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Design of a Damping Controller Using a Metaheuristic Algorithm for Angle Stability Improvement of an MIB System

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Abstract: Low frequency oscillations in large power systems may result in system instability under large disturbances. Power system stabilisers (PSS) play an effective role in damping these low frequency oscillations by injecting a modulating signal in the excitation loop of a synchronous machine. A new metaheuristic optimisation algorithm termed the sine cosine algorithm (SCA) was proposed for optimising PSS controller parameters to obtain an optimal solution with the damping ratio as an objective function. The SCA technique was examined on a single machine infinite bus (SMIB) system under distinct loading situations and matched with a moth flame optimisation technique and evolutionary programming to design a robust controller of PSS. The simulation was accomplished using a linearised mathematical model of the SMIB. The performance of a designed lead lag-controller of PSS was demonstrated using eigenvalue analysis with simulations, showing promising results. The dynamic performance was validated with respect to the damping ratio, the eigenvalue's location in the s-plane and rotor angle deviation response to demonstrate system stability.

Keywords: low frequency oscillation; damping controller; objective function; metaheuristic optimization techniques; power system stabilizer; eigenvalues; single machine infinite bus system



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1. Introduction

In recent years, significant efforts have been undertaken to improve the dynamic stability of electrical power systems. A stable electrical power system operates in equilibrium and is disturbed by load variations and power generation, especially with regard to the power injection from renewable energy systems. A large, interconnected power system needs to remain in an equilibrium state, but with the different rotor angles of a machine. This equilibrium ensures the stability of a power system within a safety margin of the system's operation by damping low frequency oscillations. These low frequency oscillations are related to a group of synchronous generators or a set of electrical power generating plants. However, the electrical torque of a machine has two components, namely, the synchronising and damping components. The damping component plays an important role in the angle stability of a power system by damping low frequency oscillations using excitation and prime mover control, whilst the synchronising torque keeps the machine in synchronism [1–4].

High gains may produce a negative damping torque and a fast response time in the machine due to the poor damping response of the automatic voltage regulator (AVR) of an excitation control system. Meanwhile, a power system stabiliser (PSS) is coordinated with the AVR of the excitation control system to damp the low frequency oscillations towards the improvement of power system stability. PSS injects a signal in the excitation system, in addition to the AVR signal, to increase the machine damping torque. This phenomenon results in the damping of low frequency oscillations in the system. PSS intensifies the level

of angle stability, transmission line power carrying capacity, and load equipment efficiency. The input to PSS is either the rotor speed or frequency, or power, or a combination of the two. The damping and synchronising performance of the synchronous generator excitation system depends on the selection and proper tuning of the parameters of the PSS and AVR controllers. The design of the PSS controller parameters requires the finding of the objective function with a linearised model and the use of suitable metaheuristic optimisation techniques. Metaheuristic optimisation techniques are used to optimise the controller's parameters by finding the maximum or minimum value of an objective function, which are some of the accomplished targets in this work [1,4].

Proper modelling of a system and damping controller devices are required to damp oscillations and improve and maintain the angle stability of a power system. Different schemes, such as PSS, flexible alternating current transmission system (FACTS), and coordination control, have been used for damping. The PSS lead lag controller, with the excitation system of the machine, controls the output power by delivering the supplementary synchronising torque, which is in phase with speed eccentricity to damp the required low frequency oscillations and improve power system stability [1,4]. PSS is the preferred method for improving power system stability by damping low frequency oscillations [5,6]; its design for multimachine by using local measurements [7]; and for the tuning of its parameters by combining transfer function–eigenfunction [8]. Different types of FACTS devices—shunt, series, shunt-series and series-series—have been used to damp low frequency oscillations in power systems through an appropriate design of controllers by inserting or absorbing reactive power. FACTS shunt devices, namely, static VAR compensators (SVC) [9,10] and static synchronous compensators (STATCOM), are used for damping low frequency oscillations and to increase angle stability [9,11]. The literature also includes a damping performance analysis [12], a dynamic control strategy to improve the power flow capabilities [13], and an enhancement of low voltage ride-through capability in power systems [14]. In coordination control, the use of PSS and FACTS devices with effective coordination amongst controllers is combined to damp both types of low frequency oscillations in an electrical power system: namely, local and inter modes. The coordination control design for SVC, STATCOM, thyristor-controlled series capacitor (TCSC) and PSS [11,12,15,16] and of PSS and series capacitive reactance compensators (SCRC) and TCSC are used to enhance damping [15,17]. Furthermore, STATCOM and static synchronous series compensator (SSSC) are coordinated with PSS-STATCOM, PSS-SSSC and unified power flow controllers (UPFC), and UPFC with PSS [18–21].

Optimisation techniques have been used to compute the appropriate parameters of PSS and FACTS-based controllers. The controller parameters are modified by optimisation techniques, such as conventional, deterministic, heuristic, and hybrid types. The heuristic technique solves optimisation difficulties using stochastic methods, and its improved techniques are known as metaheuristic algorithms. Numerous metaheuristic optimisation methods have been used to tune the parameters of controllers of PSS and FACTS devices [4]. Sequential Quadratic Programming [8] and Genetic Algorithms (GA) are used to design a robust PSS and a coordinated PSS with UPFC [22–24]. The particle swarm optimisation (PSO) algorithm was also presented to design a damping controller [5,25–27] with cuckoo, coyote optimisation and BAT optimisation algorithms [10,28–31]. The Firefly optimisation algorithm was used to design the SVC damping controller [32,33]. Various heuristic algorithms for optimisation use stochastic methods that have deficiencies in solution convergence. Tabu search (TS) has poor global search efficiency, and simulated annealing (SA) has limitations in practical applications. TS, GA, SA and PSO have deficiencies in convergence rates, that is, a local minimum stagnation problem. Several proposed methods provide good exploration in the search space but have limitations in exploitation, or vice versa [4]. The main advantage of the sine cosine algorithm (SCA) is that it allows both exploration and exploitation in the search space, that is, for the first and second halves of the iterations, respectively.

$$\Delta\dot{\psi}_{1d} = A42\Delta\delta + A43\Delta\psi_{fd} + A44\Delta\psi_{1d} + A45\Delta\psi_{1q} + A46\Delta\psi_{2q}, \quad (4)$$

$$\Delta\dot{\psi}_{1q} = A52\Delta\delta + A53\Delta\psi_{fd} + A54\Delta\psi_{1d} + A55\Delta\psi_{1q} + A56\Delta\psi_{2q}, \quad (5)$$

$$\Delta\dot{\psi}_{2q} = A62\Delta\delta + A63\Delta\psi_{fd} + A64\Delta\psi_{1d} + A65\Delta\psi_{1q} + A66\Delta\psi_{2q}, \quad (6)$$

where H refers to the constant of inertia; δ and ω express the rotor angle and speed, respectively; ψ_{fd} denotes the machine field flux; ψ_{1d} refers to the machine flux of the d -axis shock absorber; ψ_{1q} refers to the flux of the q -axis 1st shock absorber; and ψ_{2q} refers to flux of the q -axis 2nd shock absorber; K_D refers to the damping torque coefficient; K_1 and K_2 express the synchronising torque component and torque component resulting from variation in the main field flux linkage, respectively; K_{21} , K_{22} and K_{23} express the torque components resulting from the variation in the flux linkage of the d -axis shock absorber, flux linkage of the q -axis 1st shock absorber and flux linkage of the q -axis 2nd shock absorber, respectively.

