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Research paper

Optimal PSS Parameters Design Based on a Novel Objective Function for Small Signal Stability Enhancement

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Abstract

Background and Objectives: In this paper, a novel objective function is proposed for designing the power system stabilizers (PSSs). Although the object of the previous designs was to enhance the critical modes' stability, the derived stability indices were, to some extent, low and in some cases not acceptable at all. The prospect of attaining higher stability motivated authors to design a new objective function in this study. In all the previous objective functions, the same priority is accorded to all modes, and an objective function is generally defined. A novel function is presented, called Variable Slope Damping Scale (VSDS), based on the assumed variable slope for the straight line in the fan-shaped region, which is an area in the complex plane for determining the eigenvalue placement range, with a reference tip at the negative point. This can be an efficient solution to the low value of critical modes' stability. In general, more damping for critical modes and lower priority for searching non-critical modes are taken as key points. The result of applying VSDS leads to a high value of damping scales for critical modes. The nonlinear simulation results and eigenvalues analysis has demonstrated that the proposed approach in this study is highly effective in damping the most critical modes.

Methods: The proposed method assumes a variable slope for the straight line of the convergence region (specified area for placement of poles) in a fan-shaped type. Indeed, the increase in critical mode's damping scale is taken into account as a key point to introduce a powerful objective function.

Results: The value of the damping scale and also the overall dynamic stability of the test system has increased by using the proposed objective function.

Conclusion: Also, it has been shown that a variable slope convergence region is better than that of a constant slope one to the optimal tuning of WAPSS. In other words, the value of the damping scale with the proposed method over the existing techniques clearly shows that the proposed objective function is more effective than the other ones.

Introduction

In most power plants, PSS is taken into account as efficient equipment to solve oscillations and stability problems in our process [1]-[3]. Effective application of stabilizers is mostly related to the effectiveness of objective function, especially when several PSSs are considered simultaneously in power system designing. There are lots of objective functions offered to provide a better condition for PSS design. However, all of them consider the same strategy for different modes and ignore the fact that critical modes play a significant role in the overall stability of the power system. Regarding the significant effects of objective functions, there are some limitations associated with the displacement of the whole eigenvalues in each power system. It goes without saying that this issue has experienced both growing interest and extensive efforts when it came directly to the design of a powerful objective function [4]-[12].

This paper proposes a new objective function known as the VSDS objective function. It is obvious that achieving greater stability is of great importance and all equipment must be designed to meet this goal. The commonly used objective functions proposed in previous works are relatively appropriate, but they are not as effective in providing high stability. Therefore, in this paper, some thoughts and novelties are provided to address this important issue. In [4], a method is proposed for designing a wide-area power system stabilizer based on a new multi-objective function. In this function, critical modes are displaced to improve the system stability, which the stabilizer is designed in the minimum-phase with less control gain. In the objective function presented in [5], there is no limitation in the confrontation of high-frequency oscillation and just all damping factors are placed in a rectangular region. In [6], the performance of various commonly used objective functions including integral square error (ISE), integral time square error (ITSE), integral absolute error (IAE), and integral time absolute error (ITAE) are analyzed. The objective functions are used to tune the proportional–integral–derivative (PID) controller values in various power systems. The results established that their performance change based on the power system size, which is a weak point. The objective function presented in [7], similar to one in [5], the limitation of damping factors is performed, but it still has problems with the high-frequency oscillations. In [8], a multi-objective optimization procedure including both performance and robustness criteria is considered for formulating the dual-dimensional supplementary damping controller (SDC) and accelerating PSS (PSS2B). However, in designing the objective function, there is no difference between system modes, and the same method is used for their displacement. The objective function presented in [9], the problem of high-frequency oscillation has been solved, but there is no investigation on the modes works on damping factor limitation. In [10], a novel performance index is proposed to evaluate a system's ramp response. The study is applied to the tuning of a PSS of a simple power system, at several operating points of the synchronous machine. It explores the process of tuning controllers for conditions that better reflect realistic operating conditions, such as input signals of different shapes. In [11], a novel objective function based on power system exciter frequency response is proposed to design a robust PSS using heuristic optimization techniques, in order to damp the electromechanical oscillations at very low frequencies (0.1-3 Hz), that often tend to grow with time and cause system instability. The objective function presented in , which is called the damping scale objective function, all the problems with the previous well-known objective function such as lightly damped and higher-frequency modes were eliminated somewhat, and the only problem is the slight convergence difficulty. Now, the proposed objective function has all advantages of the previous method, and there are no convergence problems. In this investigation, the novelty is about finding a convergence region that result in a more damping scale for critical modes. Actually, the main idea of this paper is to deal with some particular modes by defining a special convergence region. Moreover, this method scrutinizes some issues like the non-constant slope of the convergence region or less energy consumption for un-critical modes. Also, to enhance the system stability, a combinational input of both local and remote signals was regarded for damping controllers in this study. The GRSA (a newly proposed objective function inspired by general relativity theory) with considering VSDS objective function was applied in PSSs designing, and its positive effects have been investigated. This paper has organized as follows: Second section introduces the power system model and PSSs structure, which is accompanied by a review of both new and customary objective functions. Third section presents simulation results and a comparison in investigating the efficacy of the proposed methods under various system operating conditions. Some conclusions are also explained in next section.

