INVESTIGATIONS ON SMALL SIGNAL STABILITY IN MULTIMACHINE POWER SYSTEM

Ph. D. Thesis

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This thesis is submitted as a partial
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CERTIFICATE

This is to certify that the thesis entitled, "***Investigations on Small Signal Stability in Multimachine Power System***", submitted by ***Akash Saxena*** (I.D. No. 2008 REE 102) to Malaviya National Institute of Technology Jaipur for the award of the degree of ***Doctor of Philosophy*** in Electrical Engineering is a bonafide record of original research work carried out by him under my supervision.

It is further certified that:

1. There is prima facie case for consideration of the thesis.
2. The thesis does not include any work which has at any time previously been submitted for the award of a degree.

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Abstract

The exponential growth in the demand of electricity along with rising population led to overexploitation of transmission and generation facilities, as a result, the existing power systems are operating under stressed conditions. The stressed conditions have created several stability related problems and left a question mark on the reliability of the power systems. Modern power system is a complex network having many interconnected grids and utilities. Designing of such a complex power system is a formidable challenge for power engineers. Thus, power system stability is considered as an epitome aspect while designing a foolproof system. In earlier days, stability studies were limited to transient stability analysis and to ensure transient stability high gain voltage regulators were employed with the generating units. However, complex grid connections and employment of high gain regulators resulted in oscillatory instability of power system. Oscillatory instability propagates through small signals or oscillations of low frequency (0.2 to 2 Hz) with escalating amplitude. A possible outcome of the propagation of such small signal oscillations may cause the system to collapse and may lead to blackouts and loss of economy. Cost effective control for oscillatory instability problems can be efficiently achieved by Power System Stabilizer (PSS). This thesis focuses on determination of ideal locations and designing of PSS for providing effective damping in multimachine power networks.

It is a daunting task to address and identify the effective locations of PSS in multimachine networks, as power system is subjected to different types of contingencies. An uncertainty lies in the fact that swing modes may get intensify during any contingency. Interestingly, approaches for this particular problem in the past were addressed with a set of particular operating conditions. An unabated dilemma persists that whether the location of PSS determined by traditional indexes would be suitable or not in dynamic scenario. This thesis presents a set of indexes based on probabilistic distribution of eigenvalues and overshoots, which solves the above stated problem. Real part of eigenvalue and overshoot associated with the swing modes are probabilistically distributed to make a close replica of real power system. Sensitivity Jacobians of real part and overshoot of swing modes give two indexes namely, Eigen Value Sensitivity Index and Overshoot Sensitivity Index.

A consequential comparison of the proposed approach with the traditional ones proves efficacy of the proposed approach. The simulation results are tested over two multi machine IEEE test systems.

Optimization processes are heart of planning models. In real power system, optimization processes are indispensable while dealing with estimation, designing and forecasting problems. The problem of PSS parameter estimation is a constrained optimization problem. It is worthwhile to mention here that parameters of PSS are not included in traditional eigenvalue based objective function. Grippingly in the existing literature, less emphasis has been given to study the parametric influence on objective function and the shape of objective function. The thesis presents comparative analysis of three schemes based on trajectory sensitivity. Parametric influence of PSS is observed in terms of Sensitivity Jacobians. Conventional golden section search is employed with gradient descent search for PSS parameter estimation of New England Power system. This work draws a line between evolutionary and conventional design by revealing the shortcomings of conventional single point search methods.

Aggregation of the findings turns the direction of research towards meta-heuristic techniques; and a momentous comparison of four evolutionary algorithms namely; Genetic algorithm (GA), Particle Swarm Optimization (PSO), Gravitational Search Algorithm (GSA) and Cuckoo Search Algorithm (CSA) on application of PSS to power systems is presented. The designs obtained from these algorithms are compared on the basis of success rate, convergence characteristics, time elapsed and standard deviations in the results. It is observed that the design obtained through CSA has better response in terms of settling time and overshoot of the speed deviation curves. The design is tested under different topological changes and contingencies over two multi machine IEEE test systems. The overall dynamic response validates the efficacy of the proposed design.

