

Design of Power System Stabilizer for Power System Damping Improvement with Multiple Design Requirements

G.Y.Rajaa Vikhram, S.Latha

Abstract— In this paper the optimization problem of tuning of lead-lag Power System Stabilizer (PSS) for damping of oscillations in single machine infinite bus power system with multiple design requirements is considered. The design requirements are considered as both time domain and frequency domain specifications which are initially specified before designing the PSS. The optimization based linear control design technique is used to determine the optimal controller parameters. The stabilizer contributes to the electro mechanical torque components without affecting the synchronizing torque in the system. The proposed design of power system stabilizer is tested for various disturbance conditions for damping of oscillations while satisfying the design requirements.

Index Terms— Power System Stabilizer, Damping of oscillations, Time domain and Frequency domain specifications, Optimization based Linear control design.

I. INTRODUCTION

Power System Stabilizers are used for many years to add damping to the electromechanical oscillations. It will act through the generator excitation system which produces a component of electrical torque according to the speed deviation is generated (in addition to the damping torque) [1, 2]. However it is easy to implement the PSS as its function mainly depends upon the modes of oscillation. i.e. whether it is local or inter-area mode[3]. The highly efficient stabilizer which produces a damping torque over a wide range of frequencies[4] where as less efficient stabilizer for a small range of frequencies only, which makes problem when the system changes its oscillation mode also change correspondingly.

Power System Stabilizer is used to provide additional modulation signal to the reference input of automatic voltage regulator. Due to this idea an electrical torque is produced in the generator proportional to the speed deviation. In earlier days PSS consists of lead block to adjust the input signal to give the correct phase.

General inputs to the PSS are generator shaft speed, terminal bus frequency, electrical or accelerating power. It consists of gain block, lead – lag block and a high pass filter which is called as a washout block in power system. The low frequency oscillations are observed in the power system since 1960s in the interconnected large scale power systems with weak tie-lines due to the insufficient damping provided for the system [5].

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These oscillations will grow and deteriorate the system performance and leads to system instability. It also noted that the change in loading conditions which make the machine parameters also vary for different operating conditions so that the stabilizer should maintain the stability of the system even though the change occur in a complex manner. Therefore the PSS should be robustness to the changing machine parameters, loading and operating conditions etc.

Power System Stabilizer is the effective one for damping electromechanical oscillations especially in interconnected power system. There are two optimization problem related to PSS. One is selecting the optimum location of PSS and determining the optimum stabilizer parameters. This paper deals with tuning of lead-lag stabilizer to damp out the oscillations with required design requirements. When the stabilizers are correctly tuned the the resulting damping action will be robust. The main advantage of PSS is a cost effective one when compared to the power electronics based FACTS controller when used for damping application. PSS have been used for over 20 years in the western part of United States of America Ontario Hydro. In United Kingdom it was reported that PSS have been used for damping of oscillations when the power is transmitted for long distance with weak AC tie-lines like connecting Scotland and England. However PSS is not used under normal operating condition it will be service at abnormal or unusual condition which may occur sometimes. Therefore PSS is necessary to operate along with modern excitation systems to damp out the oscillations effectively and also to enhance the system stability.

This paper deals with the tuning of lead-lag power system stabilizer for damping of oscillations in single machine infinite bus system. There are so many papers related to the design of PSS but in this work the design requirements are considered like time domain and frequency domain specifications. Settling time is considered as a main performance criteria in damping of oscillations for time domain specifications and for frequency domain specifications the gain margin and phase margin is considered. Optimization based linear control design is a graphical user interface which is available in control system toolbox in matlab software. There are different types of optimization algorithm available in the toolbox, the design requirements and constraint bounds are initially specified where the objective is to damp out the oscillations by minimizing the settling time. The same optimization algorithm is also run for frequency domain requirements. So both time and frequency domain requirements are satisfied for a single machine infinite bus system with stabilizer.

II. SINGLE MACHINE INFINITE BUS POWER SYSTEM

The design of power system stabilizer is done for single machine infinite bus system which is presented here.

