}$, $T_3$ and $T_4$. Finding this parameters formulated as an optimization problem and solved using a new bio-inspired optimization algorithm called krill herd. In the next section a brief description of KH algorithm discussed. Equation (1) was used for fitness function of optimization.

$$\text{fitness} = \frac{\sum_{i=1}^{N} \left( \int_{0}^{t_{\text{up}}} t \left| \Delta \omega_i \right| dt \right)^2}{N}$$

Where $N$ is number of operation points, $t_{\text{sim}} = 8$ is simulation time.

### 4. Krill Herd Optimization Algorithm

Krill herd algorithm is one of the bio-inspired optimization algorithms that used for solving optimization problems. It inspired from the krill herding motions. This algorithm is based on the simulation of the herding of the krill swarms in response to specific biological and environmental processes. The time-dependent position on an individual krill in 2D surface is governed by the three main actions: movement induced by other krill individuals, foraging activity, and random diffusion. Equation (2) shows the lagrangian model of these three actions [13].

$$\frac{dX_i}{dt} = N_i + F_i + D_i$$

Where, $N_i$ is the motion induced by other krill individuals, $F_i$ is the foraging motion, and $D_i$ is the physical diffusion of the $i$th krill individuals. $N_i$ for a krill individual is calculated using Equation (3).

$$N_i^{\text{new}} = N_i^{\text{max}} \alpha_i + \omega_i N_i^{\text{old}}$$

$$\alpha_i = \alpha_i^{\text{local}} + \alpha_i^{\text{target}}$$

Where, $N_i^{\text{max}}$ is the maximum induced speed, $\omega_i$ is the inertia weight of the motion induced in the range $[0, 1]$, $N_i^{\text{old}}$ is the last motion induced, $\alpha_i^{\text{local}}$ is the local effect provided by the neighbors, and $\alpha_i^{\text{target}}$ is the target direction effect provided by the best krill individuals. The foraging motion is formulated in term of two main effective parameters. The first one is the food location and the second one is the previous experience about food location. Equation (4) describes this motion.

$$F_i = V_f \beta_i + \omega_f F_i^{\text{old}}$$

$$\beta_i = \beta_i^{\text{food}} + \beta_i^{\text{best}}$$

where, $V_f$ is the foraging speed, $\omega_f$ is the inertia weight of the foraging motion in the range $[0,1]$, $F_i^{\text{old}}$ is the last foraging motion, $\beta_i^{\text{food}}$ is the food attractive and $\beta_i^{\text{best}}$ is the effect of the best fitness of the $i$th krill so far. The physical diffusion of the krill individuals is considered to be a random process, and is given by Equation (5).
\[ D_i = D_{\text{max}} \left( 1 - \frac{\text{iter}}{\text{iter}_{\text{max}}} \right) \delta \]  

(5)

Where, \( D_{\text{max}} \) is the maximum diffusion speed, and \( \delta \) is a random directional vector and its arrays are random values between -1 and 1.

Finally, the position vector of a krill individual during the interval \( t \) to \( t + \Delta t \) is given by Equation (6).

\[ X_i(t + \Delta t) = X_i(t) + \Delta t \frac{dX_i}{dt} \]  

(6)

\( \Delta t \) is a very important constant and should be carefully set according to the optimization problem. It completely depends on the search space and can be simply obtained using Equation (7).

\[ \Delta t = C_i \sum_{j=1}^{NV} (UB_j - LB_j) \]  

(7)

Where, \( NV \) is the total number of variables, \( LB_j \) and \( UB_j \) are lower and upper bounds of the \( j \)th variables, respectively, and \( C_i \) is a constant number between \([0, 2]\). Simplified flowchart of the krill herd algorithm is shown in Figure 3.