LIST OF SYMBOLS

δ	:	Rotor angle phase difference of sending end and receiving end bus voltages
ω	:	Rotor Speed
α	:	Real part of eigenvalues
β	:	Imaginary part of eigenvalues
ξ	:	Damping
ζ	:	Overshoot
A	:	System Matrix
K_S	:	PSS gain
T_1, T_2, T_3, T_4	:	Time constants
T_W	:	Wash out time Constant
J	:	Objective function
C_v	:	Nodal Voltages
P	:	Active Power
Q	:	Reactive Power
X	:	Reactance of Line
V	:	Bus voltage
X'_d	:	d-axis transient reactance
X''_d	:	d-axis sub transient reactance
X_q	:	quadrature axis reactance
X''_q	:	Sub transient reactance
H	:	Inertia constant
T'_{d0}	:	d-axis open circuit time constant
T'_{q0}	:	q-axis open circuit time constant
K_a	:	AVR gain

LIST OF SYMBOLS (continued...)

μ	:	Mean value
σ	:	Standard Deviation
ε	:	Tolerance
γ	:	Step length parameter
C_1, C_2	:	Acceleration Coefficient
G	:	Gravitational Constant
P_a	:	Alien egg probability

LIST OF NOTATIONS

AVR	:	Automatic Voltage Regulator
PSS	:	Power System Stabilizer
FACTS	:	Flexible AC Transmission System
SVC	:	Static VAr Compensator
PF	:	Participation Factor
SPE	:	Sensitivity of PSS Effect
ESI	:	Eigen Value Sensitivity Indice
OSI	:	Overshoot Sensitivity Indice
GA	:	Genetic Algorithm
PSO	:	Particle Swarm Optimization
GSA	:	Gravitational Search Algorithm
CSA	:	Cuckoo Search Algorithm
GSTHDE	:	Gradual Self Tuning Hybrid Differential Evolution
SMIB	:	Single Machine Infinite Bus
WNEDM	:	Weighted and Normalized Eigen value Distance Minimization
LMI	:	Linear Matrix Inequalities
LQR	:	Linear Quadratic Regulator
ANN	:	Artificial Neural Network

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Chapter 1
Introduction

Small signal stability is becoming a major concern for real time operation of power systems. This concern crops up from the fact that modern power system is observing growth in electricity demands and competitive business environment. These two factors along with the increase in population are creating a backbreaker situation for the power engineers. Stressed conditions are forcing interconnection of the generating units. Due to interconnection of generating utilities, interactions between units in the form of inter area oscillations are established. These oscillations should be taken care of very diligently as if they grow, the consequence may be the system collapse [1].

Damping of oscillations has been characterized as an important aspect of power system operation. The interconnection of the generation utilities came in picture from 1960, since then interactions between various generating units were matter of major concern. In earlier years when AC generators were operated in parallel, automatic control (turbine speed governor) was considered as, only source of negative damping. For troubleshoot this problem damper windings were employed with the generating units. C.Concordia *et al.* [2] raised two points in their work that firstly automatic control of governor loop was found main culprit for negative damping and secondly the economical and effective place to add damping lies somewhere else.

In early 1930 problem of negative damping was recognized but had not had practical application. In 1960, when large generating utilities were interconnected and they observed large angular swings, high response voltage regulators were recognized as a major source of negative damping [3] & [4]. Following points of consideration were emerged:

1. For inter area interactions, the amortisseur was no longer effective. As damping produced by it, reduced approximately inverse proportion to the square of the effective external impedance-plus stator impedance.

2. The propagation of automatic controls increased the probability of adverse interactions. Two basic controls namely governor effect and Automatic

Voltage Regulator (AVR) effect were characterized as source of negative damping.

3. A small oscillation in each generator that might be insignificant but may add up to a tie line oscillation. That was very significant relative to generator's rating.

