Robust Fractional Order Power System Stabilizer Design using Bacteria Foraging Algorithm for Multi-Machine Power System

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***Abstract*—Power System Stabilizers (PSSs) are supplementary controllers to enhance the damping of electromechanical oscillations in synchronous generators. A fractional order supplementary controller, which has the features as broad bandwidth, memory effect, and flatness in phase contribution, is proposed in this paper. The fractional parameter effect made the stabilizer to perform well against the wide range of disturbance uncertainties in the power system. The Fractional order PSS parameter tuning problem is modified as an optimization problem that is solved using Bacteria Foraging Algorithm (BFA) in a multimachine environment. Since BFA is highly efficient optimization technique with fast global search property and convergence, it is popular in the field of power system application domains for solving real-world optimization problems. The robustness of the proposed BFA based fractional order PSS (BFA-FoPSS) is verified in a multi-machine power system under the wide range of operating conditions and by introducing faults of different size at different locations. The efficiency of the proposed BFA-FoPSS is demonstrated through time domain simulations, eigenvalue analysis and with a performance index. Also, the results are compared with PSO based Conventional PSS (PSO-CPSS), and PSO based FoPSS (PSO-FoPSS) to establish the fractional parameter effect on the improvement of system dynamic response and the relevance of the proposed PSS for extending the dynamic stability limit of the system under various loading and generating conditions.**

Keywords*—*Stability of synchronous machines; robust control; power system stabilizer; fractional order control; bacteria foraging algorithm

I. Introduction

Power system networks have been continuously expanding and evolving into more complicated structures with a large number of interconnected loads and generating units. Due to the dynamic interactions resulting from the increased complexity of these systems, more instability problems are originated such as Low-Frequency Oscillations (LFO). These oscillations require adequate damping to avoid system collapse and power transfer limitations. At the same time, the power systems are almost operated ever close to their transient and dynamic stability limit. Therefore, it is necessary to increase power system stability margin for the smooth and continuous operation of the system. In this scenario, PSS is proposed to provide a stabilizing signal to the excitation system to suppresses the electromechanical oscillations due to any dynamic changes in the system [1], [2].

Since the Conventional PSS (CPSS) parameters are tuned with the help of a linearized system model for a particular operating point they cannot provide effective damping [3], [4]. Therefore in search for a refined PSS to overcome the demerits of CPSS, several studies have been carried out in recent years. These refinements can be classified into two groups: 1) presenting different control techniques to refine CPSS; 2) tuning of PSS parameters using artificial intelligent techniques and Meta-heuristic algorithms.

A new adaptive neuro-fuzzy based PSS and a nonlinear variable structure based PSS were described in [5] and [6] respectively for effective damping of system oscillations. H∞ based power system stabilizers are presented in [7], [8]. In [9] the systematic design of a QFT based PSS is presented. A multi-input multi-output nonminimum phase and unstable plant are selected to developed this design. A Linear Matrix Inequality based new saturated control technique has been proposed in [10]. A μ- controller based digital PSS is proposed in [11] in which bilinear transformation is adopted to transfer s-domain PSS to Z-domain PSS.

Artificial Neural Networks (ANNs) [12], [13], Genetic Algorithms (GA) [14], [15], Chaotic Optimization Algorithm (COA) [16] AND Optimal power system stabilizers based on particle swarm optimization [17], [18] are some examples of artificial intelligence techniques and evolutionary algorithms adopted for PSS refinement. Recent techniques such as Bacterial Foraging [19] and bifurcation analysis [20] etc. are also applied in PSS tuning. Because of the easiness in online tuning and due to the well-explained theory behind the working, the modern power system utilities still select PSS of integer order to provide supplementary control for machines in the system. The multimachine power system requires more robust PSS that can perform well against the wide range of loading conditions.

Recently it has seen an increase in research studies related to fractional calculus and its engineering applications [21], [22]. There are many fractional order control applications in the modern power system. Fractional order control strategy is successfully implemented in Automatic Voltage Regulator (AVR) [23], Load Frequency Control (LFC) [24], robust control of hydro plants [25], etc. The Fractional Order (FO) system has considerable memory effect, large bandwidth and good flatness in phase contribution. The large bandwidth of the FO controller makes the FoPSS accommodate the wide range of operating conditions and, therefore, can yield large stability margin also.