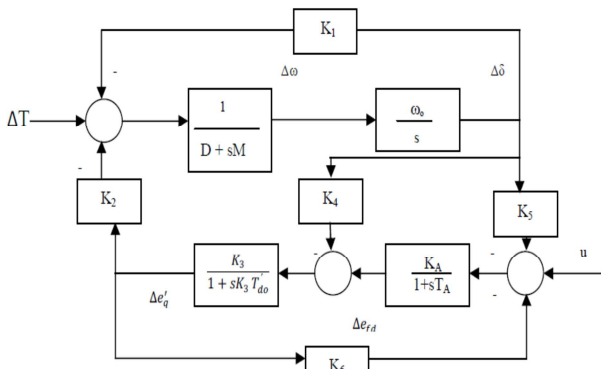


Fig.1. Block diagram of single machine infinite bus power system model

A machine which is connected to a large system through the transmission line is reduced to SMIB by thevenin's equivalent of the transmission network external to the machine. The dynamics associated with a machine connected to a large system will make no change in voltage and frequency of the thevenin's voltage i.e. E_b (infinite bus voltage) and equivalent impedance is given as $R_e + jX_e$ which is known as thevenin equivalent impedance. The nominal operating condition and system parameters are given in appendix. IEEE ST1A model of excitation system is considered and PSS consists of a lead-lag block where speed deviation $\Delta\omega$ is the input signal. From Fig.1 it shows the transfer function block diagram representation of SMIB system relating the system variables like speed, rotor angle, terminal voltage, field voltage and flux linkages. By linearizing the non linear differential equations the linear model has been developed around the nominal operating conditions.

A. Exciter and PSS:

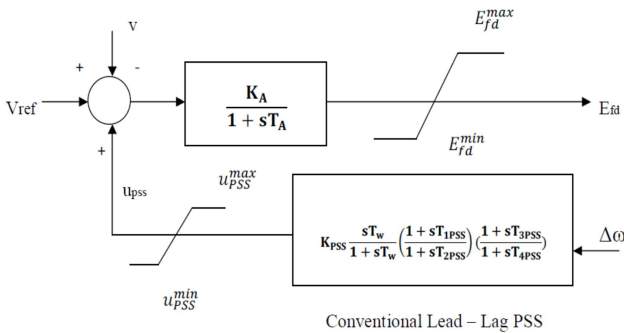


Fig.2. IEEE Type – ST1 excitation system with PSS

The transfer function model of static excitation system with PSS is shown in Fig.2. It is described as
$$pE_{fd} = (K_A(V_{ref} - V + u_{pss}) - E_{fd})/T_A \quad (1)$$

V_{ref} is the reference voltage, K_A and T_A are gain and time constant of the excitation system respectively and u_{pss} is the control signal generated by the PSS proportional to the speed deviation. From eqn (1) the terminal voltage V can be expressed as

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$$v = (v_d^2 + v_q^2)^{1/2} \quad (2)$$

$$v_d = x_q i_q \quad (3)$$

$$v_q = E'_q - x'_d i_d \quad (4)$$

B. Transfer function model of Power System Stabilizer:

From fig.3 it shows that the control signal produced by PSS in response to the speed deviation which acts through the generator excitation system. The $GEP(s)$ is the transfer function of the system whose output is the electromechanical torque component and input is control signal u_{pss} . In order to increase the damping of oscillations the speed deviation as stabilizing signal of PSS should produce the electromechanical torque component in phase with speed deviation thereby compensate for phase lag of $GEP(s)$. The transfer function model of PSS is given by

$$u_{PSS} = K_{PSS} \frac{sT_w}{1+sT_w} \left(\frac{1+sT_{1PSS}}{1+sT_{2PSS}} \right) \left(\frac{1+sT_{3PSS}}{1+sT_{4PSS}} \right) \Delta\omega \quad (5)$$

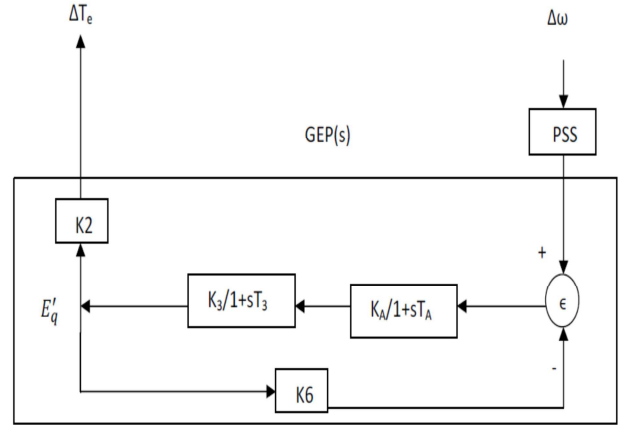


Fig.3. Transfer Function model which shows the relationship between electrical component of the torque (ΔT_e) produced by the regulator in response to the speed deviation ($\Delta\omega$)