![Figure 3: Flowchart of the KH algorithm](image)

5. Dynamic Model of the SMIB Power System Equipped With IPFC

The power system under study shown in Figure 4. The system consists of a generator which is connected to the infinite bus through the two parallel transmission lines. An elementary IPFC consisting of two three phase GTO based VSCs, each compensating a different transmission line by series voltage injection is installed on the two transmission lines. The nonlinear dynamic model of the power system of Figure 4 described in Equations (8-12) as follows:

\[ \dot{\delta} = \omega_0 (\omega - 1) \]  

(8)

\[ \dot{\omega} = \frac{P_m - P_e - P_D}{2H} \]  

(9)
\[
\dot{E}_q' = \frac{-(E_q + E_{fd})}{T_d'}
\]
\[
\dot{E}_{fd} = -\frac{E_{fd} + K_a(V_{se} - V_t)}{T_a}
\]
\[
\frac{dv_{dc}}{dt} = \frac{3m_1}{4C_{dc}}\left[\cos \delta_1 \sin \delta_1 \left[\frac{i_{ld}}{i_{lq}}\right] + \frac{3m_2}{4C_{dc}}\left[\cos \delta_2 \sin \delta_2 \left[\frac{i_{ld}}{i_{lq}}\right]\right]\right]
\]

Where

\[P_x = P_1 + P_2 = v_{di}i_{di} + v_{qi}i_{qi} \quad \nu_{di} = E_q' - x_{di}'i_{di} \quad \nu_{qi} = (v_{di}^2 + v_{qi}^2)^{1/2} \quad i_{di} = i_{ld} + i_{ld}^2 \]
\[E_q = E_q' + (x_d - x_d')i_{di} \quad i_{qi} = i_{lq} + j_{lq} \quad i_{ld} = i_{ld} + i_{ld}^2 \]

\[P_x, P_2\] are the power flow in each of transmission lines and \(\delta\) is the rotor angle of the synchronous generator in radians, \(\omega\) is rotor speed in rad/sec, \(V_t\) is the terminal voltage of the generator, \(E_q'\) is generator internal voltage, \(E_{fd}\) is the generator field voltage, \(v_{dc}\) is voltage at DC link. \(I_1\) and \(I_2\) are the transmission line currents. From Figure 4 we can get:

\[i_{ld} = \frac{x_{1ld}E_q' + x_{1ld}v_{dc}m_2 \sin \delta_2 - x_{1ld}v_{dc}m_1 \sin \delta_1 - x_{1ld}v_b \cos \delta}{2} \]
\[i_{ld} = \frac{x_{2ld}E_q' + x_{2ld}v_{dc}m_2 \sin \delta_2 - x_{2ld}v_{dc}m_1 \sin \delta_1 - x_{2ld}v_b \cos \delta}{2} \]
\[i_{lq} = \frac{x_{1lq}v_{dc}m_2 \cos \delta_2 - x_{1lq}v_{dc}m_1 \cos \delta_1 + x_{1lq}v_b \sin \delta}{2} \]
\[i_{lq} = \frac{x_{2lq}v_{dc}m_2 \cos \delta_2 - x_{2lq}v_{dc}m_1 \cos \delta_1 + x_{2lq}v_b \sin \delta}{2} \]

Where \(x_{1ld}, x_{2ld}, x_{2ld}, x_{1ld}, x_{2ld}, x_{2ld}\) and \(x_{2ld}\) are calculated based on \(x_{di}, x_{di}', x_{di}^2\) and \(x_{di}^2\).

**Figure 4:** SMIB equipped with IPFC
6. Linearized Model

The linear Heffron-Philips model of SMIB system installed with IPFC is obtained by linearizing Equations (8-12).

\[
\Delta \delta = \omega_0 \Delta \omega
\]  \hspace{1cm} (17)

\[
\Delta \dot{\omega} = \frac{\Delta P_m - \Delta P_f - D \Delta \omega}{2H}
\]  \hspace{1cm} (18)

\[
\Delta E'_{iq} = \frac{-\Delta E_{iq} + \Delta E_{iq}'}{T_{d1}}
\]  \hspace{1cm} (19)

\[
\Delta E_{iq} = \frac{-\Delta E_{iq} + K_a (\Delta V_{ref} - \Delta V_t)}{T_a}
\]  \hspace{1cm} (20)

\[
\Delta v_{dc} = K_s \Delta \delta + K_s \Delta E'_{iq} - K_q \Delta v_{dc} + K_{em1} \Delta m_1 + K_{cm1} \Delta \delta_1 + K_{em2} \Delta m_2 + K_{cm2} \Delta \delta_2
\]  \hspace{1cm} (21)