In this paper, by taking the advantages of fractional order control, a structural change in multimachine PSS as FoPSS is introduced. A new optimization scheme known as bacterial foraging algorithm (BFA) [26] is used for the FoPSS parameter design. A PSO-FoPSS is designed and compared with PSO-CPSS to evaluate the superiority of the FO controller and also with proposed BFA-FoPSS for comparing the effects of different optimization techniques for providing effective damping to electromechanical oscillations and extending the power system stability limit.

II. Power System Model and PSS Structure

A. Dynamic Model of the Multi Machine System

The dynamic model of multi-machine power system is given in non-linear form as in (1) [4]

$$\begin{aligned} \dot{\delta_i} &= \omega_0(\omega - 1) \\ \dot{\omega_i} &= \frac{P_m - P_e - D\omega}{M} \\ \dot{E_{q_i}^{'}} &= \frac{-E_q + E_{FD}{}^{'}}{T_{do}} \\ \dot{E_{FD_i}^{'}} &= \frac{E_{FD} + K_a(U_{ref} - U_t)}{T_a} \end{aligned} \tag{1}$$

Where i=1,2...n (the generators 1 to n) ω, rotor speed in pu and δ , rotor angle in pu. $Eq^{'}$ denotes internal voltage and E_{FD}, field voltage. $T_{do}^{'}$ and T_a are excitation circuit and regulator time constants. P_m and P_e, mechanical input power and electrical output power, respectively.

B. Multi-machine PSS Structure

The generalized structure of CPSS is shown in Fig. 1. The front end is a wash-out filter, a high pass filter to eliminate steady state bias from PSS output. The gain determines the damping level of the PSS. The heart of the PSS is the cascade of lead-lag filters which implements the phase compensation algorithm to compensate the difference in phase between the resulting electric torque and excitation system input. The output signal V_{PSS} is the voltage signal to the excitation system.

The input signal is the speed deviation $\Delta\omega$. Other possibilities are the deviation in active power or frequency. The mathematical representation of i^{th} CPSS with control gain K_S, washout time constant T_w, as well as leading time constants T_1 and T_2 and lagging time constants T_3 and T_4 for two-stage lead-lag compensator is expressed as,

$$G_{PSS_i} = K_{S_i}\frac{sT_{w_i}}{(1+sT_{w_i})}\frac{(1+sT_{1_i})}{(1+sT_{2_i})}\frac{(1+sT_{3_i})}{(1+sT_{4_i})} \tag{2}$$

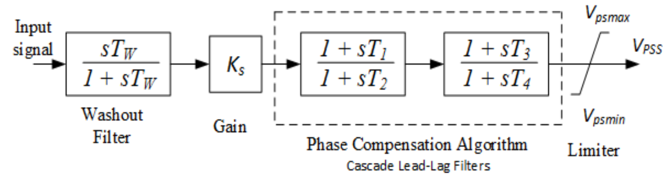


Fig. 1: General PSS structure model.

III. The Theory of Fractional Calculus

The idea of fractional calculus has been proposed since 1695 with the possible approach associated with G. W. Leibnz and G.F.A L Hôpital. It is a generalization of ordinary calculus including the differentiation and integration of the functional operator 'D' associated with an order 'r' which is not restricted to integer numbers. The continuous integrodifferential operator is defined as [21],

$$\begin{aligned} {}_gD_h^r = \; & d^r/dt^r && R(r) > 0 \\ = \; & 1 && R(r) = 0 \\ = \; & \int_g^h (d\tau) && R(r) < 0 \end{aligned} \tag{3}$$

Where g and h are the limits of the operation, generally $r \in R$ but it could also be a complex number [22].

A. Fractional Order Lead-Lag Compensator

The robustness properties of PSS can be enhanced by employing fractional order structure, which is the focus of this paper. Hence, it is essential to establish the robustness characteristics of the fractional order lead-lag compensator which is the heart of PSS. The fractional order lead-lag compensator has been investigated in [22]. The transfer function of the fractional order counterpart of the lead/lag compensator can be expressed as,

$$\begin{aligned} C(s) &= k\Big(\frac{s+1/\mu}{s+1/x\mu}\Big)^q \\ &= kx^q\Big(\frac{1+s\mu}{1+sx\mu}\Big)^q \qquad 0 < x < 1, q \in R \end{aligned} \tag{4}$$