Where T_w is called as washout time constant, K_{pss} is gain of power system stabilizer and T_{1pss} , T_{2pss} , T_{3pss} , T_{4pss} are lead-lag time constants of PSS respectively. Usually T_w and T_{2pss} , T_{4pss} are prespecified and K_{pss} , T_{1pss} , T_{3pss} only have to be determined. By the method of optimization based linear control design the parameters of PSS are tuned using optimization algorithm which satisfies the time domain and frequency domain specifications are taken as optimum controller parameters.

C. Proposed Control Scheme

To analyse the performance of PSS for damping of low frequency oscillations which associated with electromechanical modes the following control schemes are proposed.

- i) PSS only is considered, in this case, the tuning parameters are $K_{pss}, T_{1pss}, T_{3pss}$.
- ii) Step response bounds from 0 to 15 seconds is considered
- iii) The main task of the PSS design is to damping of oscillations for a wide range of disturbances and satisfying the time domain specifications like settling time, overshoot and frequency domain specification like Gain margin and Phase margin. Settling time is considered as a main performance criteria for damping of oscillations.

To minimize the objective function J .

$$J = \int_{t=0}^{t=t_{sim}} t(|\Delta\omega|) dt \quad (6)$$

The constraints are stabilizer parameter upper and lower bounds and the design of PSS is formulated as optimization problem as follows

Minimize J

Subject to

$$K_{pss}^{min} \leq K_{pss} \leq K_{pss}^{max}$$

$$T_{1pss}^{min} \leq T_{1pss} \leq T_{1pss}^{max}$$

$$T_{3pss}^{min} \leq T_{3pss} \leq T_{3pss}^{max}$$

III. OPTIMIZATION BASED LINEAR CONTROL DESIGN – SMIB WITH PSS DESIGN

Optimization based linear control design is a technique available in control system toolbox in matlab software. It is used to optimize the systems for LTI models by optimizing the controller parameters in SISO design tool. It is also known as optimization based tuning which change the controller parameters only and not the structure itself. The controller with initial parameters is specified which are tuned with additional design requirements and constraints are the parameter bounds. It provides great flexibility in providing additional design requirements, selecting tuning parameters and real time updating of the controller parameters.

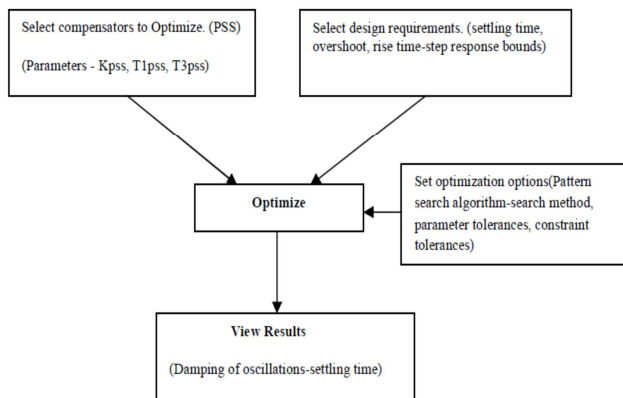


Fig.4. Optimization Overview

The design requirements are control design specifications. It is very difficult to transform power system objectives into control design specifications. However the designed power system damping controller should satisfy the following stability and performance criteria.

- A minimum damping ratio should be maintained for critical modes and greater than 0.1 for low frequency modes like inter-area modes.
- The settling time is the main damping criteria for oscillations in time domain specifications which should be lower than the desired value.
- The damping action should not deteriorate the system to unacceptable condition and should maintain the performance and stability of the system. This is because lower the damping the phase margin is reduced.

A. Design Requirements:

Time domain specifications:

Rise Time	: 5 sec
Settling Time	: 10 sec
% Overshoot	: 10
% Rise	: 1
% Settling	: 5
% Undershoot	: 10

Step response bounds from 0 to 15seconds.