The PSS lead lag controller structure contains a washout block with time constant T_W to reduce exaggeration of damping during critical circumstances, as shown in Figure 2. Constants T_1 and T_2 are used for phase compensation and gain constant K_{stb} to provide the required damping over the range of frequencies of low frequency oscillations. PSS gives a supplementary signal to the AVR that produce electrical torque in the direction of the speed deviation of the rotor. Phase compensation supports a phase offset in the phase lag between the exciter input and the electrical output. The input signal to PSS is the rotor speed, electrical power generated in the machine or a combination of these.

$$\Delta\dot{v}_1 = \frac{K_5}{T_R}\Delta\delta + \frac{K_6}{T_R}\Delta\psi_{fd} + \frac{K_{61}}{T_R}\Delta\psi_{1d} + \frac{K_{62}}{T_R}\Delta\psi_{1q} + \frac{K_{63}}{T_R}\Delta\psi_{2q} - \frac{1}{T_R}\Delta v_1 \quad (7)$$

$$\Delta\dot{v}_2 = K_{stb}(\Delta\dot{\omega}_r) - \frac{1}{T_W}\Delta v_2 \quad (8)$$

$$\Delta\dot{v}_s = \frac{T_1}{T_2}(\Delta\dot{v}_2) + \frac{1}{T_2}\Delta v_2 - \frac{1}{T_2}\Delta v_s \quad (9)$$

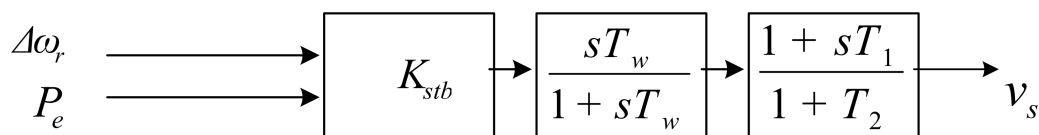


Figure 2. Block diagram of the PSS.

The system in Figures 1 and 2 expressed by a linearised state space mathematical model is represented as follows:

$$\dot{X} = aX + bU, \quad (10)$$

$$\dot{X} = [\Delta\dot{\omega}_r \ \Delta\dot{\delta} \ \Delta\dot{\psi}_{fd} \ \Delta\dot{\psi}_{1d} \ \Delta\dot{\psi}_{1q} \ \Delta\dot{\psi}_{2q} \ \Delta\dot{v}_1 \ \Delta\dot{v}_2 \ \Delta\dot{v}_s], \quad (11)$$

$$X = [\Delta\omega_r \ \Delta\delta \ \Delta\psi_{fd} \ \Delta\psi_{1d} \ \Delta\psi_{1q} \ \Delta\psi_{2q} \ \Delta v_1 \ \Delta v_2 \ \Delta v_s], \quad (12)$$

$$a = \begin{bmatrix} -\frac{K_D}{2\pi f_0} & -\frac{K_1}{2H} & -\frac{K_2}{2H} & -\frac{K_{21}}{2H} & -\frac{K_{22}}{2H} & -\frac{K_{23}}{2H} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & A_{32} & A_{33} & A_{34} & A_{35} & A_{36} & 0 & 0 & 0 \\ 0 & A_{42} & A_{43} & A_{44} & A_{45} & A_{46} & 0 & 0 & 0 \\ 0 & A_{52} & A_{53} & A_{54} & A_{55} & A_{56} & 0 & 0 & 0 \\ 0 & A_{62} & A_{63} & A_{64} & A_{65} & A_{66} & 0 & 0 & 0 \\ 0 & \frac{K_5}{T_R} & \frac{K_6}{T_R} & \frac{K_{61}}{T_R} & \frac{K_{62}}{T_R} & \frac{K_{63}}{T_R} & -\frac{1}{T_R} & 0 & 0 \\ A_{81} & A_{82} & A_{83} & A_{84} & A_{85} & A_{86} & 0 & -\frac{1}{T_W} & 0 \\ A_{91} & A_{92} & A_{93} & A_{94} & A_{95} & A_{96} & 0 & -\frac{T_1}{T_W} \frac{1}{T_2} + 1 & -\frac{1}{T_2} \end{bmatrix} \quad (13)$$

$$b = \begin{bmatrix} \frac{1}{2 \cdot H} & 0 \\ 0 & 0 \\ 0 & \frac{\omega_0 R_{fd}}{l_{adu}} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ \frac{K_{stb}}{2 \cdot H} & 0 \\ \frac{K_{stb}}{2 \cdot H} \cdot \frac{T_1}{T_2} & 0 \end{bmatrix} \quad (14)$$

$$U = \begin{bmatrix} \Delta T_m \\ \Delta E_{fd} \end{bmatrix} \quad (15)$$

$$A_{32} = -\frac{\omega_0 R_{fd} m_1 \dot{l}_{ads}}{l_{fd}}, \quad (16)$$

$$A_{33} = -\frac{\omega_0 R_{fd}}{l_{fd}} \left(1 - \frac{\dot{l}_{ads}}{l_{fd}} + m_2 \ddot{l}_{ads} \right), \quad (17)$$

$$A_{34} = -\frac{\omega_0 R_{fd}}{l_{fd}} \left(-\frac{\dot{l}_{ads}}{l_{fd}} + m_3 \ddot{l}_{ads} \right), \quad (18)$$

$$A_{35} = -\frac{\omega_0 R_{fd} m_4 \ddot{l}_{ads}}{l_{fd}}, \quad (19)$$

$$A_{36} = -\frac{\omega_0 R_{fd} m_5 \ddot{l}_{ads}}{l_{fd}}, \quad (20)$$

$$A_{42} = -\frac{\omega_0 R_{1d} m_1 \ddot{l}_{ads}}{l_{1d}}, \quad (21)$$

$$A_{43} = -\frac{\omega_0 R_{1d} \ddot{l}_{ads}}{l_{1d}} \left(m_2 - \frac{1}{l_{fd}} \right), \quad (22)$$

$$A_{44} = -\frac{\omega_0 R_{1d}}{l_{1d}} \left(\ddot{l}_{ads} m_3 - \frac{\ddot{l}_{ads}}{l_{1d}} + 1 \right), \quad (23)$$

$$A_{45} = -\frac{\omega_0 R_{1d} m_4 \ddot{l}_{ads}}{l_{1d}}, \quad (24)$$

$$A_{46} = -\frac{\omega_0 R_{1d} m_5 \ddot{l}_{ads}}{l_{1d}}, \quad (25)$$

$$A52 = -\frac{\omega_o R_{1q} n_1 \ddot{l}_{aqs}}{l_{1q}}, \quad (26)$$

$$A53 = -\frac{\omega_o R_{1q} n_2 \ddot{l}_{aqs}}{l_{1q}}, \quad (27)$$

$$A54 = -\frac{\omega_o R_{1q} n_3 \ddot{l}_{aqs}}{l_{1q}}, \quad (28)$$

$$A55 = -\frac{\omega_o R_{1q}}{l_{1q}} \left(1 - \frac{\ddot{l}_{aqs}}{l_{1d}} + n_4 \right), \quad (29)$$

$$A55 = -\frac{\omega_o R_{1q}}{l_{1q}} \left(1 - \frac{\ddot{l}_{aqs}}{l_{1d}} + n_4 \right), \quad (30)$$

$$A62 = -\frac{\omega_o R_{2q} n_1 \ddot{l}_{aqs}}{l_{2q}}, \quad (31)$$

$$A63 = -\frac{\omega_o R_{2q} n_2 \ddot{l}_{aqs}}{l_{2q}}, \quad (32)$$

$$A64 = -\frac{\omega_o R_{2q} n_3 \ddot{l}_{aqs}}{l_{2q}}, \quad (33)$$

$$A65 = -\frac{\omega_o R_{2q} \ddot{l}_{aqs}}{l_{2q}} \left(n_4 - \frac{1}{l_{1q}} \right) \quad (34)$$

$$A66 = -\frac{\omega_o R_{2q}}{l_{2q}} \left(\ddot{l}_{aqs} n_5 - \frac{\ddot{l}_{aqs}}{l_{2q}} + 1 \right), \quad (35)$$