Problem Statement

The problem statement is defined in three parts as follows:

A. Power system model and PSSs structure

The closed-loop nonlinear modeling can be constructed with a set of nonlinear differential-algebraic equations by the following form:

$$\dot{X} = f(X, U) \quad (1)$$

Regardless of the damping controller's structure, the linearized incremental model of the interconnected power system around an equilibrium point is generally shown as follows:

$$\Delta\dot{X} = A\Delta X + B\Delta U \quad (2)$$

This paper implements a commonly utilized lead-lag PSS and the IEEE-type-ST1 excitation system, which are similar to Fig.1, [2]. The considered PSS structure and i^{th} angular speed deviation are denoted as follows:

$$G_i(s) = K_i \frac{T_w s}{(1+sT_w)} \frac{(1+sT_{1i})(1+sT_{3i})}{(1+sT_{2i})(1+sT_{4i})} \tag{3}$$
$$\Delta\omega_i = (\gamma_L \Delta\omega_{Li} + \gamma_R \textstyle\sum_k \Delta\omega_{Rk})$$

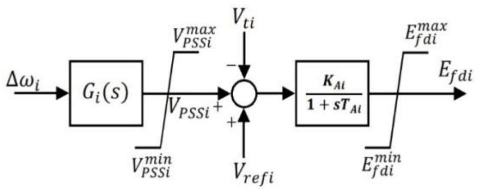

Fig. 1: Overall interconnection of i^{th} PSS with IEEE-type-ST1 excitation system.

In this paper, the input signal of PSSs is not just a local signal, and a combination of local and remote signals is considered as the input signal. In this regard, the second equation, which determines the input signal of the i^{th} generator, is based on the local signal and combination of all remote signals impacting the determined generator. It should be mentioned that remote inputs for each generator will be selected based on a sensitive analysis of its state variables. The weighting coefficients can be calculated by the optimization method, but constant values are also acceptable. The values of parameters are available in the Appendix section.

B. Overview of Previous Objective Function

Up to now, there have been several attempts with the presentation of a different objective function in order to achieve higher small-signal stability. A schematic of these convergence regions in four well-known objective functions is depicted as shaded areas in Fig. 2. The objective function depicted in Fig. 2(d) has been constructed by defining the damping scale function in the form of (4) [12]. As such, this damping scale objective can be written as below (5):

$$\chi \equiv \frac{-(\sigma-\sigma_0)}{\sqrt{(\sigma-\sigma_0)^2+\omega^2}} \times 100\% \tag{4}$$

$$Min\ F_1 = \sum_{y=1}^{n_y} (\chi_0 - \min_{1\le q\le n_q} \chi_q)_y \tag{5}$$

In the mentioned convergence region, damping factors and damping scales of eigenvalues are respectively lower than σ_0 and upper than χ_0. Furthermore, the slope of the straight line of the fan-shaped region can be calculated as following [12]:

$$Slope_{\chi_0} = \pm\sqrt{\frac{1}{\chi_0^2}-1} = \pm \frac{1}{\left|\frac{\zeta_0}{\sqrt{1-\zeta_0^2}} - \frac{\sigma_0}{\omega}\right|} \tag{6}$$

As it is obvious in Fig. 2(d), there is not any problem associated with the existence of high-frequency or low-frequency lightly damped modes. So, the substantial drawback of prior works has been resolved in this work. For $\sigma_0 = 0$ in the (6), $Slope_{\chi_0}$ will has the same value as $Slope_{\zeta_0}$, and for σ_0 on the negative side of the damping scale axis, the magnitude of $Slope_{\chi_0}$ is smaller than that of $Slope_{\zeta_0}$ [12].