4. Higher tie line loading increased both the tendency to oscillate and the importance of the oscillation.

The high gain AVRs introduced a negative damping in the system and oscillatory instability [3]-[5]. Literature witnessed the effort of researchers for exploring the behavior of synchronous machine under small perturbations [2] & [5]-[8]. Much more emphasis was given to observe behavior of the synchronous machine, effect of different configurations of synchronous machines for different power generating stations in [5] & [8]. In presence of high gain excitation system value of damping became negative [8]-[13]. Power System Stabilizer (PSS) proved as the cost effective control of this problem [13]-[15].

In the past two decades, the employment of auxiliary excitation control signals for improving the small signal stability of power systems has acknowledged much attention [16] & [17]. PSS design problem consists of two sub modules, determination of ideal locations in multimachine networks and PSS parameters estimation [17]-[89].

PSS location identification is first stage of design problem. Methods based on residue were discussed in detail by N. Martins *et al.* [9]. Perez *et al.* [33] presented a participation index for penetrating the effective locations of PSS. However, the work was based on establishing physically motivated frame work for understanding the philosophy of linear time invariant models of dynamic systems. Residue methods were based on modal control theory of linear time invariant systems [21] & [23]. H.F.Wang *et al.* [11]-[12] presented a decisive evaluation of various indices for PSS location identification where two groups of indices were compared. These two groups were based on residue [5]-[10] and Damping Torque Analysis (DTA) [34] & [35]. An effort was made by author(s) to formulate the correlation between these two methodologies.

Following conclusions were drawn from this work.

1. For certain operating conditions residue methods and DTA methods gave same results.

2. A relationship was established between the indexes obtained from DTA and residue methods by using modal controllability and observability.

Method of Participation Factor (PF) [16] gained much more acclaimed and often considered as a best solution for finding out the effective locations in power system. Yuan-Yih Hsu *et al.* [16] indicated that the location identified by right eigen value index [32], was highly undesirable as it provided damping with higher PSS gains. However, the location determined by participation factor was able to give accurate damping with low PSS gain, which is acceptable in lieu of low deviation in voltage profile.

The calculation of eigen's and indices are often addressed with a particular set of operating condition [27] & [38]-[40]. Power system is a dynamic system where, operating conditions are kept on changing with time. There is an acute shortage of the set of indices which, not only give effective results in every operating condition but also computationally efficient. The probabilistic distribution is a suitable way to incorporate various operating conditions simultaneously [34]-[37] & [89]. This thesis proposes a set of indices based on probability distribution of the real part of the eigen and overshoot, to find out the effective locations of PSS in multi machine systems.

Nowadays, the Conventional Power System Stabilizer (CPSS) [17]-[89] is widely used by power system utilities. Recently, several approaches based on modern control theory have been applied to PSS design problem. These include pole placement [17]-[24], Linear matrix inequalities (LMI) [25]-[30], eigenvalue sensitivity based approach [31]-[40] adaptive [41]-[73], variable structure, intelligent control [74]-[82], trajectory sensitivity based approach [83]-[104] and design based on application of evolutionary algorithms [104]-[152]. Despite the potential of modern control techniques with different structures, power system utilities still prefer the CPSS structure [74], [76], [77] & [82]-[84]. The reasons behind that might be the ease of on-line tuning and the lack of assurance of the stability related to some adaptive or variable structure techniques.