Frequency domain specifications:

Gain Margin	- > 6db
Phase Margin	- 30 to 60 degree

The main task is to damp out the oscillations in the SMIB system by the designed PSS with stabilizer parameters as a

constraints with various disturbances. In addition to that the optimization algorithm should satisfy the above specified requirements for the response of speed, rotor angle and terminal voltage of the SMIB system. Settling time is considered as a main performance criteria, because, the damping of oscillations is represented through the reduction of settling time. The following results shows the main significant to the settling time, however other design requirements are more or less satisfied depends upon the optimization algorithm chosen.

IV. RESULTS AND DISCUSSION

Matlab simulations are carried out for SMIB system with PSS alone. Fig.5 shows the response of SMIB system with initial parameters of PSS for damping of oscillations for the step input disturbance. From the figure it is observed that the oscillations are stay for longer duration which is about 45seconds.

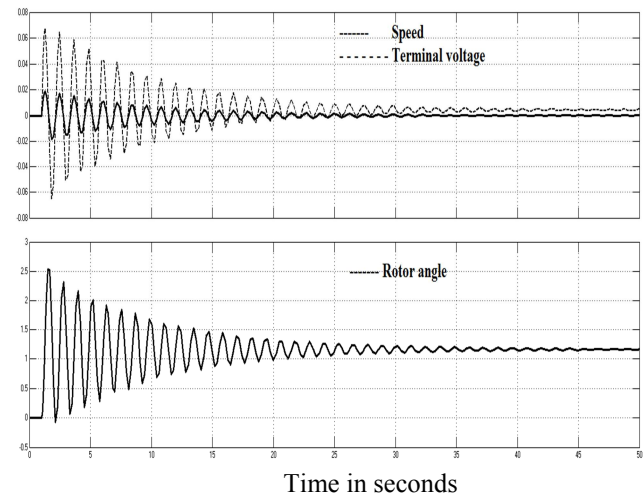


Fig.5. Speed, Rotor angle, and Terminal voltage response of SMIB system with initial Stabilizer parameters.

The Pole-Zero map of SMIB system with initial PSS parameter values is shown in fig.6. It is observed that the system is marginally stable i.e. a pair of poles lying on the imaginary axis.

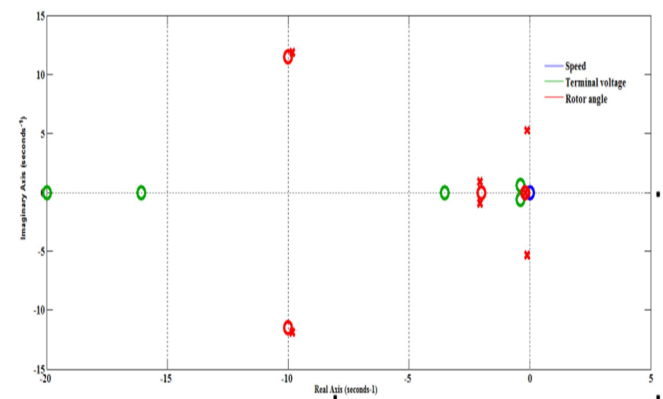


Fig.6. Pole-Zero map of SMIB system with initial PSS

To make the system stable and also to damp out the oscillations the optimization based linear control design method is used to design the stabilizer. By using control system design toolbox the various optimization algorithm is used to determine the optimum gain and time constant of stabilizer for damping, enhance the stability and also satisfy the time and frequency domain specifications.