C. Proposed Objective Function

In the proposed objective function (VSDS) it has been assumed that there is a variable slope for the straight line of the fan-shaped region, which its value is different in each range of damping factor interval $[\sigma_0\ \sigma_d]$. This variable slope has been considered for the most important modes and σ_d depicts the endpoint of this range. Indeed, the elevate of the critical mode's damping is taken into account as a key point to introduce a powerful objective function. Considering the incremental slope in the VSDS and its less energy expenditure for uncritical modes, it provides a higher damping scale and frequency limitation. Since the effectiveness of the last introduced well-known objective function has been compared to previous ones in [12], this objective function will be considered as a comparison criterion in designing a new proposed objective function. The objective function must be optimized to limit the eigenvalues considering the different damping scale values in each damping factor interval. The objective function can be expressed as follows:

$$\begin{cases} Min\ F_2 = \sum_{y=1}^{n_y} (\sum_{i=1}^{n_q} [\chi_k' - \chi_i])_y \\ for\ \sigma_i \in\ (\sigma_k' \text{ or } [\sigma_d\ -\infty)) \end{cases} \tag{7}$$

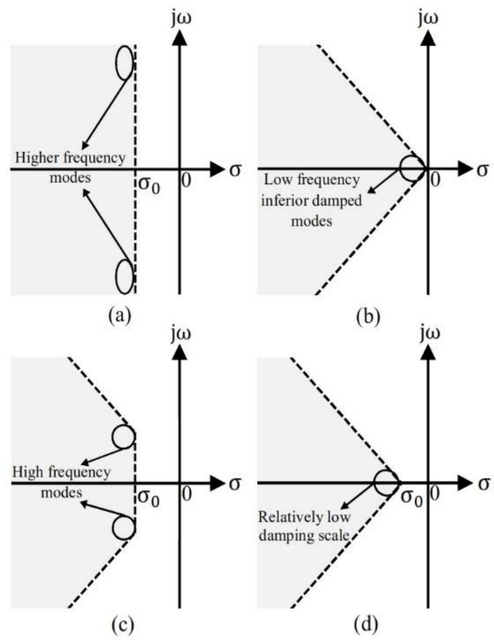

Fig. 2: Convergence regions of four objective functions. (a) Rectangular region of damping factor [5]. (b) Fan-shaped region with tip at the origin of damping ratio [13]. (c) D-shaped region of damping factor and damping ratio [7]. (d) Fan-shaped region with tip at σ_0 and the damping ratio ζ_0 of damping scale [12].

where χ'_k and σ'_k are shown in Fig. 3(a), and they can be computed as follows (indices of i and k are associated with different eigenvalue and interval step numbers, respectively):

$$\chi'_k = \begin{cases} \chi_k & \sigma \in [\sigma_0 \; \sigma_d] \\ \chi_f & \sigma \in [\sigma_d \; -\infty) \end{cases} \quad (8)$$

The parameter of χ_k is defined as follows:

$$\chi_k = \{\chi_0 - (k-1) * m \,|\sigma \in \sigma'_k\} \quad (9)$$

where,

$$\sigma_{k-1} \le \sigma'_k < \sigma_k; \qquad \sigma_k = \sigma_0 - k * r \quad (10)$$

In (7), all of the operating conditions have taken into consideration by the first sigma operator, and the value of inner parenthesis under different damping factor intervals has determined by the second sigma operator. The values of the required constant parameters such as k; r; m and etc. are listed in Appendix (Table A2).

As it is obvious in (11), the slope of the convergence curve is directly in the effect of χ'_k and varies by its change. In a specific interval, χ'_k is equal to χ_k, and it reduces by the rate of (k-1) × m times. As such, we have various values for χ'_k, and they will be obtained by the same procedure at different intervals (see Fig. 3(a)).

The slope of the convergence region, similar to (6), is computed as:

$$Slope_{\chi'_k} = \pm\sqrt{\frac{1}{(\chi'_k)^2} - 1} \quad (11)$$

According to (11), the slope of the convergence region is variable in different ranges. In the range of $[\sigma_0\,, \sigma_d]$, the value of $Slope_{\chi'_k}$ is smaller than $Slope_{\chi_0}$ and for $\sigma < \sigma_d$, these values are equal. The evaluation of the proposed objective function in Table 1 demonstrates its superiority, as it has other significant features in addition to the considerable characteristics of the well-known objective functions It should be mentioned that axis scales of the depicted figures in this section are not exact, and they are considered just for the sake of better presentation of our objective function characteristics (all of the terms/variables are defined in the nomenclature section).

Table 1: Evaluation of well-known objective functions

Convergence region	Component	High Frequency limitation	Damping factor limitation	High damping scale
Fig.2. (a)	σ	No	Yes	No
Fig.2. (b)	ξ	No	No	No
Fig.2. (c)	σ, ξ	No	Yes	No
Fig.2. (d)	χ	Yes	Yes	No
Fig.3. (b)	χ'	Yes	Yes	Yes

Simulation Results and Discussion

The case study here is a 10-machine 39-bus system as a medium multi-machine power system, which is shown in Fig. 4. Generally speaking, the PSS optimum parameters will be obtained by applying objective functions (OFs) of F_1 and F_2 and considering below constrained optimization problems.