Where q represents the fractional commensurate order of the compensator, $1/\mu = \omega_z$ and $1/x\mu = \omega_p$ are the zero frequency and pole frequency respectively. The Bode diagram of the fractional order compensator as a lead compensator ($q > 0$) are as shown in Fig. 2. The value of x corresponds to the distance between ω_z and ω_p and the magnitude of μ corresponds to the pole-zero position on the frequency axis. The value x and μ depends on the fractional order of the systems. It is clear that if values of x and μ are constants, the maximum phase φ_m that compensator can contribute and the slope of the magnitude curve of C(s) will be increased by increasing the value of the fractional commensurate order. The characteristics of the lead compensator C(s) at maximum phase compensation ϕ_m are:

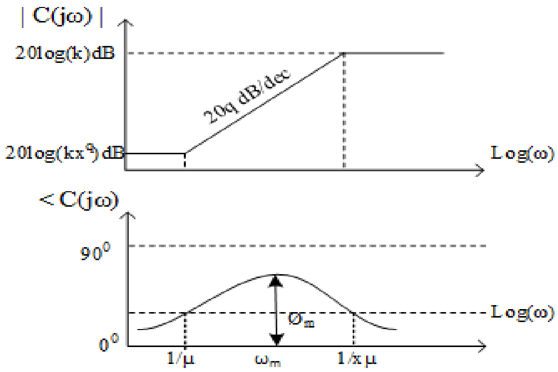


Fig. 2: Bode plot of C(s) when $q > 0$.

$$|C(j\omega)|_{\omega=\omega_m} = \left(\sqrt{\frac{(\mu\omega_m)^2+1}{(x\mu\omega_m)^2+1}}\right)^q = \left(\frac{1}{\sqrt{x}}\right)^q \qquad (5)$$

$$\arg(C(j\omega))_{\omega=\omega_m} = \phi_m = q sin^{-1}\left(\frac{1-x}{1+x}\right) \qquad (6)$$

At a lower fractional order q, the pole-zero separation will be more and vice versa. Therefore, the phase $\arg(C(j\omega))$ stands still for a certain frequency range. This property of fractional order lead compensator is illustrated with a typical example for the order of the compensator selected as 1, 0.5 and 0.2 in Fig. 3. It can be seen that as the order of the controller decreases, the phase contribution becomes flattered for a certain frequency range. The FO controller becomes more flexible and robust in design than its integer order counterpart because of this flatness in phase contribution.

B. Fractional Order PSS

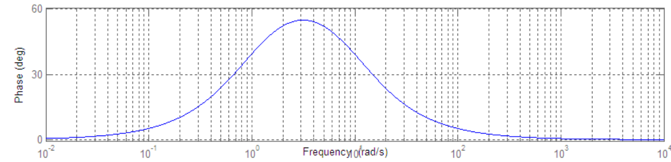
By considering the FO lead/lag compensator structure explained in section III, a typical FoPSS can be described in transfer function form as,

$$G_{FoPSS_i} = K_{FoPSS_i}\frac{(sT_{wi})^r}{(1+sT_{w_i})^r}\frac{(1+sT_{1_i})^r}{(1+sT_{2_i})^r}\frac{(1+sT_{3_i})^r}{(1+sT_{4_i})^r} \qquad (7)$$

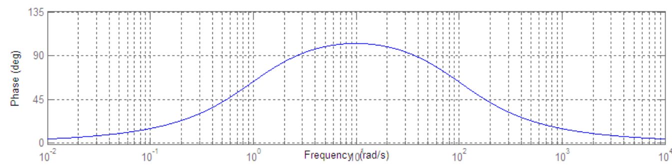
where $s^r = L[\frac{d^r}{dt^r}]$ the Laplace operator of the fractional derivative with order r; $0 \leq r \leq 1$. Due to the memory effect of the fractional order controllers [22], the FoPSS can utilize the fault history of the system to generate the desired output signal. The large bandwidth exhibited by FoPSS can replace the washout component $\frac{(sT_{\omega i})^r}{1+(sT_{\omega_i})^r}$presented in(9). Therefore the transfer function of FoPSS has the form.

$$G_{FoPSS_i} = K_{FoPSS_i}\frac{(1+sT_{1_i})^r}{(1+sT_{2_i})^r}\frac{(1+sT_{3_i})^r}{(1+sT_{4_i})^r} \qquad (8)$$

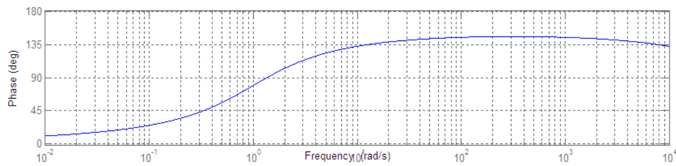
Optimization algorithms used in this work to tune the FoPSS parameters is described in the next section.