$$A81 = -\frac{K_D}{2H} K_{stb}, \quad (36)$$

$$A82 = -\frac{K_1}{2H} K_{stb}, \quad (37)$$

$$A83 = -\frac{K_2}{2H} K_{stb}, \quad (38)$$

$$A84 = -\frac{K_{stb} K_{21}}{2H}, \quad (39)$$

$$A85 = -\frac{K_{stb} K_{22}}{2H}, \quad (40)$$

$$A86 = -\frac{K_{stb} K_{23}}{2H}, \quad (41)$$

$$A91 = -\frac{K_{stb} K_D T_1}{2 \cdot H \cdot T_2}, \quad (42)$$

$$A92 = -\frac{K_{stb} K_1 T_1}{2 \cdot H \cdot T_2}, \quad (43)$$

$$A93 = -\frac{K_{stb} K_2 T_1}{2 \cdot H \cdot T_2}, \quad (44)$$

$$A94 = -\frac{K_{stb} K_{21} T_1}{2 \cdot H \cdot T_2}, \quad (45)$$

$$A95 = -\frac{K_{stb} K_{22} T_1}{2 \cdot H \cdot T_2}, \quad (46)$$

$$A96 = -\frac{K_{stb}K_{23}T_1}{2 \cdot H \cdot T_2}, \quad (47)$$

where $K_1, K_2, K_{21}, K_{22}, K_{23}, K_3, K_4, K_5, K_6, K_{61}, K_{62}$ and K_{63} are DeMello–Concordia constants used for designing an excitation system with a lead lag controller of PSS of the SMIB system; $l_{adu}, R_{fd}, l_{fd}, \hat{l}_{ads}$ and $\ddot{l}_{ads}$ are the unsaturated mutual inductance between the rotor and the stator in a d -axis, rotor field resistance, mutual inductance between the stator and the rotor in the d -axis, saturated transient mutual inductance in the d -axis and saturated sub-transient mutual inductance in the d -axis, respectively; R_{1d}, R_{1q} and R_{2q} are the resistance of the d -axis shock absorber, q -axis 1st shock absorber and q -axis 2nd shock absorber, respectively; l_{1d}, l_{1q} and l_{2q} are the mutual inductances of the d -axis shock absorber, q -axis 1st shock absorber and q -axis 2nd shock absorber, respectively; $\hat{l}_{aqs}$ and $\ddot{l}_{aqs}$ are the saturated transient and sub-transient mutual inductances in the q -axis, respectively. A comprehensive calculation of the SMIB system shown in Figures 1 and 2 and all parameter values for a synchronous generator, transmission lines and an exciter with PSS and AVR can be found in references [34,35].

3. Objective Function to Tune the PSS Parameters

To optimise the PSS parameters, the angle stability of the system was calculated by eigenvalue analysis, whilst a single objective function was considered based on the minimisation of the real part of eigenvalues. The eigenvalue having a bigger real value ensures better system stability. The eigenvalues can be taken from matrix (A) of the system of the linearised state space mathematical model with the command in MATLAB.

$$\lambda_k = \text{eig}(A), \quad (48)$$

where $k = 1, 2, 3 \dots n$; n shows the number of state variables in the given system and number of eigenvalues; $\text{eig}()$ refers to the built-in function of MATLAB. An objective function is formulated to maximise the damping ratio to shift the eigenvalues towards a real axis to minimise the amplitude of oscillations, as shown in Figure 3:

$$\text{Maximisation } f = \min(\xi_{ij}), \quad (49)$$

$$\xi_i = \frac{\sigma_i}{\sqrt{\sigma_i^2 + \omega_i^2}},$$

where σ_i is the real part, and ω_i is the imaginary part of the system eigenvalues.

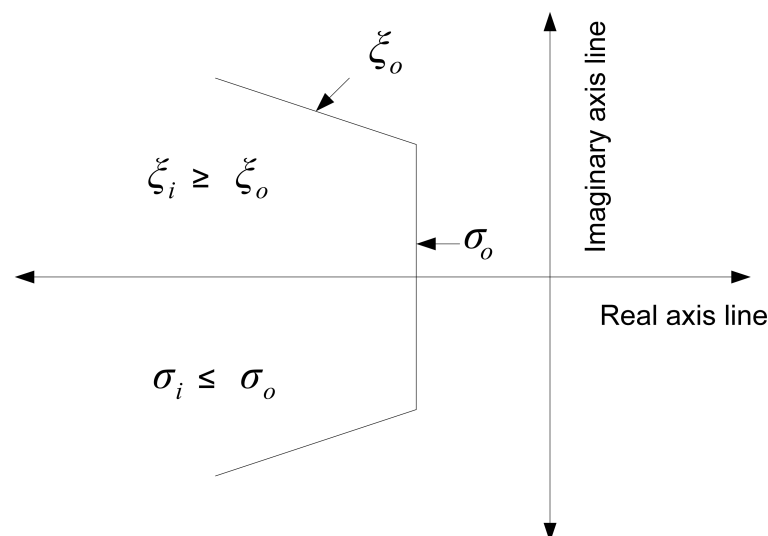


Figure 3. Eigenvalue's locations on the s-plane.

The T_1 , T_2 and K_{stb} parameters of the lead lag controller are required when optimising a subject to the following conditions.

$$\begin{aligned} T_{1, \min} &\leq T_1 \leq T_{1, \max}, \\ T_{2, \min} &\leq T_2 \leq T_{2, \max}, \\ K_{stb, \min} &\leq K_{stb} \leq K_{stb, \max}. \end{aligned}$$

4. SCA

Optimisation is a process or mathematical procedure of obtaining the best values of the parameters of a system in the search space. SCA is a population-based algorithm that starts with a set of random solutions, stochastically searches optima and works in two phases: exploration and exploitation. In the exploration phase, the algorithm finds promising areas in the search space by producing a set of results that contain random outcomes unexpectedly with high-rate randomness. In the exploitation phase, the algorithm mostly emphasises the gradual changes in random solutions [36]. The following equation represents the changing positions for both phases:

$$X_{i,j}^{t+1} = X_{i,t} + r_1^t \times \sin r_{2,j} \times |r_{3,j} Q_{d,j}^t - X_{i,j}^t|, \quad (50)$$

$$X_{i,j}^{t+1} = X_{j,t} + r_1^t \times \cos r_{2,j} \times |r_{3,j} Q_{d,j}^t - X_{i,j}^t|, \quad (51)$$

$$X_{i,j}^{t+1} = \begin{cases} X_{i,t} + r_1^t \times \sin r_{2,j} \times |r_{3,j} Q_{d,j}^t - X_{i,j}^t|, & r_{4,j} < 0.5 \\ X_{j,t} + r_1^t \times \cos r_{2,j} \times |r_{3,j} Q_{d,j}^t - X_{i,j}^t|, & r_{4,j} \geq 0.5 \end{cases}, \quad (52)$$

where $Q_{d,j}^t$ is the position of destination in the j th dimension, $X_{i,t}$ is the current solution at the t th iteration, r_1^t is a random number that determines the region of position, $r_{2,j}$ is a random number that defines the direction outwards or towards the station point, $r_{3,j}$ is the random number importance at the station, $r_{4,j}$ a random number ranging from zero to one, and $||$ shows an absolute value. To obtain a favourable region in a given domain and converge it to the universal optima, the SCA algorithm provides a balance during exploitation and exploration by changing the sine and cosine ranges using Equation (53), which is expressed as follows:

$$r_1^t = a - t \frac{a}{T}, \quad (53)$$

where t is the current iteration, a is a constant number, and T is the maximum number of iterations. The effects of sine and cosine on Equations (50) and (51) are two-dimensionally demonstrated in Figure 4 and can be extended to higher dimensions. These equations describe a domain between two results in a given search domain, and their patterns allow a solution to reposition and ensure exploitation of a region between two results. The optimisation technique should search outside the space that has subsequent destinations to control the exploration in a given search domain. The achieved changing amplitude range of cosine sine functions is shown Figure 5. Random number $r_{2,j}$ that has a range in $(0, 2\pi)$ decides whether the place is outside or inside. The pseudocode of the SCA algorithm is presented in Table 1.