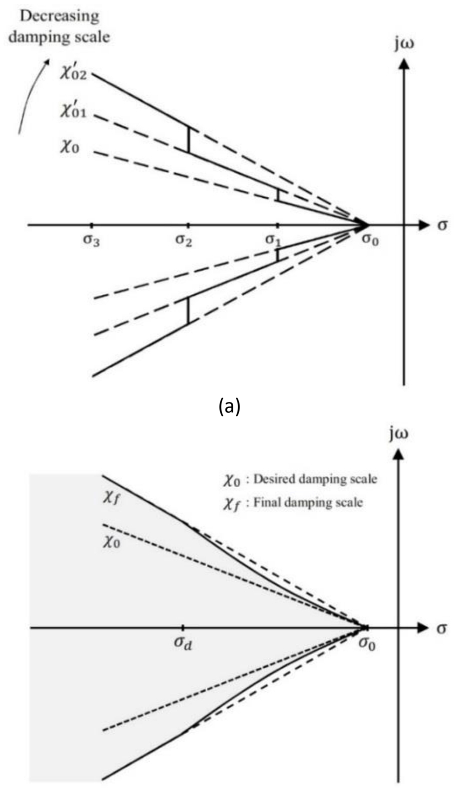

Fig. 3: (a) Slope change of convergence region, (b) Convergence region of the proposed objective function.

Minimize (OFs) subject to:

$$K_i^{min} \le K_i \le K_i^{max} \quad (12)$$

$$T_{1i}^{min} \le T_{1i} \le T_{1i}^{max} \quad (13)$$

$$T_{2i}^{min} \le T_{2i} \le T_{2i}^{max} \quad (14)$$

$$T_{3i}^{min} \le T_{3i} \le T_{3i}^{max} \quad (15)$$

$$T_{4i}^{min} \le T_{4i} \le T_{4i}^{max} \quad (16)$$

The range of optimizing our parameters is [0:001 50] for K_i and [0:01 1.0] for T_{1i}, T_{2i}, T_{3i} and T_{4i}. Furthermore, the optimization algorithm of GRSA has been chosen to be used in this optimization procedure. In the way of designing the proposed PSSs, OFs (F_1 and F_2) and GRSA are utilized to pursue a comparative study in our objective functions. In this paper, PSSs' parameters are optimized based on two kinds of an objective function, and the design based on each of which is considered as a scenario.

A. Tested system

The single-line diagram of the IEEE 10 machine (New England) power system (Fig. 4) is considered for simulation and the detail of system data is taken from . In this study, in order to achieve the overall dynamic stability of the test system with the presented approaches, all generators, except G2, which is an equivalent power source of the U.S.-Canadian interconnection system, are equipped with PSSs. To design robust PSSs, two different operating conditions in addition to our base case are characterized by the system under both severe loading conditions and critical line outage. Here the "Robust" term is used in this concept that the designed controllers will be responsive to load changes and will keep the system stable. The three cases are defined as:

Base case: normal condition.

Case 1: outage of the line between buses 21-22.

Case 2: outage of the line between buses 21-22 and 10% increase in the loads at even buses.

The above-mentioned cases are chosen based on the authors' knowledge which is obtained by various simulated cases. The obtained results also demonstrate that the above-mentioned cases are two sensitive ones for designing the PSSs. The results of sensitivity analysis, as it is needed for designing PSSs, illustrate the oscillation among given i^{th} and k^{th} generators as follows:

Considering "$\sim$" as oscillation symbol, $G_1 \sim G_3$,$G_4 \sim (G_2 \,\&\, G_6)$, $G_5 \sim G_4$ and $G_7 \sim G_6$. Therefore, all of generators G1, G4, G5 and G7 are select to equip with the WAPSSs installation. The feedback combination signal of the i^{th} generator is $\omega_i - \sum_k \omega_k$.

B. Eigenvalue Analysis and Simulation Results

The worst numerical values of stability characteristic out of eigenvalue's analysis under multiple operating conditions are summarized in Table 2. For the sake of brevity, only some critical modes are presented. Additionally, for each of objective function different values of χ_0 are considered over the maximum obtained value regarded to them. To give more details, 4:08% is considered for F_1 and 8:16% for F_2 both of which are obtained based on GRSA. After describing the accuracy of tuning method, our objective function can be assessed on the basis of root locus analysis at three operating points, which they are drawn into the complex s-plane as shown in Fig. 5. For space constraint reason and the significance of dominant poles, only the eigenvalues in the right side of -4 in horizontal axis are considered. The Root-Locus plot shows the placement of eigenvalues bounded based on the objective functions of F_1 and F_2 with the tip at the σ_0. According to that, higher values of critical modes' damping scale are clearly visible for the proposed objective function. In this way, it can be concluded that the proposed method effectively extend the power system stability limitations. Furthermore, convergence characteristic of objective functions under applied optimization technique has been depicted in Fig. 6. The PSS parameters searched by F_2 and utilizing GRSA method, and in addition, the requirement data in the process of evaluating proposed approach are written in Appendix (Tables A1 and A2).