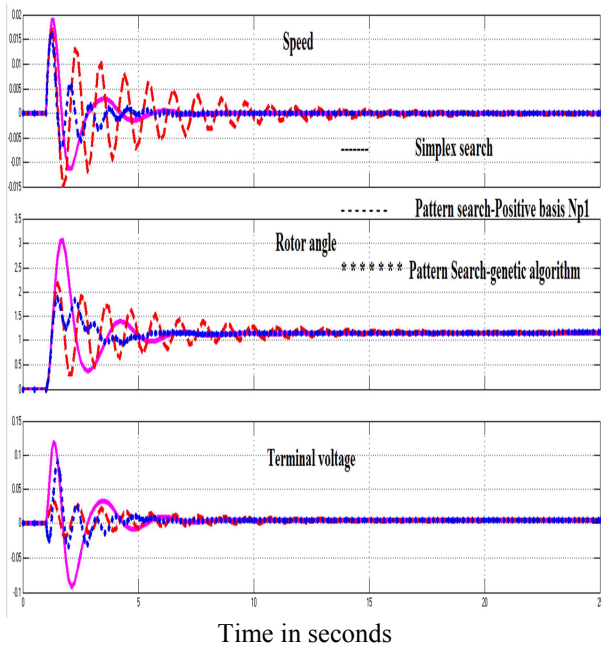


Fig.7. Speed, Rotor angle, and Terminal voltage response of SMIB system with Simplex and Pattern search optimization tuned Stabilizer parameters.

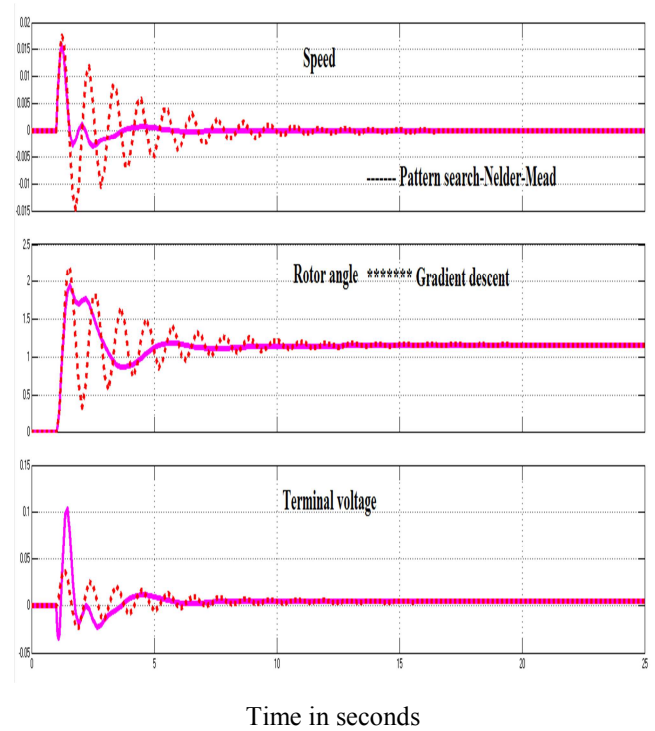


Fig.11. Speed, Rotor angle, and Terminal voltage response of SMIB system with Pattern search-Nelder-Mead and Gradient descent optimization tuned Stabilizer parameters.

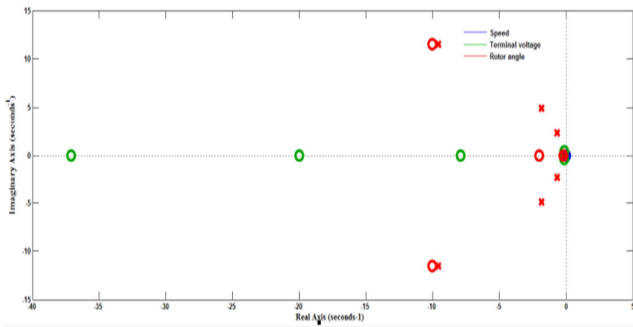


Fig.8. Pole-Zero map of SMIB system with Simplex algorithm tuned PSS

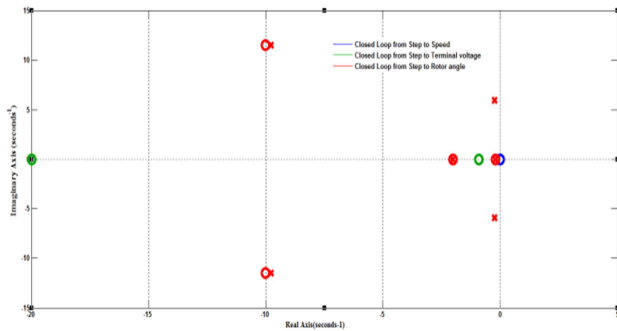


Fig.9. Pole-Zero map of SMIB system with Pattern search-Positive basis Np1 algorithm tuned PSS