Where

\[
\Delta P_e = K_s \Delta \delta + K_s \Delta E'_{iq} - K_q \Delta v_{dc} + K_{pm1} \Delta m_1 + K_{pm1} \Delta \delta_1 + K_{pm2} \Delta m_2 + K_{pm2} \Delta \delta_2
\]  \hspace{1cm} (22)

\[
\Delta E_q = K_s \Delta \delta + K_q \Delta E'_{iq} - K_q \Delta v_{dc} + K_{qem} \Delta m_1 + K_{qcm} \Delta \delta_1 + K_{qem} \Delta m_2 + K_{qcm} \Delta \delta_2
\]  \hspace{1cm} (23)

\[
\Delta V_r = K_s \Delta \delta + K_s \Delta E'_{iq} - K_q \Delta v_{dc} + K_{vem} \Delta m_1 + K_{vcm} \Delta \delta_1 + K_{vem} \Delta m_2 + K_{vcm} \Delta \delta_2
\]  \hspace{1cm} (24)

The model has 28 K-constants which are functions of system parameters and the initial operating conditions [14].

7. Simulation Results

A single machine infinite bus power system installed with IPFC considered for analysis, parameters of which are given in [14]. In multiple operation points, Using KH algorithm optimization problem solved and parameters of the PSS3B and IPFC based POD controller obtained as Table 1.

| Table 1: Optimization Results Using KH Algorithm |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|                | K_1 | K_2 | K_3 | K_5 | T_1 | T_2 | T_3 | T_4 |
| m_1 based POD controller | 7.1116 | 2.8962 | 4.6266 | 4.0332 | 1.5952 | 1.1796 | 1.5607 | 0.6286 |
| δ_1 based POD controller | 9.2945 | 21.0805 | 10.2110 | 10.2559 | 1.6015 | 1.1180 | 0.8595 | 0.9755 |
| m_2 based POD controller | 15.4613 | 15.9442 | 1.2472 | 19.6475 | 0.3001 | 0.7086 | 0.6534 | 0.2601 |
| δ_2 based POD controller | 8.4403 | 13.4196 | 5.2152 | 7.0487 | 1.1988 | 1.6103 | 1.4488 | 0.9877 |
| No POD controller (only PSS3B) | 8.0120 | 11.2015 | 4.5261 | - | 1.0012 | 1.2350 | - | - |
**Case 1. No POD controller and No PSS3B**

In this case of simulation, power system under study linearized around operating point $P_e = 0.8$ p.u. eigenvalues for the power system at this operating point are shown in Table 2. The system contains a pair of complex eigenvalues having low damping ratio 0.0086. In the following cases performance of various control methods on damping all oscillations is evaluated.

**Case 2. Only PSS3B**

The system eigenvalues in the presence of the PSS3B power system stabilizer is shown in Table 3. As shown in Table 3 the minimum complex eigenvalue pair’s damping ratio has increased to approximately 0.1593. Response of the system to step change in mechanical torque shown in Figure 5.

**Case 3. PSS3B and POD controller $m_1$**

The system eigenvalues in the presence of coordinated tuned PSS3B and $m_1$ based POD controller is shown in Table 4. As shown in Table 4 the minimum complex eigenvalue pair’s damping ratio has increased to approximately 0.1797. Response of the system to step change in mechanical torque shown in Figure 6.
Figure 5: Response of the system to step change in mechanical torque in operating point $P_e=0.8$ pu. With PSS3B only. (a): Rotor speed deviation, (b): Electrical power deviation. Red-dotted: No PSS3B and No POD, Blue-dashed: PSS3B and No POD.