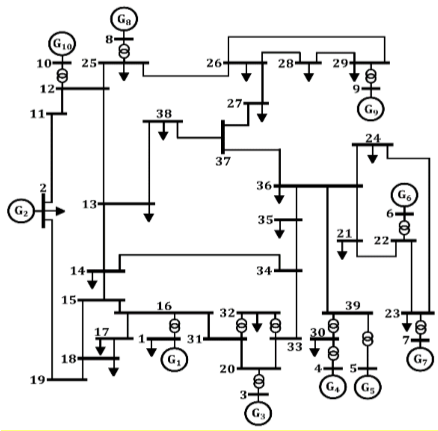

Fig. 4: Single-line diagram of 10-machine 39-bus (New England) Test System.

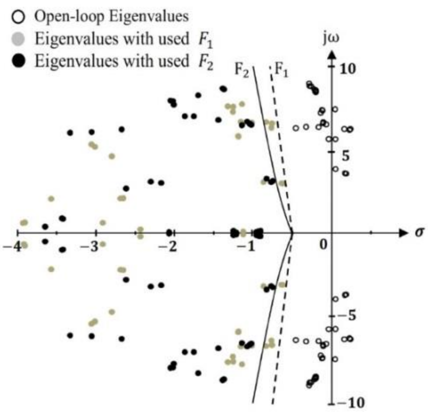

Fig. 5: Dominant eigenvalues of the system result by three operating conditions.

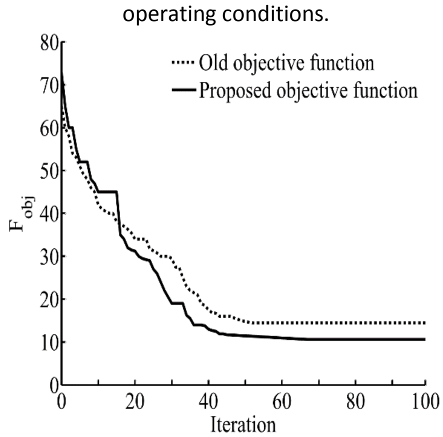

Fig. 6: Convergence characteristic of the proposed objective function.

Table 2: Dynamic stability characteristics of the test system in different conditions

Case type		Base Case				Case 1				Case 2			
sorted		f (Hz)	σ	ζ(%)	χ(%)	f(Hz)	σ	ζ(%)	χ(%)	f(Hz)	σ	ζ(%)	χ(%)
Non-PSSs		**0.593**	**0.049**	**-1.32**	**-14.5**	**0.556**	**0.168**	**-4.81**	**-18.7**	**0.551**	**0.184**	**-5.32**	**-19.38**
		0.959	**0.238**	**-3.95**	**-12.1**	**0.959**	**0.161**	**-2.68**	**-10.9**	**0.866**	**0.048**	**-0. 88**	**-10.02**
		1.001	-0.070	1.12	-6.81	0.867	-0.005	0.09	-9.04	**1.139**	**0.013**	**-0. 18**	**-7.15**
		1.133	-0.123	1.73	-5.29	1.127	-0.115	1.63	-5.41	**0.950**	**0.227**	**-9.04**	**-3.80**
F_1	Max σ	1.012	**-0.75**	11.86	4.08	0.461	**-0.62**	21.08	4.31	0.463	**-0.62**	20.90	4.20
		0.474	**-0.86**	27.95	12.24	1.008	**-0.76**	11.95	4.14	0.970	**-0.76**	12.48	4.38
		0.001	**-1.12**	100	99.00	1.018	**-1.01**	15.7	8.06	1.022	**-0.83**	12.89	5.21
	Min ζ	1.012	-0.75	**11.86**	4.08	1.008	-0.76	**11.95**	4.14	0.970	-0.76	**12.48**	4.38
		1.116	-1.25	**17.63**	10.72	1.018	-1.01	**15.7**	8.06	1.022	-0.83	**12.89**	5.21
		1.024	-1.15	**17.66**	10.13	1.162	-1.25	**16.9**	10.24	1.186	-1.14	**15.14**	8.57
	Min χ	1.012	-0.75	11.86	**4.08**	1.008	-0.76	11.95	**4.14**	0.463	-0.62	20.9	**4.20**
		1.024	-1.15	17.66	**10.13**	0.461	-0.62	21.08	**4.31**	0.970	-0.76	12.48	**4.38**
		1.116	-1.25	17.63	**10.72**	1.018	-1.01	15.7	**8.06**	1.022	-0.83	12.89	**5.21**
F_2	Max σ	0.506	**-0.82**	25.20	10.27	0.474	**-0.76**	25.00	9.00	0.484	**-0.74**	23.90	8.16
		0.029	**-0.90**	98.01	91.07	0.016	**-0.92**	99.40	97.25	0.020	**-0.95**	99.14	96.41
		1.005	**-1.04**	16.28	8.55	1.026	**-1.07**	16.46	8.90	0.998	**-1.02**	16.09	8.30
	Min ζ	1.005	-1.04	**16.28**	8.55	1.321	-1.37	**16.29**	10.43	0.998	-1.02	**16.09**	8.30
		1.329	-1.38	**16.41**	10.59	1.026	-1.07	**16.46**	8.90	1.008	-1.03	**16.20**	8.49
		1.266	-1.69	**20.88**	14.90	0.993	-1.14	**18.00**	10.24	1.328	-1.38	**16.33**	10.50
	Min χ	1.005	-1.04	16.28	**8.55**	1.026	-1.07	16.46	**8.90**	0.484	-0.74	23.90	**8.16**
		0.506	-0.82	25.20	**10.27**	0.474	-0.76	25.00	**9.00**	0.998	-1.02	16.09	**8.30**
		1.329	-1.38	16.41	**10.59**	0.993	-1.14	18.00	**10.24**	1.008	-1.03	16.20	**8.49**