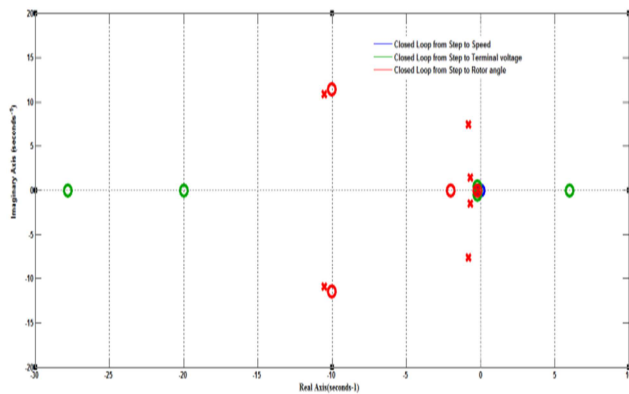


Fig.10. Pole-Zero map of SMIB system with Pattern search-Genetic algorithm tuned PSS

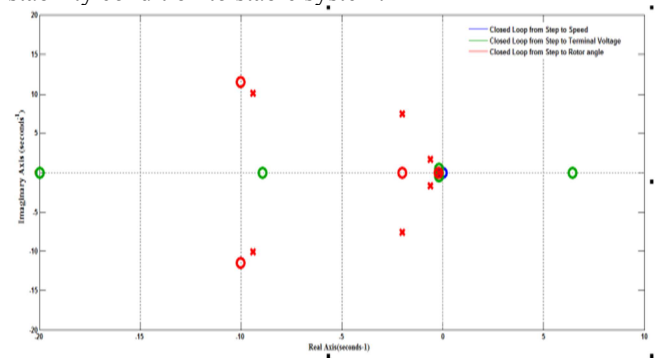


Fig.12. Pole-Zero map of SMIB system with Pattern search-Nelder Mead algorithm tuned PSS

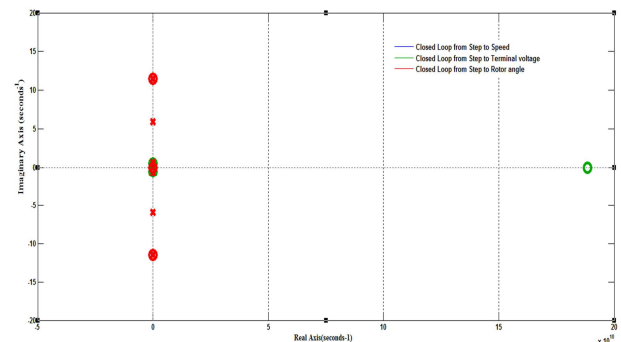


Fig.13. Pole-Zero map of SMIB system with Gradient descent algorithm tuned PSS

Table.1 shows the comparison of different types of optimization algorithm used for linear control design of PSS to damp out the oscillations and stability enhancement with time domain and frequency domain requirements. The settling time is considered as main performance criteria for time domain specification, for frequency domain specification the sign is not important for gain margin whether it is positive or negative rather the stability of the system should be noticed. The design requirements are already specified. From the table it is observed that time domain specifications are completely satisfied but frequency domain specification of gain and phase margin is just satisfied to its specified value but stability is enhanced.

Fig.15. shows the comparison of Gain and Phase Margin for speed, rotor angle and terminal voltage response of SMIB system for different optimization techniques. First we have to determine whether the system is stable or not. And then to find out the magnitude of stability, only sign is not enough. When the controller is connected to the system its performance should not be degraded. From the bode plot response of the system with tuned controller it is concluded that when the gain cross over frequency is less than phase cross over frequency for open loop, closed loop will be stable. And also the gain margin may be negative, but when phase margin is negative the system becomes unstable. For the robustness of the system the gain margin should be greater than 2db and phase margin should be 30 to 60 degree.