(a) q=1



(b) q=0.5



(c) q=0.2

Fig. 3: Phase diagram of $C(s) = k'\left(\frac{1+s\mu}{1+sx\mu}\right)^q, k' = 1, \mu = 10, x = 0.1$.

IV. Design Methodology

The standard PSO and BFA algorithms are employed for optimal tuning of the FoPSS parameters for the selected power system. From the detailed Eigenvalue analysis and after that participation factor method for the PSS response, the optimum location of the PSS for the IEEE Three machine nine bus system is identified as machine G2. Therefore, machine G2 is equipped with Fo-PSS.

A. Bacterial Foraging Optimization Algorithm (BFOA)

Kevin Passino in 2002 proposed Bacterial Foraging Optimization Algorithm (BFOA). The animals who have successful foraging strategies are naturally selected for existence. A poor foraging strategy may eliminate or shaped to a new improved one after many generations. BFA is based on the foraging strategy of a swarm of E.coli bacteria present in the humane intestine. The foraging behavior of these bacteria can be explained by four steps such as Chemotaxis, Swarming, Reproduction and Elimination and Dispersal [26].

In Chemotaxis process at each step, with the activity of run (a unit move of bacterium in the same direction)or tumble (a unit move with random direction) a step fitness will be evaluated. After reproduction step only the first half of the population is survived according to the health status and these will split into two identical bacteria and keeps the population as constant. For the next generation, the bacterium which has minimum cost function is retained. For a new chemotactic stage, the distances of each bacterium from the global optimum bacterium are evaluated for swarming. The flow chart of the BFA is shown in Fig. 4.

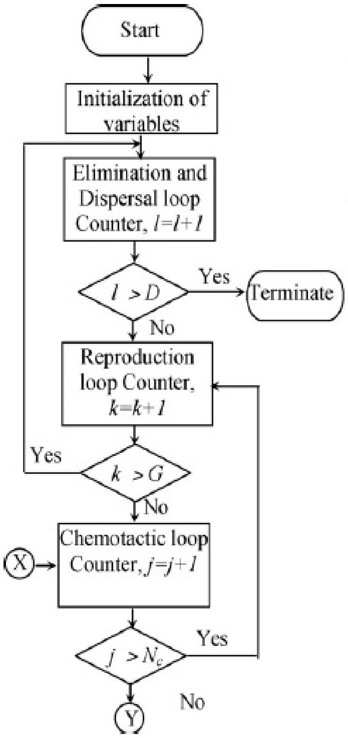


Fig. 4: Flowchart of the bacteria foraging algorithm [19].

B. Objective Function

The objective is to tune the Fo-PSS parameters to achieve the optimal dynamic performance of rotor speed to satisfy the requirements of maximum damping, minimum settling time and minimum overshoot. The fitness function selected for BFA method should reflect all these requirements. One choice of such a function is the Integral of the Time multiplied Absolute value of the Error (ITAE). The error is defined as the deviation of rotor speed of the generators from its nominal value. Hence, the objective function can be defined in the following form.

$$J = \sum_{i=1}^{N_g=3} \int_0^t (t(|\Delta\omega_i|)dt \tag{9}$$

Where $\Delta\omega_i$ is the deviation in rotor speed, and the parameter N_g represents the total number of synchronous generators in the system. For the better control effort, the controller should have minimum ITAE. The tuning problem can be structured as the optimization problem to minimize the ITAE error with constraints $K_{FOimin} \leq K_{FO_i} \leq K_{FOimax}$, $T_{imin} \leq T_i \leq T_{imax}$ and $0 \leq q \leq 1$. Where K_{FO_i},T_i, and q denote all the gains, time constants and the fractional order of the Fo-PSS, respectively.