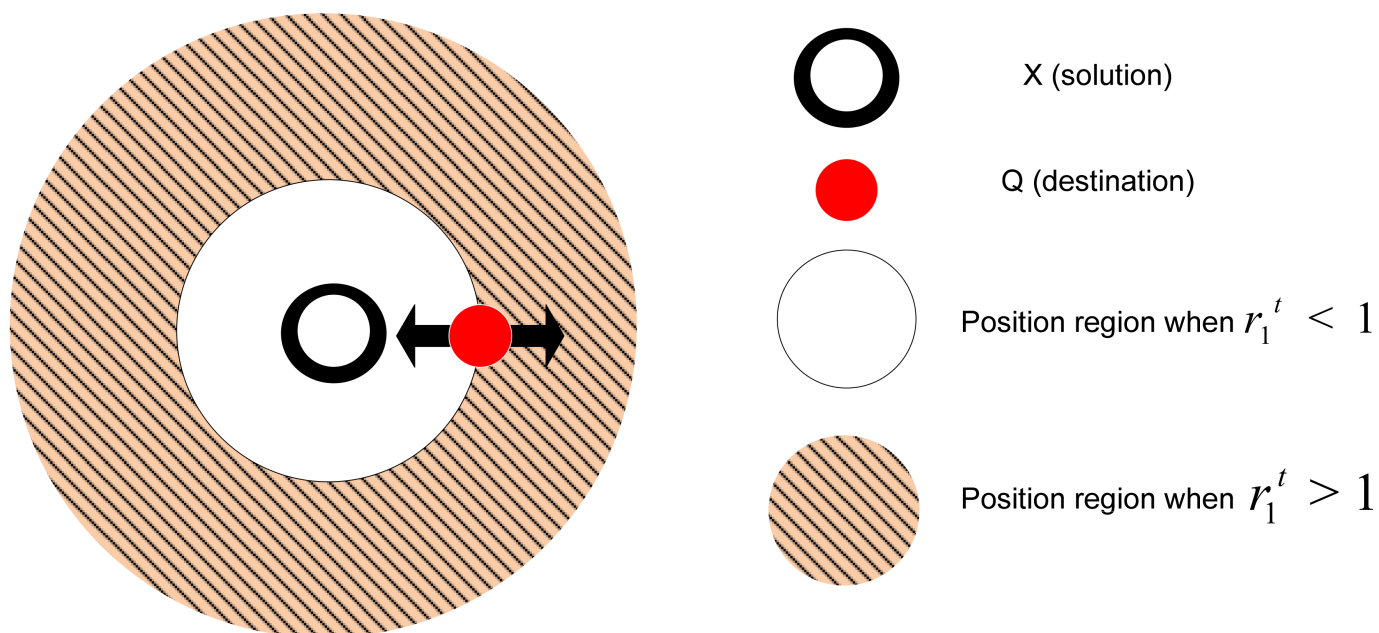


Figure 4. Effects of sine cosine in Equations (50) and (51) on the upcoming locality.

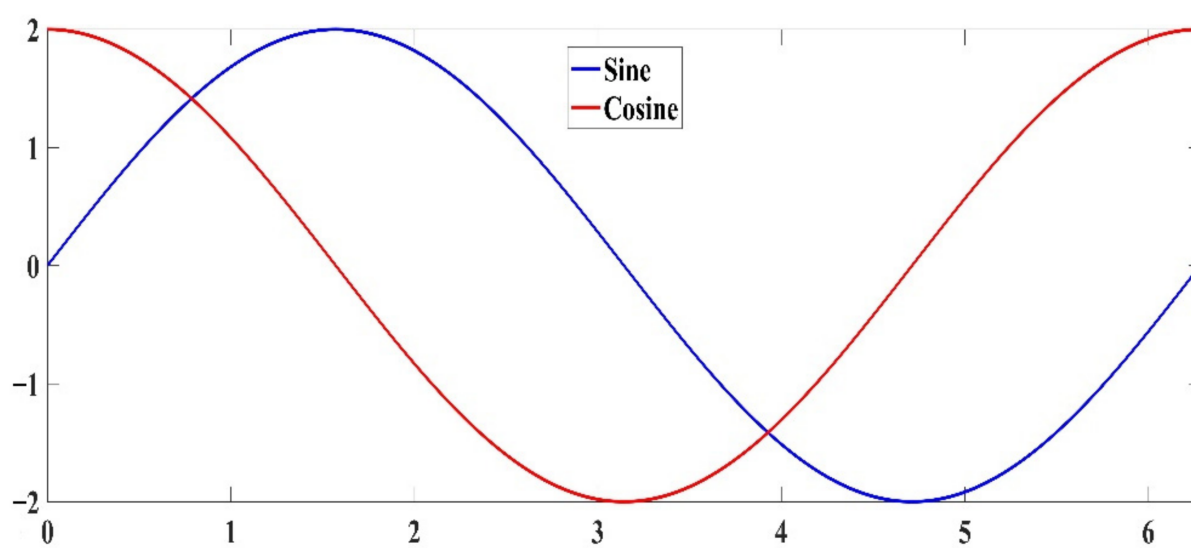


Figure 5. Cosine and sine with an amplitude scale of $(-2, 2)$ and period range of $\{0, 2\pi (6.283185)\}$.

Table 1. Pseudocode of SCA.

SCA Pseudocode
<pre> Initialise the population for i = 1:size(X,1) Objective values(1,i) = fobj(X(i,:)); if i == 1 Destination position = X(i,:); Destination fitness = Objective values(1,i); elseif Objective values(1,i) < Destination fitness Destination position = X(i,:); Destination fitness = Objective values(1,i); end if All objective values(1,i) = Objective values(1,i); end for whilst iteration maximum iterations do r1 = a - t*(a)/max_iteration) calculate the number using Equation () for i = 1 to n do for j = 1 to n do r2 = 2 * pi * rand() r3 = 2 * (rand()) r4 = rand() Update r2, r3 and r4 for Equation () end for if r4 < 0.5 % Equatoin () X(i,j) = X(i,j) + (r1 * sin(r2) * abs(r3 * Destination position(j) - X(i,j))); else % Equation () X(i,j) = X(i,j) + (r1 * cos(r2) * abs(r3 * Destination position(j) - X(i,j))); if Objective values(1,i) < Destination fitness Destination position = X(i,:); Destination fitness = Objective values(1,i); end if end if end for Convergence curve(t) = Destination fitness; if mod(t,50) == 0 display(['At iteration', num2str(t), 'the optimum is', num2str(Destination fitness)]); end show the best amongst solutions end whilst </pre>

5. Moth Flame Optimisation (MFO) Algorithm

The MFO algorithm is a population-based metaheuristic algorithm developed by Mirjalli [37]. MFO initially randomly generates moths in a given search space, calculates the fitness position of each moth and tags the best value by flame. MFO updates the moth's positions by using the three functions to converge global optima as follows:

$$MFO = (I, P, T), \quad (54)$$

$$N(i, j) = (ub(i) - lb(j)) \times rand() + lb(i), \quad (55)$$

$$S(N_i, F_j) = G_i \cdot e^{dt} \cdot \cos(2\pi t) + F_j, \quad (56)$$

where I denotes the early positions of moths in a given search domain; T represents the concluding process of search; P shows the moth's motion in a given search space; lb and ub are the lower and upper bounds, respectively; t denotes a real number having values between -1 and 1 ; d refers to the spiral shape of the path of a moth; and G_i represents the

displacement between the j th flame and the i th moth. MFO updates the number of flames to emphasise the exploitation process by reducing the flame number. The logarithmic spiral equation ensures the exploitation and exploration processes to find the moth position near the flame in a given search domain.

$$\text{Flame no} = \text{round} \left(n - l \frac{n-l}{t} \right), \quad (57)$$

where t represents the total number of iterations, l shows the present iteration number, and n refers to the total number of flames. The pseudocode of the MFO algorithm is given in Table 2.

Table 2. Pseudocode of MFO.

MFO Algorithm Pseudocode
Randomly initialise the population for the moth flame by moth position N_i for $i = 1$ to n do calculate fitness function f_i end for whilst iteration maximum iterations do reform the location of N_i calculate the number of flames using Equation () weigh up f_i , the fitness function f_i if iteration == 1 next $F = \text{rank}(N)$ and $OF = \text{rank}(ON)$ else $F = \text{rank}(Nt - 1, Nt)$ and $OF = \text{rank}(ONt - 1, ONt)$ end if for $i = 1$ to n do for $j = 1$ to n do reform the values of t and r determine the value of G using Equation () update $N(i,j)$ to its moth using Equation () end for end for end whilst show the best amongst solutions P

6. Evolutionary Programming Algorithm

The EP algorithm is a heuristic technique constructed using a natural process to obtain the best solution in the search space (i.e., biological evolution and population, both for random and selection). This algorithm mainly has six steps, as follows: initialisation by creation of random results; a Gaussian random variable is used for the mutation process; statistics obtained by calculating the high, low and average values of a fitness function; updating of the optimum result and combinations; selection of the maximum value of the fitness function for the next iteration; and closing of the programme after the set criteria are reached. The standard deviation in the offspring is expressed as follows:

$$\sigma_k = \beta \cdot \frac{J(x_l)}{J_{max}} (p_k^{max} - p_k^{min}), \quad (58)$$

where x_l is the trial solution of fitness equation $J(x_l)$, and β is a search factor. The offspring x_{l+n} can be defined as follows:

$$x_{l+n} = x_l + \left\{ N \left(0, \sigma_1^2, \dots, N \left(0, \sigma_m^2 \right) \right\}, \quad (59)$$

where $l = 1, \dots, n$.