Adequate damping is necessary for preventing propagation of small signals in the power network, for this very reason PSS tuning is more important aspect than penetrating effective location. A well placed PSS with poor tuning will not serve the purpose. Adaptive control strategies were discussed in detail by O.P.Malik, *et al.* [48]-[50] with self optimizing pole shifting adaptive control. Further in [50] neural network got trained over the full working range of the generating unit with a large variety of disturbances. Design of traditional PSS was based on robust linear design methods, which were failed to inculcate all operating conditions [53]-[55]. A rule based stabilizer was designed by Hoang *et al.* [51]. Fuzzy logic control based on empirical control was employed in design of adaptive PSS. Further approaches related with non linear adaptive design were employed in the work [57]-[62]. Sharou zhang *et al.* [63] proposed a new improved simple adaptive control law based PSS for quadratic performance index. PSS presented in this design was able to maintain good dynamic response and regulation precision. Self tuning stabilizer with decentralized structure was presented by Wu Chi-Jui *et al.* [70]. PSS design based on adaptive law had a good ease of control but training and learning of the network agents on hypothetical simulations and contingencies, put a question mark on the performance of these designs in real operations [71]-[73].

Coordination of PSS with Flexible AC Transmission System (FACTS) devices were observed in the work [11], [12], [19]-[21]. Further approaches for employment of FACTS devices as damping controller were reported in [32] & [102]. M.J. Gibbard *et al.* [19] developed a method based on induced torque coefficients for simultaneous coordination of PSS and FACTS device stabilizers. The proposed coordination scheme employed linear programming. Static VAR Compensators (SVCs) were employed with PSS in this approach. Martins *et al.* [9] presented an index for effective placement of SVCs and PSS. Calculation of this index was based on right and left eigenvalue of the system matrix [32]. Although employment of FACTS devices for damping enhancement was reported in literature yet these devices were prominently recognized as compensating devices for obtaining voltage control [136].

Trajectory sensitivity approach [83]-[104] was employed to know the parametric influence on conventional objective functions in many approaches. Hiskens *et al.* [101] & [102] presented an approach based on trajectory sensitivity for minimizing generator angles and terminal voltages from their post disturbance values. A systematic optimization based approach was employed for designing the STATCOM controllers [91]. The approach was based on external control to enforce the practical limits of saturation. Trajectory sensitivity concept was discussed by M.A.Pai *et al.* [94], [96] & [98]. Transient stability of the power system containing series and shunt compensator was proposed in [100]. Further trajectory sensitivity approach [104] was applied for preventive generation rescheduling and shunt/series compensation for improving transient stability. In this work parametric influence was studied through trajectory sensitivities. Venayagamoorthy *et al.* [85] proposed an approach based on the optimal tuning of output limits of PSS. For this approach authors employed Feed Forward Neural Networks (FFNN). This adaptive control was designed to identify trajectory sensitivities and thereafter, it was used to compute second order derivatives of objective function.

Trajectory sensitivity approach is useful to determine the parametric influence on the objective function [83]. In real power system most of the objective functions are unknown, to determine the effect of PSS parameters on objective function, this thesis proposes three PSS parameters estimation schemes based on trajectory sensitivity.

Several intelligent algorithms [74], [76]-[82] & [105]-[152] were employed for solving complex optimization problems. These algorithms were namely Genetic Algorithm (GA) [130] & [133], Particle Swarm Optimization (PSO) [115], and Tabu Search (TS) [76], Intelligent Reconfiguration Algorithm [139], Ant Colony Optimization [141], Bacterial Foraging Algorithm [143] etc. These search paradigms were based on population and had a unique set of features and properties, which made them unique. Some of the features were based on exploration and others were on exploitation [128]. From these approaches a conclusion was drawn that, it was essential to test the proposed design on hard conditions. As design obtained under hard conditions will hold good in all conditions [76]. Abido *et al.* [73]-[77], [79] & [80] formulated such hard conditions in their work to present a robust design of PSSs. Surprisingly less importance was given to the solution quality obtained from these algorithms [73]-[80]. Success rate and convergence of these algorithms were not only dependent of some decision variables but also on the nature of optimization problem. S.K.Wang [82] presented a chronological comparison of all conventional objective functions for 16 generator 68 bus system. Ant direction based hybrid differential evolution approach for designing PSS was reported by Wang *et al.* [81].