C. Nonlinear Time-Domain Simulation

The nonlinear time-domain simulation of the power system is conducted, which uses a power flow program to calculate the dynamic initial conditions, and Differential- Algebraic-Equations (DAEs) of the power system is solved with MATLAB/Simulink through using the Ordinary Differential Equation (ODE) solver which is presented in. Additionally, to ascertain the designed PSSs' robustness in the state of variable operating conditions, there is a study which completely investigates the system response by considering three following disturbance (Corresponding to D:1, D:2, and D:3):

- A three-phase short circuit fault at bus 39 at t = 1s. The fault is cleared by tripping the line between buses 36-39 after 100 ms.
- 0.05 pu increment in V_{ref} of the G_3 excitation system at t = 1s, with a duration of 100 ms.
- 50% load increasing at bus 35 at t = 1s with a duration of 100 ms.

Because of space constraints, some studies are only conducted with considering the first disturbance.

D. Evaluation of Objective Functions

The main goal of this section is to concentrate on the positive effect of the proposed objective function by considering the first scenario under various operating conditions. Since all of the state variables of the system, such as speed response and generators' rotor angle deviation, obviously demonstrate the behavior of the power system, rotor angle deviations are selected to be analyzed here.

The rotor angle of G_3 with respect to G_1 (as reference generator) under the presence of the first disturbance is depicted graphically in Fig. 7(a)-Fig.7 (c). These figures show that the generators' response by applying the old objective functions undergo more oscillations. In contrast, designed PSSs by considering proposed objective function can effectively mitigate the oscillations so that settle faster and reach the new steady-state condition. The latest figure shows that the designed PSSs can be effective even under severe conditions and robustness will be obtained.

E. Evaluation of Performance Indices

In order to do a clear and complete system response for different disturbances, two common performance indices (PI) which are respectively associated with the settling time and overshoot in speed response (ISTSE, and ISE) [9], are described as (17) and (18). It has been shown that these indices are more appropriate ones than others for representing system characteristics.

$$ISTSE\ (PI_1) = \sum_{i=1}^{n_m} \int_{t=0}^{t=t_{sim}} (t \times \Delta\omega_i(t))^2 dt \qquad (17)$$

$$ISE\ (PI_2) = \sum_{i=1}^{n_m} \int_{t=0}^{t=t_{sim}} (\Delta\omega_i(t))^2 dt \qquad (18)$$

Furthermore, Table 3 represents the information about the performance indices of PI_1 and PI_2 by considering all three disturbances in the mathematical equations. Here, it is obvious that the obtained result of performance indices for the second scenario is better in all of the disturbances. As such, from the stability point of view, it should be noted that there has been supremacy in relation to our proposed technique in different disturbances.