Table 4: Eigenvalues of the linearized SMIB at operating point $P_e=0.8$ pu, with PSS3B and $m_1$ POD

<table>
<thead>
<tr>
<th>Eigenvalues</th>
<th>Damping Ratio</th>
<th>Frequency</th>
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</thead>
<tbody>
<tr>
<td>$-124.45$</td>
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<td>0</td>
</tr>
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<tr>
<td>$-0.1040$</td>
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<td>0</td>
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</table>

Figure 6: Response of the system to step change in mechanical torque in operating point $P_e=0.8$ pu. With PSS3B and $m_1$ POD controller. (a): Rotor speed deviation, (b): Electrical power deviation. Red-dotted: No PSS3B and No POD, Blue-dashed: PSS3B and No POD, Black-solid: PSS3B and POD.
Case 4. PSS3B and POD controller $\delta_1$

The system eigenvalues in the presence of coordinated tuned PSS3B and $\delta_1$ based POD controller is shown in Table 5. As shown in Table 5 the minimum complex eigenvalue pair’s damping ratio has increased to approximately 0.2123 but the other mode’s damping have decreased. Response of the system to step change in mechanical torque shown in Figure 7.

<table>
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<td>-1.0222</td>
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<td>0</td>
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</table>

Figure 7: Response of the system to step change in mechanical torque in operating point $P_e=0.8$ pu. With PSS3B and $\delta_1$ POD controller. (a): Rotor speed deviation, (b): Electrical power deviation. Red-dotted: No PSS3B and No POD, Blue-dashed: PSS3B and No POD, Black-solid: PSS3B and POD.

Case 5. PSS3B and POD controller $m_2$

The system eigenvalues in the presence of coordinated tuned PSS3B and $m_2$ based POD controller is shown in Table 6. As shown in Table 6 the minimum complex eigenvalue pair’s damping ratio has increased to approximately 0.1327 and the other mode’s damping ratio have increased well. Response of the system to step change in mechanical torque shown in Figure 8.
Table 6: Eigenvalues of the linearized SMIB at operating point $P_e = 0.8$ pu, with PSS3B and $m_2$ POD controller

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<th>Eigenvalues</th>
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Figure 8: Response of the system to step change in mechanical torque in operating point $P_e=0.8$ pu. With PSS3B and $m_2$ POD controller. (a): Rotor speed deviation, (b): Electrical power deviation. Red-dotted: No PSS3B and No POD, Blue-dashed: PSS3B and No POD, Black-solid: PSS3B and POD.

Case 6. PSS3B and POD controller $\delta_2$

The system eigenvalues in the presence of coordinated tuned PSS3B and $\delta_2$ based POD controller is shown in Table 7. As shown in Table 7 the minimum complex eigenvalue pair’s damping ratio has increased to approximately 0.1504. Response of the system to step change in mechanical torque shown in Figure 9. Based on simulation results $\delta_2$ based POD controller is not suitable to be tuned coordinated with PSS3B. Whereas $m_2$ based POD controller prove to be suitable in order to tune coordinated with PSS3B to damp power system oscillations.
Table 7: Eigenvalues of the linearized SMIB at operating point $P_e = 0.8$ pu, with PSS3B and $\delta_2$ POD controller

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Figure 9: Response of the system to step change in mechanical torque in operating point $P_e=0.8$ pu. With PSS3B and $\delta_2$ POD controller. (a): Rotor speed deviation, (b): Electrical power deviation. Red-dotted: No PSS3B and No POD, Blue-dashed: PSS3B and No POD, Black-solid: PSS3B and POD.

Conclusion

In this paper, coordinated tuning of PSS3B with IPFC in single machine infinite bus power system is proposed. The damping controllers considering the various control signals of the IPFC designed based on linearized model. Optimal tuning of the controllers formulated as an optimization problem and solved using krill herd optimization algorithm. The eigenvalues analysis and response of the system to step change in mechanical torque used to demonstrate the effectiveness of the proposed method. Studies reveal that the most effective input signal of IPFC utilized for damping the low frequency oscillation coordinated with PSS3B is found to be the input signal $m_2$, providing robust performance under different operation conditions. Whereas the control signal $\delta_1$ is inefficient in providing the damping coordinated with PSS3B.
References