The pseudocode of the EP algorithm is presented in Table 3 [31].

Table 3. Pseudocode of EP.

Evolutionary Programming Algorithm Pseudocode
Initialise the population for $i = 1$ to n do //parents// for $j = 1$ to K populations do describe $x_{j,par}(i)$ and $J(x_{j,par}(i))$ end for //offspring// for $j = 1$ to N populations do $x_{j,off}(i) = \alpha \times (x_{j,par}(i)_{max} - x_{j,par}(i)_{max}) \times \frac{x_{j,par}(i)}{x_{j,par}(i)_{max}}$ Calculate $x_{j,off}(i)$ end for merge both offspring and parents sort $x(i)$ in descending arrangement of $J(x(i))$ pick best one-half $x(i)$ value, the same as brand-new $x_{j,par}(i)$ if $ J(x(i)_{max}) - J(x(i)_{min}) < 10^{-4}$ then end if $i = i + 1$ end for

7. Advantages of SCA over MFO and EP

A balance in the exploration and exploitation processes is required to obtain an optimum solution for a damping controller. Various metaheuristic algorithms for optimisation have used stochastic methods that have deficiencies in solution convergence. Several proposed methods provide good exploration in a search space but are limited in exploitation, or vice versa.

Metaheuristic optimisation techniques are used to find the maxima or minima. These techniques are either swarm-based or evolution-based algorithms. Swarm-based algorithms include PSO, firefly algorithm, ant colony algorithm, gravitational search algorithm (GSA) and immune algorithm (IA). Evolution-based algorithms include evolutionary programming differential algorithm, EP, and GA. GA and PSO have the limitation of premature convergence due to the local minimum stagnation problem. GSA has the limitation in solving complex optimisation problems. IA works better during the exploration process than in the exploitation process to find optimal solutions for a damping controller. EP works better in the exploitation process than in the exploration process. Some other optimisation techniques, such as TS and SA optimisation techniques, have slow convergence rates and are incapable of solving multimodal problems [4].

The advantage of the SCA over other algorithms is that it allows exploration and exploitation in a search space, that is, for the first and second halves of the iterations, respectively. The main advantage of the SCA optimisation technique is that it shows better results in the exploration and exploitation processes to find the maxima or minima in eigenvalue analysis. The proposed SCA was validated with MFO and EP techniques.

8. Results and Discussion

This work considers PSS, which was designed for the SMIB system, and three optimisation algorithms to perform the small signal stability analysis. Numerous operating loading conditions were considered to assess the angle stability analysis. Eigenvalues were obtained by using MATLAB software to gauge the system stability. A metaheuristic optimisation algorithm, namely, SCA, was considered to fine-tune the PSS parameters. The results were validated with MFO and EP optimisation algorithms. K_{stb} , T_1 and T_2 were the optimised enlisted parameters of a single lead lag compensator for the SMIB system. K_{stb} is gain constant, T_1 is the phase lead constant, and T_2 is the phase lag constant. The parameters for SMIB and PSS are presented in Table 4 [1,34]. A comparison amongst the SMIB with unoptimised PSS parameters, SMIB system with optimised PSS parameters

by SCA, SMIB system with optimised PSS parameters by MFO and SMIB system with optimised PSS parameters by EP were carried out with five loading conditions (Table 5).

Table 4. Parameters for the SMIB and PSS.

Modules	Parameters
Generator	$H = 3.50$, $E_t = 1.0 < 36^\circ$, $X_d' = 0.30$, $R_a = 0.0030$, $X_d = 1.810$, $X_q = 1.760$, $T_{do}' = 8$, $K_{sd} = 0.84910$, $K_{sq} = 0.84910$.
Power line	$X_e = 0.650$, $X_L = 0.160$, $R_e = 0.0$
AVR with PSS-LL controller	$T_R = 0.020$, $T_w = 1.40$, $K_A = 200.0$

Table 5. Different loading conditions.

Loading Conditions	Active Power, P (p. u)	Reactive Power, Q (p. u)
1	P = 0.9	Q = 0.2
2	P = 0.9	Q = 0.3
3	P = 0.9	Q = 0.4
4	P = 0.5	Q = 0.5
5	P = 0.2	Q = 0.7

Where T_w , K_A and T_R , denote the washout time constant of PSS, exciter gain constant and time constant, respectively; X_L , X_e and R_e represent load reactance, transmission line reactance and resistance, respectively; E_t denotes the machine terminal voltage; K_{sq} and K_{sd} refer to machine field torque coefficients in the q -axis and d -axis, respectively; X_q and X_d express the machine armature reactance in the q -axis and d -axis, respectively; and T_{do}' refers to the armature machine open circuit field time constant.

Optimisation algorithms SCA and MFO that used the following parameter range as stated in Table 6 were considered for fine-tuning PSS parameters: r_1 is the random number that determines the region of position, and its value reduces from 2 to 0 with the increase in iteration to the maximum number iteration; r_2 is a random number that defines the direction towards or outwards the destination point, and its value is in the range 0 to 2π ; r_3 is random number weight of the destination, and its value is in the range of 0 to 2; and r_4 is the random number that determines which equation (sine or cosine) of the algorithm is used in the current iteration. The value of parameter β of the EP algorithm for tuning of the PSS parameters is illustrated in Table 6.

Table 6. Parameters for optimisation techniques.

Optimisation Techniques	Parameters Range	Optimised PSS Parameter Range Limit
SCA	$r_1 = 2$ to 0, $r_2 = 0$ to 2π , $r_3 = 0$ to 2, $r_4 = 0$ to 1	$T_{1,min} = 0.001$, $T_{1,max} = 0.2$ $T_{2,min} = 0.001$, $T_{2,max} = 0.1$ $K_{stb,min} = 9$, $K_{stb,max} = 200$
MFO	$d = 0.00025$, $t = -1$ to 1	
EP	$\beta = 0.1$	

The work presents a performance analysis of three optimisation techniques to conduct the small signal stability analysis for the SMIB system. The PSS parameters were optimised by using different optimisation techniques, and eigenvalues related to electromechanical modes were obtained. The damping ratio was selected as an objective function. The damping ratio of loading condition 1 for SMIB was obtained, and is provided in Table 7. The region of eigenvalue locations in the s -plane and rotor angle deviation are shown in Figures 6 and 7, respectively. The proposed PSS-SCA technique provides better damping of angle deviation and location of eigenvalues compared with the other optimisation

methods. The location of eigenvalues in the proposed PSS-SCA algorithm provides more shift towards the real axis of the s-plane to limit the abrupt variation in the amplitude of angle deviation and increases the system stability by moving eigenvalues more to the left of an imaginary axis line. The PSS-SCA system required 46 iterations to converge to the maximum objective function having its exact optimisation parameter values $r_1 = 1.54$, $r_2 = 5.7675$, $r_3 = 1$ and $r_4 = 0.6481$ for loading condition 1 compared with the other methods of optimisation (Table 7). The PSS-MFO and PSS-EP systems take 103 and 19 iterations to converge on the results and have exact optimisation parameter values $d = 0.00025$, $t = -0.5556$ and $\beta = 0.1$. The PSS-EP system has a better convergence with minimum objective function value. The proposed technique offers better objective function with respect to the other two procedures and has satisfactory computational efficiency compared with the PSS-EP system.