V. Time Domain Simulations

The study system selected to establish the efficacy of the new stabilizer to extend the stability limit by providing adequate damping to electro-mechanical oscillations is IEEE three machine nine bus system [4]. This system contains three generators with nine buses. Three constant impedance loads A, B and C, are connected to buses 5, 6 and 8, respectively. A one-line diagram of the test system is shown in Fig. 5. The system is suitable to permit the illustration of a number of stability concepts and results. The selected loading and generating conditions are listed in Table I.

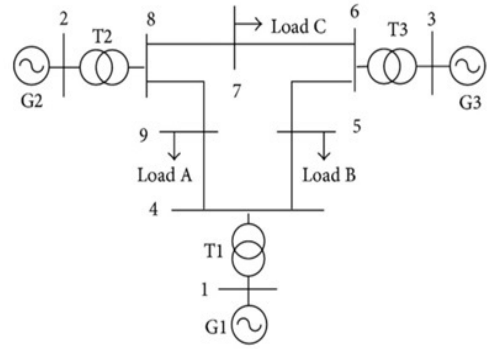


Fig. 5: The single-line diagram of IEEE three machine nine bus system [4].

TABLE I: System Generating and Loading Conditions

	Nominal		light		heavy	
	P	Q	P	Q	P	Q
Generator						
G1	0.72	0.27	0.576	0.216	0.864	0.324
G2	1.63	0.07	1.304	0.056	1.956	0.084
G3	0.85	-0.1	0.68	-0.08	1.02	-0.13
Load						
A	1.25	0.5	1	0.4	1.5	0.6
B	0.9	0.3	0.72	0.24	1.08	0.36
C	1	0.35	0.8	0.28	1.2	0.42

TABLE II: Optimum PSS Parameters

Method	T_1	T_2	T_3	T_4	K_{FoPSS}	r
PSO-FoPSS	0.005	0.014	0.051	0.012	5.1	0.793
BFA-FoPSS	0.057	0.012	0.061	0.013	8.85	0.895
PSO-CPSS	0.018	0.032	0.059	0.021	5.89	-

Since the generator G2 is to be equipped with FoPSS according to the optimum allocation strategy, the corresponding parameters are to be tuned.

The optimum of FoPSS and CPSS parameters based on the selected objective function using PSO and BFA are given in Table II. Performance comparison is made to show the effectiveness of the proposed FoPSS over a PSO based CPSS and a PSO based FoPSS.

The system eigenvalues and damping ratio of mechanical mode are given in Table III for the considered loading conditions. It is clear that the eigenvalues associated with the electromechanical modes have been shifted to the left of the s-plane with the proposed controllers. Also, the values of the damping ratios are significantly improved.

The validation of the effectiveness and robustness under severe disturbance is confirmed by applying two different fault scenario in the proposed system:

TABLE III: Electromechanical Modes and Damping Ratios of Test System Under Different Loading Conditions

Method	Nominal loading	Heavy loading	Light loading
Without PSS	$-0.1982 \pm 7.852i, 0.02523$	$-0.1962 \pm 6.3112i, 0.0310$	$-0.0198 \pm 6.3259i, 0.00313$
	$-0.4368 \pm 11.9845i, 0.0364$	$-0.2658 \pm 11.0258i, 0.0241$	$-0.1235 \pm 11.025i, 0.0112$
PSO-CPSS	$-1.9871 \pm 6.1258i, 0.3085$	$-1.9584 \pm 5.0369i, 0.3623$	$-1.9856 \pm 4.398i, 0.4114$
	$-2.7512 \pm 5.9637i, 0.0.4188$	$-2.0165 \pm 5.3258i, 0.3540$	$-1.0698 \pm 4.0297i, 0.2565$
PSO-FoPSS	$-3.9845 \pm 8.6323i, 0.4190$	$-3.065 \pm 7.6842i, 0.37041$	$-3.2597 \pm 6.543i, 0.4459$
	$-3.86544 \pm 9.0125i, 0.3941$	$-3.0258 \pm 6.0256i, 0.4487$	$-3.298 \pm 7.03641i, 0.4064$
BFA-FoPSS	$-3.6523 \pm 7.5648i, 0.4347$	$-3.5612 \pm 6.3258i, 0.4905$	$-4.0365 \pm 6.3534i, 0.5362$
	$-4.9823 \pm 9.1596i, 0.4778$	$-4.0125 \pm 8.1268i, 0.4427$	$-4.0235 \pm 7.0216i, 0.4971$