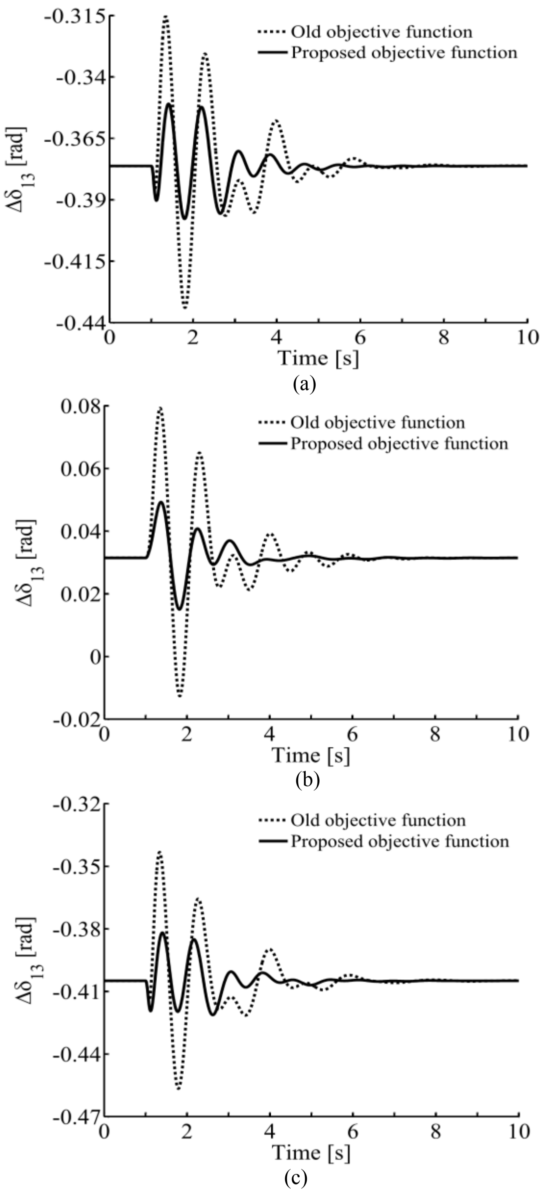

Fig. 7: Rotor angle deviation with the first disturbance (a) Base case for evaluating of objective function (b) Case 1 for evaluating of objective function (c) Case 2 for evaluating of objective function.

Table 3: Performance indices of the system response under different scenarios and disturbances

Scenario	Parameter	Disturbance		
		D.1	D.2	D.3
S.1	PI_1	0.0318	1.0665	0.0124
	PI_2	0.1716	2.5131	0.3427
S.2	PI_1	0.0290	0.9221	0.0117
	PI_2	0.1533	2.1974	0.3226

Conclusion

The purpose of this paper was to introduce a novel objective function and use it in designing powerful PSSs. To overcome the low value of the obtained damping scale in old objective functions, some additional restrictions have been applied to the convergence region and led to the VSDS objective function. To be more specific, further displacements of critical modes were considered to enhance the overall dynamic stability of the power system. To prove the superiority of the proposed function, a comparison study has been taken place over the values of damping scale and performance indices. It has been shown that a variable slope convergence region is better than that of a constant slope one in obtaining optimal parameters. Small signal analysis and time-domain simulations have been implemented on a multi-machine power system and the effectiveness of the proposed method has been demonstrated.

Appendix

Optimal parameters of the designed PSSs and also requirement data for evaluating the proposed approach are listed in Table A1 and Table A2, respectively.

Table A1: Optimal parameters of the designed PSSs

Parameter	Symbol	Unit	Value
Damping factor interval number	k	-	1:1000
Desired value of damping factor	σ_d	-	-10.5
Factor of gradient reduction	m	-	0.0001
Step length of damping factor intervals	r	-	0.01
Initial value of damping factor	σ_0	-	-0.5
Number of operating conditions	n_y	-	3
Number of steps in slope change	n_k	-	1000
Washout time constant	T_w	Sec	10
Weight of local machine feedback signal	γ_L	-	1
Weight of remote machine feedback signal	γ_R	-	-1

Table A2: Requirement data

Gen	Old Objective Function				
	K	T_1	T_2	T_3	T_4
G_1	16.9523	0.5033	0.1708	0.3986	0.0209
G_3	2.6856	0.3305	0.0206	0.6281	0.2350
G_4	45.0241	0.5252	0.0201	0.4207	0.5239
G_5	4.8984	0.3366	0.0200	0.3934	0.1849
G_6	45.3028	0.6905	0.2952	0.3499	0.0228
G_7	2.895	0.5971	0.0200	0.8119	0.6676
G_8	3.0008	0.4011	0.2050	0.5041	0.0229
G_9	5.5970	0.5146	0.0205	0.1888	0.2132
G_{10}	12.405	0.1861	0.1607	0.4746	0.0244
	Proposed Objective Function				
	K	T_1	T_2	T_3	T_4
G_1	8.9127	0.6506	0.0203	0.5743	0.3967
G_3	6.8628	0.2696	0.1584	0.4414	0.0382
G_4	49.3471	0.3670	0.3838	0.6252	0.0210
G_5	46.7737	0.4394	0.2333	0.3453	0.0200
G_6	5.7158	0.4169	0.3143	0.7340	0.0215
G_7	6.7360	0.3990	0.3317	0.4173	0.0233
G_8	5.2918	0.2736	0.2544	0.6973	0.0209
G_9	30.0610	0.1307	0.0242	0.6043	0.1316
G_{10}	3.4127	0.6069	0.4990	0.4321	0.0221