Table 7. Comparison of the PSS optimised parameters, eigenvalues and damping ratio for loading condition 1 of the SMIB.

Methods	Loading Condition 1			
	PSS-SCA	PSS-MFO	PSS-EP	PSS-U
PSS optimised parameters	$T_1 = 0.03224$ $T_2 = 0.00179$ $K_{stb} = 31.75167$	$T_1 = 0.03739$ $T_2 = 0.0050$ $K_{stb} = 31.52837$	$T_1 = 0.06511$ $T_2 = 0.00142$ $K_{stb} = 35.44624$	$T_1 = 0.1$ $T_2 = 0.04$ $K_{stb} = 9$
Objective function	0.7420	0.7240	0.6770	0.1267
Number of iterations	46	103	19	NA

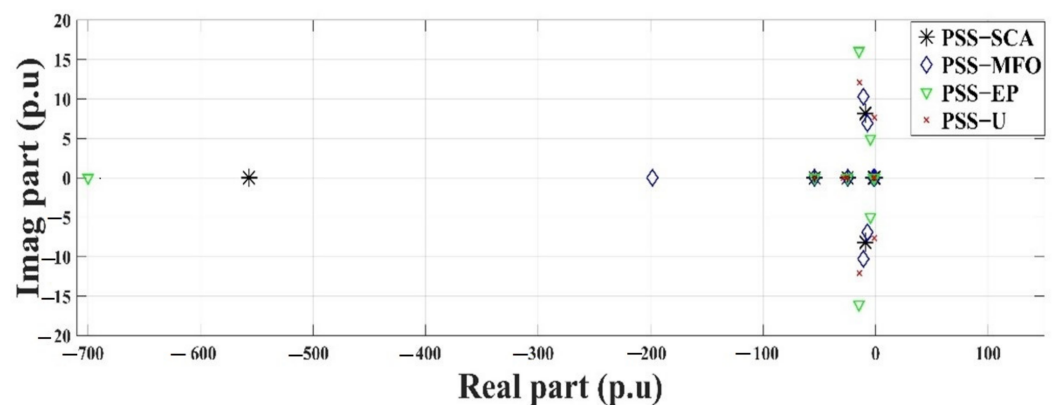


Figure 6. Eigenvalue's location on the complex s-plane for loading condition 1 of the SMIB with PSS.

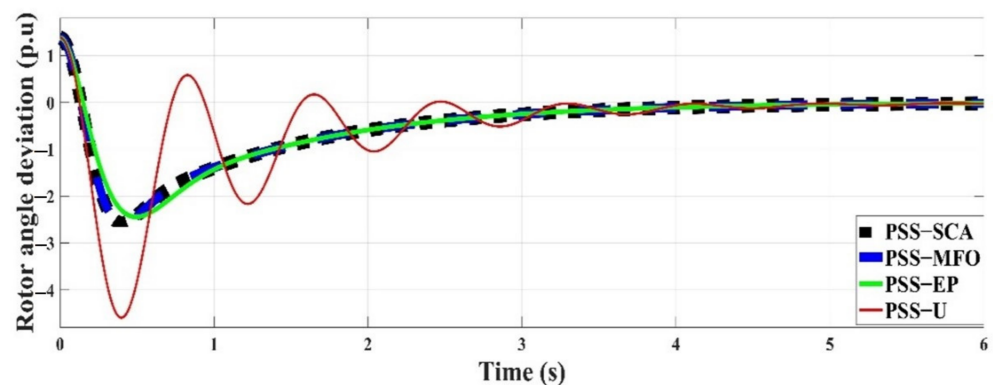


Figure 7. Rotor angle deviation for loading condition 1 of the SMIB with PSS.

The PSS parameters were optimised by using different optimisation techniques, and the eigenvalues related to the electromechanical modes were obtained. The damping

ratio as objective function and the damping ratio of loading condition 2 for the SMIB are provided in Table 8. The region of eigenvalue locations in the s-plane and rotor angle deviation are shown in Figures 8 and 9, respectively. The proposed PSS-SCA technique provides better damping of angle deviation and location of eigenvalues compared with other optimisation methods. In terms of the location of eigenvalues, the proposed PSS-SCA algorithm provides more shift towards the real axis of the s-plane to limit the abrupt variation in the amplitude of angle deviation and increases system stability by moving eigenvalues more to the left of an imaginary axis line. The PSS-SCA system required 44 iterations to converge the maximum objective function having the exact optimisation parameter values $r_1 = 1.12$, $r_2 = 0.3150$, $r_3 = 1$ and $r_4 = 0.5961$ for loading condition 2 compared with the other methods of optimisation (Table 8). The PSS-MFO and PSS-EP systems take 96 and 23 iterations to converge on the results and have exact optimisation parameter values $d = 0.00025$, $t = -0.9041$ and $\beta = 0.1$, respectively. The PSS-EP system has better convergence with minimum objective function value. The proposed technique offered better objective function with respect to both other procedures and has satisfactory computational efficiency compared with the PSS-EP system.

Table 8. Comparison of the PSS optimised parameters, eigenvalues and damping ratio for loading condition 2 of the SMIB.

Methods	Loading Condition 2			
	PSS-SCA	PSS-MFO	PSS-EP	PSS-U
PSS optimised parameters	$T_1 = 0.02499$	$T_1 = 0.02888$	$T_1 = 0.06651$	$T_1 = 0.1$
	$T_2 = 0.00150$	$T_2 = 0.00413$	$T_2 = 0.00152$	$T_2 = 0.04$
	$K_{stb} = 32.96348$	$K_{stb} = 32.83729$	$K_{stb} = 37.41522$	$K_{stb} = 9$
Objective function	0.7340	0.7227	0.6609	0.1209
Number of iterations	44	96	23	NA

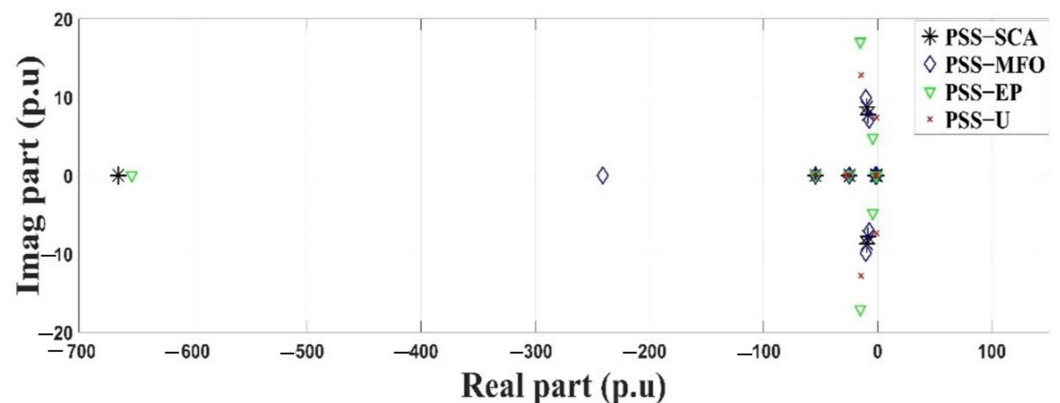


Figure 8. Eigenvalue's location on the complex s-plane for loading condition 2 of the SMIB with PSS.

The PSS parameters are optimised by using different optimisation techniques, and the eigenvalues related to the electromechanical modes obtained, damping ratio as objective function and damping ratio of loading condition 4 for the SMIB are provided in Table 10. The region of eigenvalue locations in the s-plane and rotor angle deviation are shown in Figures 12 and 13, respectively. The proposed PSS-SCA technique provides better damping of angle deviation and location of eigenvalues compared with the other optimisation methods. In terms of the location of eigenvalues, the proposed PSS-SCA algorithm provides more shift towards the real axis of the s-plane to limit the abrupt variation in amplitude of angle deviation and increase the system stability by moving eigenvalues more to the left of an imaginary axis line. The PSS-SCA system required 42 iterations to converge to the maximum objective function having the exact optimisation parameter values $r_1 = 1.16$, $r_2 = 5.9751$, $r_3 = 1$ and $r_4 = 0.8489$ for loading condition 4 compared with the other methods

of optimisation (Table 10). The PSS-MFO and PSS-EP systems take 94 and 20 iterations to converge on the results and have the exact optimisation parameter values $d = 0.00025$, $t = -0.0713$ and $\beta = 0.1$, respectively. PSS-EP system has better convergence with the minimum objective function value. The proposed technique offered better objective function with respect to both other procedures and has satisfactory computational efficiency compared with the PSS-EP system.