TABLE IV: Time Domain Analysis

Method	Peak overshoot(pu)			Settling Time(s)		
	ω_1	ω_2	ω_3	ω_1	ω_2	ω_3
Disturbance scenario 1						
PSO-CPSS	0.052	0.038	0.037	11.1	16.45	19.54
PSO-FoPSS	0.013	0.011	0.012	9.115	9.46	9.996
BFA-FoPSS	0.003	0.004	0.003	5.683	5.428	5.275
Disturbance scenario 2						
PSO-CPSS	0.033	0.033	0.028	20.27	21.44	11.28
PSO-FoPSS	0.039	0.034	0.012	8.332	11.58	8.133
BFA-FoPSS	0.002	0.008	0.01	5.595	5.671	7.156

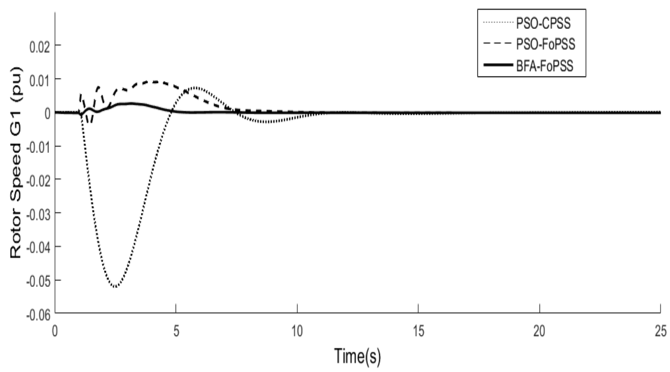


Fig. 6: G1 Rotor Speed deviation following disturbance scenario 1.

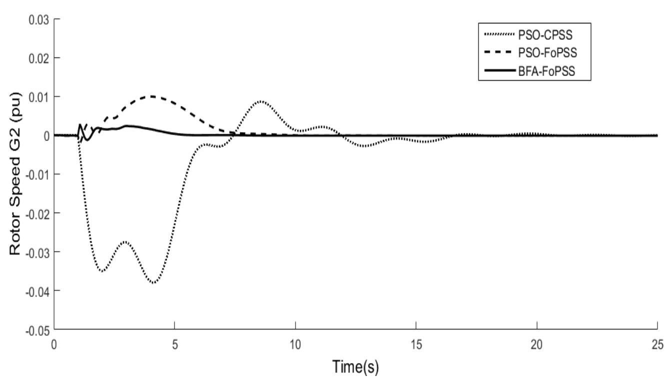


Fig. 7: G2 Rotor Speed deviation following disturbance scenario 1.

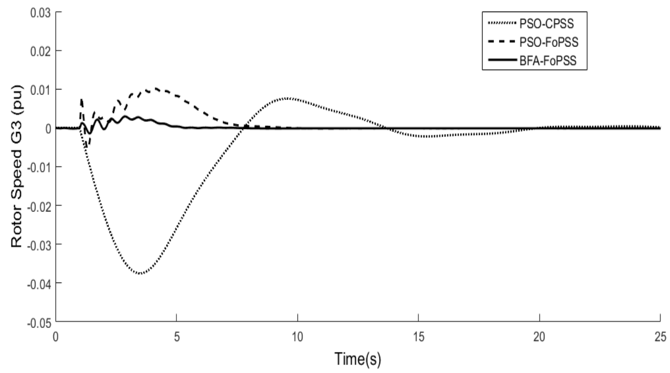


Fig. 8: G3 Rotor Speed deviation following disturbance scenario 1.

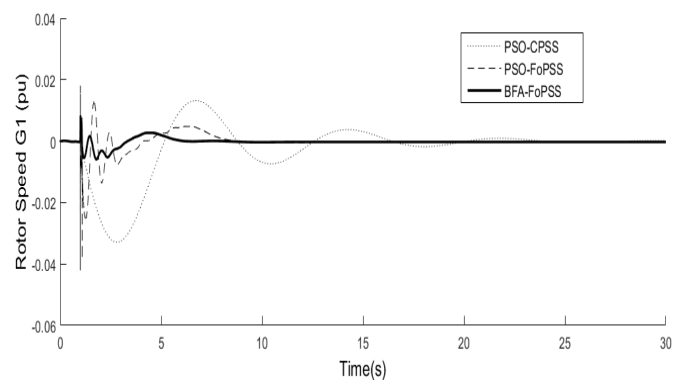


Fig. 9: G1 Rotor Speed deviation following disturbance scenario 2.