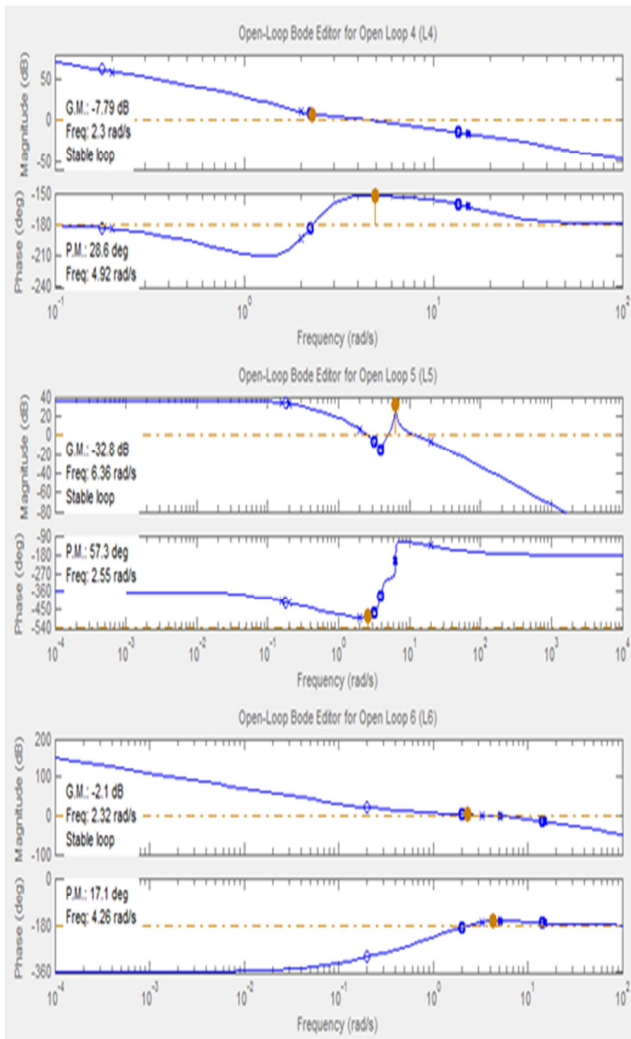


Fig.14. Magnitude and Phase plot for the Speed, rotor angle and terminal voltage of SMIB system with Simplex search algorithm tuned PSS.

Fig.16. shows the bar graph representation for comparison of settling time for speed, rotor angle and terminal voltage response of SMIB system for different optimization techniques. The response of the system for the given disturbance is growing in oscillations, so that the settling time is more than 35 seconds. So a controller must be designed to make the system stable and also to improve the damping. When PSS is connected to the system it improves the stability of the system and the oscillations are reduced. The settling time is reduced less than 25 seconds as observed from bar graph.

Among the different optimization algorithm used for tuning of PSS in SMIB system the pattern search - nelder mead algorithm performs better in reducing the settling time and maximum overshoot of speed, rotor angle and terminal voltage responses is reduced while satisfying the time domain specifications.

For optimization based tuning of PSS it is observed that the pattern search – Nelder mead method performs better among all other methods by increase in both gain and phase margin values.

Table: 1 – Comparison Of Different Types Of Optimization Methods For Linear Control Design Of Pss With Multiple Time And Frequency Domain Specifications

Time Domain Specifications – Main Performance Criteria (Settling Time)														
Frequency Domain Specifications – Gain Margin & Phase Margin														
Optimization Method	Optimization Parameter Settings		Power System Stabilizer Tuned Parameter Values			Settling Time (sec)			Gain Margin (db)			Phase Margin (degree)		
	Parameter/Function/Constraint Tolerance	Max. No. of Iterations	K_{ps}	$1+sT_{1ps}/1+sT_{2ps}$	$1+sT_{3ps}/1+sT_{4ps}$	Speed	Rotor angle	Terminal voltage	Speed	Rotor angle	Terminal voltage	Speed	Rotor angle	Terminal voltage
Simplex Search	0.001	300	13.088	$0.24+s3.90/s^2$	$0.57+s5.66/s^2$	3.75	8.5	7.8	-7.79	-32.8	-2.1	28.6	57.3	17.1
Pattern Search-Positive basis Npl	0.001	300	4.34	$-1.90e-14s-2.35e-13/s^2$	$-2.36e-14s-1.96e-13/s^2$	21	28	25	42.1	-22	42.1	4.4	61.3	4.4
Pattern Search-Genetic Algorithm	0.001	300	4.1939	$0.24+s0.66/s^2$	$-1.69+s4.8/s^2$	6	7.6	7	7.45	-9.73	-7.17	12	46.1	18.9
Pattern Search-Nelder – Mead	0.001	300	779.27	$-0.20+s0.8/s^2$	$0.03+s0.34/s^2$	4.9	8.1	7.7	12.3	-21.4	-4.98	24.4	44.5	38.6
Gradient descent	0.001	300	51.284	$-1.11e-9s-0.00017/s^2$	$0.0016s-2347.77/s^2$	15.1	17	15.1	-25.6	-22.6	-17.4	5.93	60.9	5.91