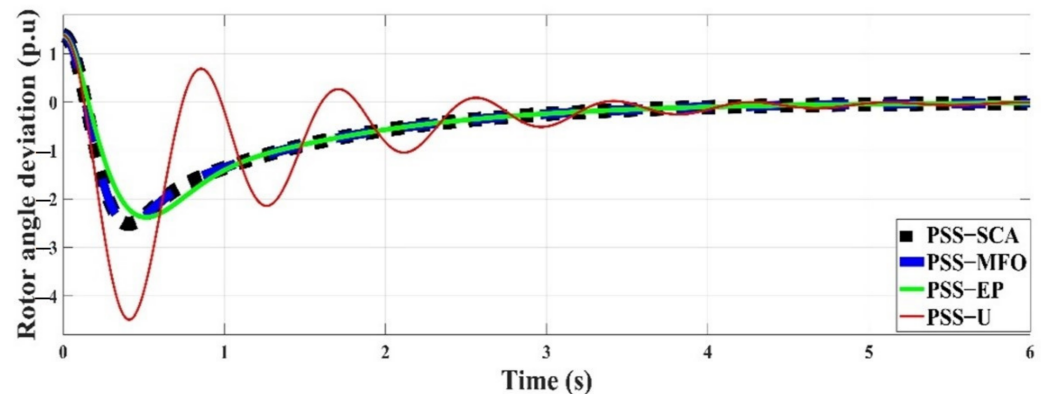


Figure 9. Rotor angle deviation for loading condition 2 of the SMIB with PSS.

The PSS parameters are optimised by using different optimisation techniques, and the eigenvalues related to the electromechanical modes were obtained. The damping ratio as objective function and damping ratio of loading condition 3 for the SMIB are provided in Table 9. The region of eigenvalue locations in the s-plane and rotor angle deviation are shown in Figures 10 and 11, respectively. The proposed PSS-SCA technique provides better damping of angle deviation and location of eigenvalues compared with the other optimisation methods. In terms of the location of eigenvalues, the proposed PSS-SCA algorithm provides more shift towards the real axis of the s-plane to limit the abrupt variation in amplitude of angle deviation and increase the system stability by moving eigenvalues more to the left of an imaginary axis line. The PSS-SCA system required 34 iterations to converge the maximum objective function, having the exact optimisation parameter values $r_1 = 1.32$, $r_2 = 0.8214$, $r_3 = 1$ and $r_4 = 0.2036$ for loading condition 3 compared with the other methods of optimisation (Table 9). The PSS-MFO and PSS-EP systems take 102 and 23 iterations to converge on the results and have exact optimisation parameter values $d = 0.00025$, $t = -0.4802$ and $\beta = 0.1$, respectively. The PSS-EP system has a better convergence with minimum objective function value. The proposed technique offered better objective function with respect to both other procedures and has satisfactory computational efficiency compared with the PSS-EP system.

Table 9. Comparison of the PSS optimised parameters, eigenvalues, damping factor and damping ratio for loading condition 3 of the SMIB.

Methods	Loading Condition 3			
	PSS-SCA	PSS-MFO	PSS-EP	PSS-U
PSS optimised parameters	$T_1 = 0.01780$	$T_1 = 0.02630$	$T_1 = 0.06711$	$T_1 = 0.1$
	$T_2 = 0.001403$	$T_2 = 0.01103$	$T_2 = 0.00154$	$T_2 = 0.04$
	$K_{stb} = 33.9990$	$K_{stb} = 33.27788$	$K_{stb} = 38.34156$	$K_{stb} = 9$
Objective function	0.7300	0.7121	0.6337	0.1145
Number of iterations	34	102	23	NA

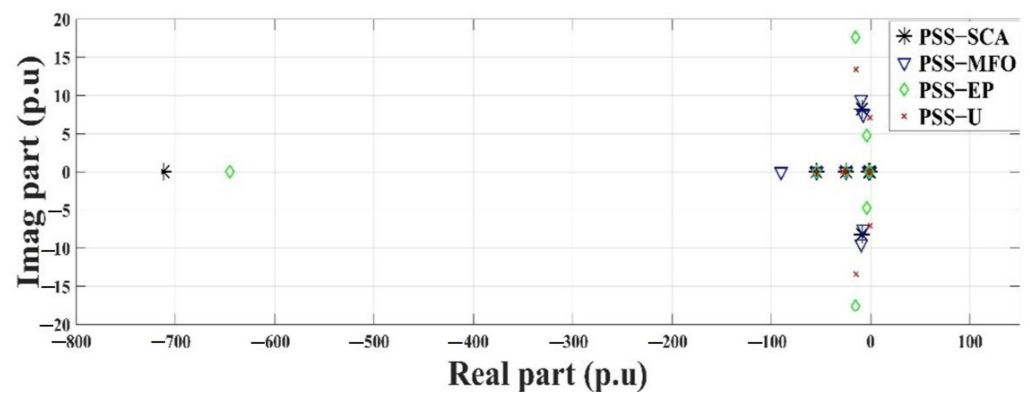


Figure 10. Eigenvalue's location on the complex s-plane for loading condition 3 of the SMIB with PSS.

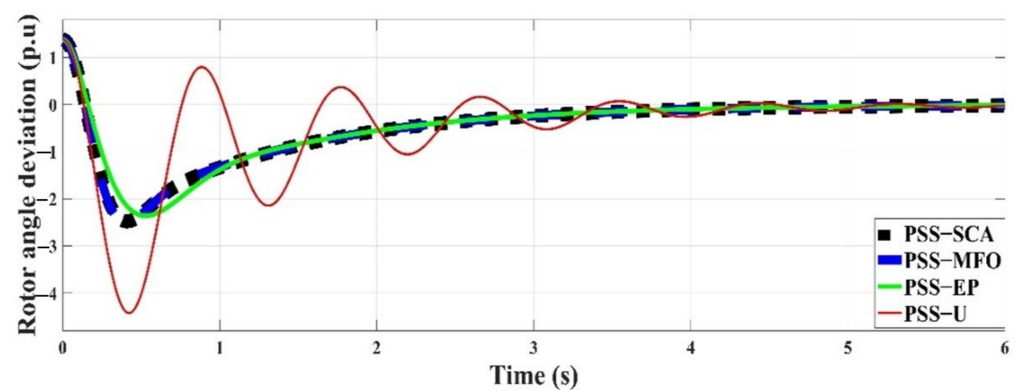


Figure 11. Rotor angle deviation for loading condition 3 of the SMIB with PSS.

Table 10. Comparison of the PSS optimised parameters, eigenvalues, damping factor and damping ratio for loading condition 4 of the SMIB.

Loading Condition 4				
Methods	PSS-SCA	PSS-MFO	PSS-EP	PSS-U
PSS optimised parameters	$T_1 = 0.04316$	$T_1 = 0.05327$	$T_1 = 0.04259$	$T_1 = 0.1$
	$T_2 = 0.05061$	$T_2 = 0.06027$	$T_2 = 0.04422$	$T_2 = 0.04$
	$K_{stb} = 53.25110$	$K_{stb} = 54.32393$	$K_{stb} = 49.64898$	$K_{stb} = 9$
Objective function	0.7559	0.7407	0.6764	0.1144
Number of iterations	42	94	20	NA

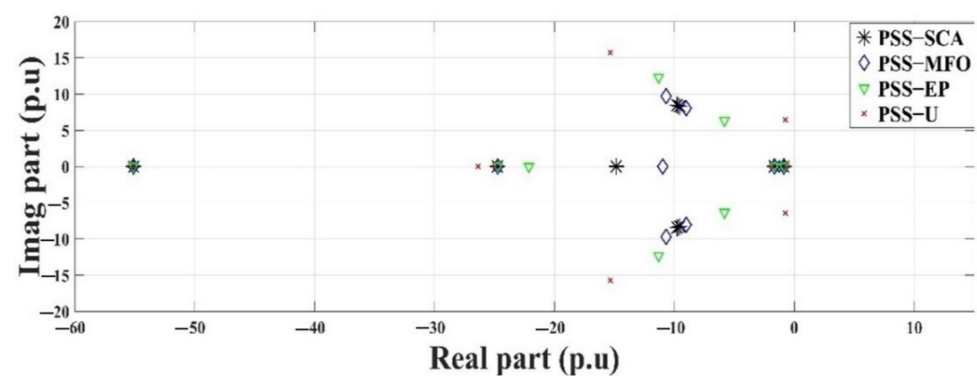


Figure 12. Eigenvalue's location on the complex s-plane for loading condition 4 of the SMIB with PSS.