Scenario 1: A three phase fault at $1.083s$ at line $5-7$ near bus 7.

Scenario 2: Outage of line $2-3$.

Fig. 6 to 11 show the response of rotor speed deviation of three generators due to the disturbances with PSO-CPSS, PSO-FoPSS, and BFA-FoPSS. It is clear from the simulation results that the system which accommodates the proposed FoPSS is more stable and robust in heavy loading condition. In addition, the system with FoPSS has smaller mean settling time and overshoot when comparing with the case of classical CPSS. A quantitative analysis is also done on time domain specifications like settling time and peak overshoot for each

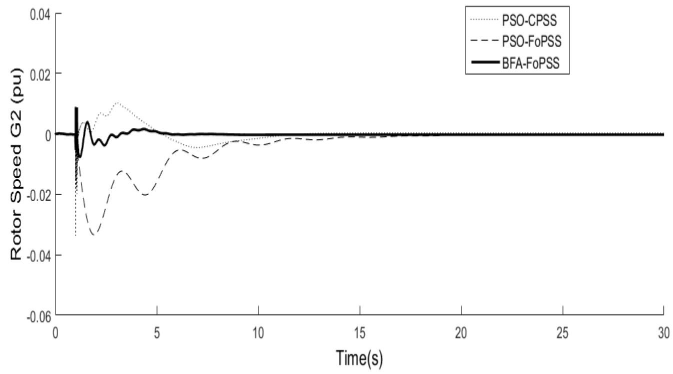


Fig. 10: G2 Rotor Speed deviation following disturbance scenario 2.

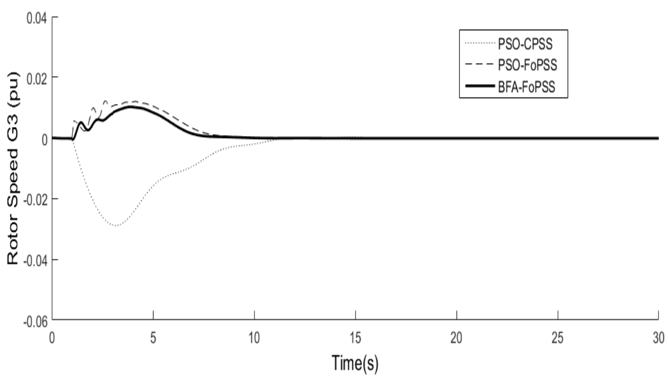


Fig. 11: G3 Rotor Speed deviation following disturbance scenario 2.

case and listed in Table IV. The ITAE errors are calculated for the selected fault scenarios and given in Table V. It can be seen that the BFA-FoPSS has the smaller ITAE index than the others. This indicates that the settling time, undershoot and overshoot in rotor speed and rotor angle deviations of all generators are greatly reduced by employing the proposed fractional order PSSs.

The overall results depict that the proposed fractional order PSSs have better-stabilizing capability under all fault scenarios and operating conditions and have a robust performance. So the designed fractional order controller is validated for providing efficient dynamic stability by damping the electromechanical oscillations during severe disturbances in the system. The results also establish that the FoPSS can achieve better damping characteristics to the oscillating modes of the system and can stabilize the system rapidly. From the comparison with CPSS, it can be seen that the proposed FoPSS extends the power system stability limit by attenuating the electromechanical oscillations effectively with minimum settling time.

VI. Conclusion

This paper presents a robust Fractional Order Power System Stabilizer (FoPSS) whose parameters are optimized through BFA for the effective damping of a multi-machine system. The FoPSS improves the dynamic response of the system by assuring robustness and achieving an acceptable performance in the system uncertainties better than the integer order PSS. The simulation results show that the proposed FoPSS can accommodate the wide range of operating conditions and system variations because of the memory effect of the fractional order system. At the same time, the proposed controller has more parameter sensitivity and robust stability for various loading conditions. Application of the proposed FoPSS whose parameters are tuned through recently developed optimization techniques and implementing in large multimachine power systems are the future scope of this work.

TABLE V: ITAE Index Value for Different Algorithms

	Diturbance	
Method	Scenario 1	Scenario 2
PSO-CPSS	1.1651	1.5914
PSO-FoPSS	0.2031	1.0592
BFA-FoPSS	0.1159	0.5561

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