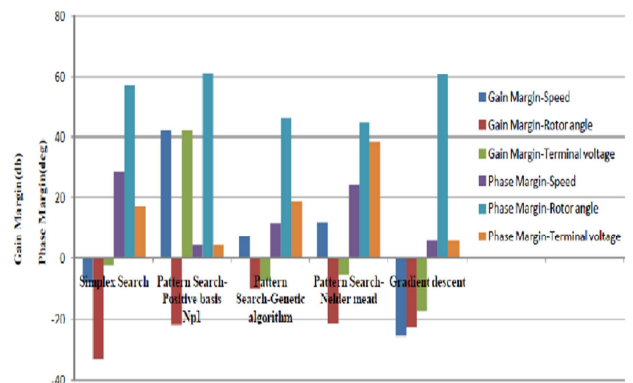


Fig.15. Comparison of Gain and Phase Margin for speed, rotor angle and terminal voltage response of SMIB system for different control schemes.

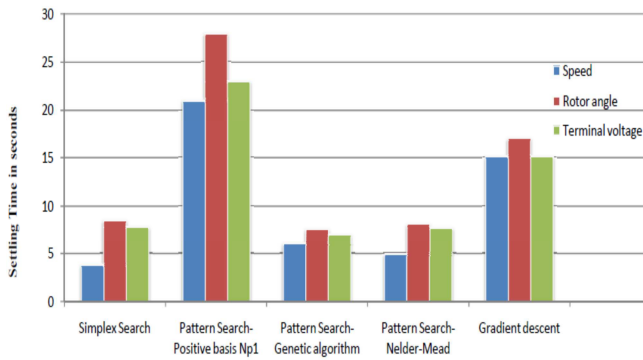


Fig.16. Comparison of settling time for speed, rotor angle and terminal voltage response of SMIB system for different optimization techniques.

V. CONCLUSION

This paper proposes a simple technique for design of Power System Stabilizer for damping of oscillations using optimization based linear control design technique. Different types of optimization algorithms are used to determine the optimum parameters of stabilizer for damping of oscillations. The performance of different algorithm is compared, based on the settling time the pattern search – genetic algorithm performs better than other algorithm, based on phase margin pattern search – nelder mead method perform better than other algorithm. By this simple compensator design technique the oscillations are damped out quickly and the stability is improved from marginally stable to completely stable system. Time domain and frequency domain requirements are satisfied with overall improvement in stability.

APPENDIX A: The linearized system equations

$$\begin{aligned} \Delta \dot{\delta} &= \omega_o \Delta \omega \\ \Delta \dot{\omega} &= -\frac{1}{M} [-\Delta P_e - D \Delta \omega] \\ \Delta \dot{e}_q &= \frac{1}{T_{do}} [-\Delta e_q + \Delta E_{fd} - (x_d - x'_d) \Delta I_{Ld}] \\ \Delta \dot{E}_{fd} &= -\frac{1}{T_A} (\Delta E_{fd} - K_A \Delta V_t) \end{aligned}$$

APPENDIX B: System Parameters

All the quantities are in per unit, except as indicated. $M=9.26s, T_{do}=7.76s, x_d=1.0, x'_d=0.3, x_q=0.6, D=0, K_A=50, T_A=0.05s, P=1, Q=0.25, x_e=0.2p.u, K_1=0.5995, K_2=0.9263, K_3=0.5294, K_4=0.4319, K_5=-0.0878, K_6=0.6004.$

APPENDIX C: Nomenclature

- D – damping constant of the generator
- E_{fd} – field voltage
- E'_q - transient EMF in q-axis of the generator
- K_A – gain of the excitation system
- T_{do} – open circuit field time constant
- T_A – time constant of the excitation system
- u_{pss} – output signal of the pss
- v – terminal voltage of the generator
- v_d – d-axis component of the terminal voltage
- v_q – q-axis component of the terminal voltage
- x_d – d-axis reactance of the generator
- x_q – q-axis reactance of the generator

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