Author Contributions

B. Ehsanmaleki and H. Beiranvand have found a new method for enhacing existing objective function. H. Beiranvand presented new method for carring out of nonlinear time-domain simulation. B. Ehsanmaleki and P. Naderi interpreted the results and wrote the manuscript.

Conflict of Interest

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the ethical issues including plagiarism, informed consent, misconduct, data fabrication and, or falsification, double publication and, or submission, and redundancy have been completely witnessed by the authors.

Abbreviations

A, B	Constant matrices of state-space equations
C_r	Crossover probabilities
d	Dimension of particle position
Dn	Dimension of cloud
E_{fdi}	Field voltage of i^{th} excitation system (V)
En	Entropy or uncertainty measurement of qualitative concept
Ex	Mathematical expectation of cloud drop
F_1	Damping scale objective function
F_2	Variable slope damping scale objective function
f_{ave}	Average value of function
f_g	Best solution for optimization algorithm till now
f_{rand}	Random selected objective function value in current subspace
FNC	Forward normal cloud generator
G_i	Transfer function of i^{th} PSS
K_{Ai}	Gain of i^{th} excitation system
k	Subscript index of machine numbers
K_i	Optimal value of i^{th} PSS's stabilizer gain
$K_{V,ij}(t)$	Distance of best position and a random particle position in search subspace *s*
l	Number of particle
M_g	Maximum generation
M_p	Mutation probabilities
m	Factor of gradient reduction
N_p	Population size
n	Number of state variable
n_k	Number of steps in slope change
n_q	Number of system's eigenvalues
n_y	Number of system's operating condition
n_m	Number of test system's machine
q	Subscript index of system's eigenvalues
r	Step length of damping factor intervals
S_s	Search space size
S	Number of search subspaces
$Slope_{\zeta_0}$	Convergence region slope in old objective function (°)
$Slope_{\chi_0}$	Convergence region slope in objective function F_1 (°)
$Slope_{\chi'_k}$	Convergence region slope in objective function F_2 (°)
s	Denotation of complex plane
$sign$	Signum function
S_s	Search space size
T_{Ai}	Time constant of i^{th} excitation system
T_{ji}	j^{th} optimal time constant of i^{th} PSS
T_w	Washout time constant
t_{sim}	Simulation time duration
$T_i(t)$	Best particle position obtained in exploration till now
$T_{ij}(t)$	Best position of j^{th} component of i^{th} particle
$T^{rand,s}$	Random position in search subspace *s*
$T^{Best,s}$	Best position in search subspace *s*
$T_j^{Best,s}(t)$	j^{th} component of best position in search subspace *s*
TG	Global best particle position obtained in tensor till now
TB_i	Best position obtained in the exploration till now
$X_i(t)$	Cloud drop of i^{th} agent
$X_{i,rand}$	Negative random selected cloud drop of i^{th} agent
y	Subscript index of system operating condition
U	Vector of input variable
$V_{ij}(t)$	Velocity vector of i^{th} agent of j^{th} dimention
V_{PSSi}	Output voltage of i^{th} PSS (V)
V_{refi}	Reference voltage of i^{th} generator (V)
V_{ti}	Terminal voltage of i^{th} generator(V)
X	Vector of state variable

γ_L	Weight of local machine feedback signal
γ_R	Weight of remote machine feedback signal
σ	Damping factor of eigenvalue
σ_0	Initial value of damping factor
σ_d	Desired value of damping factor
σ_k	Damping factor of k^{th} step
σ'_k	Damping factor of k^{th} interval
σ_i	Damping factor of i^{th} eigenvalue
ω_{Li}	Angular speed of i^{th} local machine (rad/s)
ω_{Rk}	Angular speed of k^{th} remote machine (rad/s)
ω_i	Angular speed of i^{th} machine (rad/s)
χ_i	Damping scale of i^{th} eigenvalue
χ_q	Damping scale of q^{th} eigenvalue
χ_0	Expected damping scale's value in different conditions
χ_f	Final damping scale value in different conditions
χ'_k	Damping scale's expected value of k^{th} interval
ζ_0	Initial value of damping ratio
ω_t	Weighting factor in step length equation
ε	Very small number
∂	Symbol of deviation
Δ	Symbol of difference
$\sum.$	Symbol of summation

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