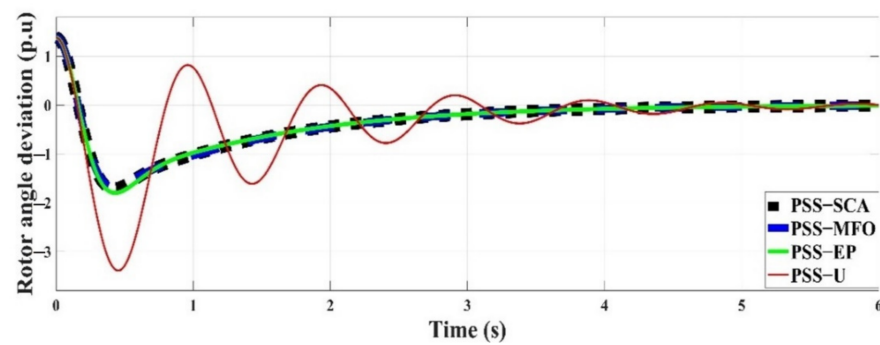


Figure 13. Rotor angle deviation for loading condition 4 of the SMIB with PSS.

The PSS parameters are optimised by using different optimisation techniques, and the eigenvalues related to the electromechanical modes obtained, damping ratio as objective function and damping ratio of loading condition 5 for SMIB are provided in Table 11. The region of eigenvalue locations in the s-plane and rotor angle deviation are shown in Figures 14 and 15, respectively. The proposed PSS-SCA technique provides better damping of angle deviation and location of eigenvalues compared with the other optimisation methods. In terms of the location of eigenvalues, the proposed PSS-SCA algorithm provides more shift towards the real axis of the s-plane to limit the abrupt variation in amplitude of angle deviation and increase the system stability by moving eigenvalues more to the left of an imaginary axis line. The PSS-SCA system required 38 iterations to converge the maximum objective function having the exact optimisation parameter values $r_1 = 1.24$, $r_2 = 0.0609$, $r_3 = 1$ and $r_4 = 0.9532$ for loading condition 5 compared with the other methods of optimisation (Table 11). The PSS-MFO and PSS-EP systems take 99 and 13 iterations to converge on the results and have exact optimisation parameter values $d = 0.00025$, $t = -0.6495$ and $\beta = 0.1$, respectively. The PSS-EP system has better convergence with the minimum objective function value. The proposed technique offered better objective function with respect to both other procedures and has satisfactory computational efficiency compared with the PSS-EP system.

Table 11. Comparison of the PSS optimised parameters, eigenvalues, damping factor and damping ratio for loading condition 5 of the SMIB.

Loading Condition 5				
Methods	PSS-SCA	PSS-MFO	PSS-EP	PSS-U
PSS optimised parameters	$T_1 = 0.02396$	$T_1 = 0.03471$	$T_1 = 0.02888$	$T_1 = 0.1$
	$T_2 = 0.04134$	$T_2 = 0.04984$	$T_2 = 0.04339$	$T_2 = 0.04$
	$K_{stb} = 140.61181$	$K_{stb} = 147.61060$	$K_{stb} = 154.93417$	$K_{stb} = 9$
Objective function	0.8299	0.7839	0.6384	0.0641
Number of iterations	38	99	13	NA

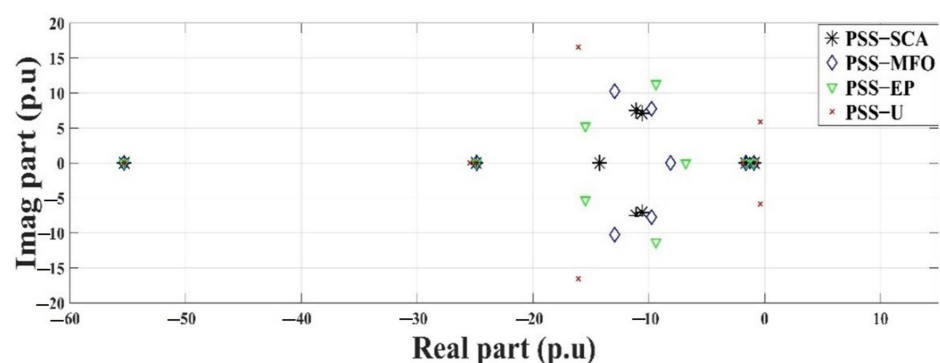


Figure 14. Eigenvalue's location on the complex s-plane for loading condition 5 of the SMIB with PSS.

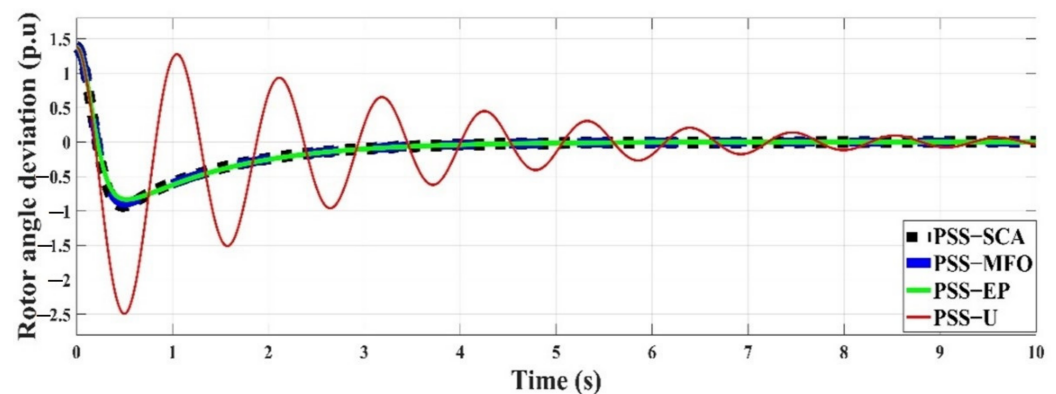


Figure 15. Rotor angle deviation for loading condition 5 of the SMIB with PSS.

9. Conclusions

This work presents a metaheuristic optimisation algorithm technique for fine-tuning a lead lag controller of PSS related to the angle stability of the SMIB system. The design of a vigorous lead lag controller of the AVR system of the SMIB system was formulated with a minimum damping ratio as an indicator by developing its mathematical model to perform eigenvalue analysis and objective function. Five methods based on EP, MFO and SCA computation algorithms for optimising the T_1 , T_2 and K_{stb} parameters of the controller based on objective function as damping ratio were designed. The use of optimisation methods moved the eigenvalues more to the real axis line and left side of the imaginary axis of the complex s-plane. The results showed that SCA provided better damping of low frequency oscillations compared with EP, MFFO and unoptimised PSS.

The dynamic performance was validated with respect to damping ratio, the eigenvalue's location in the s-plane and rotor angle deviation response, and ensured system stability. MFO converged with the maximum iterations (i.e., 92–103 iterations), followed by the SCA and EP techniques that converged at 34–46 and 13–23 iterations, respectively. The total iterations utilising the SCA method is insignificant yet adequate. In conclusion, the SCA optimisation algorithm found improved computations of the best possible parameters of the damping controller to boost system stability and matched with those attained with the MFO and EP procedures. In contrast with the optimisation methods built on five cases for the PSS lead lag controller using damping ratio as the objective function, the PSS-SCA-based method demonstrated the best stability performance.

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