Yang *et al.* [127] proposed Cuckoo Search Algorithm (CSA), which was nature inspired and mimic the behavior of cuckoos. Rashedi *et al.* [132] proposed a beautiful analogy between optimization process and gravitational law, which was named as Gravitational Search Algorithm (GSA) [132]-[134]. Evolutionary algorithms were employed for PSS design in literature [116]-[124]. Abido *et al.* [77] presented an optimal multi objective design by using genetic algorithm. Various operating conditions were treated as a finite set of plants and multi objective approach was formulated with damping factor, damping ratio of the poorly damped modes. Real coded GA was used in this work. The similar approach was found in [80], author used an objective function based on damping factor, and optimization process was solved by using Simulated Annealing (SA) approach.

In the thesis work, momentous comparison of four evolutionary algorithms is presented namely GA, PSO, GSA and CSA. Optimization problem is solved with a conventional objective function based on speed deviations of the rotor. A decisive evaluation is presented on the basis of solution quality obtained from the algorithms. Parameters for analysis are overshoot value, settling time, Figure of Demerit (FOD), standard deviation of the objective function values.

A brief survey of literature related to research work, and research objectives formulated on the basis of the critical review of literature are presented in following chapter.

Chapter 2
Literature Review

This chapter presents a critical literature review and pays credit to those researchers who have contributed in the field of small signal stability. This thesis presents small signal stability analysis in multi machine system. This chapter reviews the technical literature related to various aspects of small signal stability in power system to ascertain proposed research work and to form research objectives. Fundamentals of the small signal stability along with the methods of enhancement of damping, tuning and location identification of Power System Stabilizer (PSS) are briefly discussed in the chapter. The research objectives are found on the basis of critical assessment of the literature.

2.1 INTRODUCTION

In early days new generating units in electric utility systems were required to extend the power generation limit and power transfer capabilities. To ensure secure and reliable operation, these units were equipped with continuously-acting voltage regulators. As these units upheld a larger percentage of the generating capacity, it became obvious that the voltage regulator action had an unfavorable impact upon the stability of the power system, due to the oscillations of small magnitude and low frequency which were typically in the range of (0.7 – 2) Hz for local mode and (0.1 - 0.8) Hz for inter-plant or inter-area mode [1]-[4]. Prima facie these oscillations seemed to be an issue of less importance to address in large power networks. However, without proper handling and control, these oscillations persist and grow with time and finally spread throughout in the system, eventually causing the system collapse [1] & [2]. Repercussions of these small disturbances, along with the prevention fall in the scope of Small Signal Stability Analysis. Preceding section presents introductory details of the small signal stability.

2.2 SMALL SIGNAL STABILITY

Stability issues have already gained prominence with every passing day. The need of the hour is to develop a robust system, which is not likely to give up in the wake of blackouts and different contingencies. IEEE/CIGRE Joint Task Force committee [15] defines the power system stability as follows “Small-disturbance (or small-signal) rotor angle stability is concerned with the ability of the power system to maintain synchronism under small disturbances. The disturbances are considered to be sufficiently small that linearization of system equations is permissible for purposes of analysis".

Cost effective control of such low magnitude and frequency disturbances are well handled by PSS. PSS is a part of supplementary excitation control system [13]-[15]. The device is used to introduce effective damping of electromechanical oscillations via modulation of generator excitation. Although modern control methods have been used by several researchers to minimize the prescribed objective function which was based on either eigen property analysis or deviation of the speed of rotors. Power system utilities still prefer the conventional lead-lag power system stabilizer structure. Since the PSS has engrossed the interest of researchers, extensive research has been conducted in the following fields:

- Effect of PSS on system stability
- Effective PSS locations
- PSS tuning methods
- Practical experience in design, installation & operation of PSS.

Fig. 2.1 shows the conventional Delta-Omega PSS. A stabilizer is design by suitable selection of time constants T_w, T_1, T_2, T_3, T_4 and stabilizer gain K_{STAB}. In practical situation a torsional filter is used for attenuating the stabilizer gain at turbine generator shaft torsional frequencies and may be neglected while designing PSS.

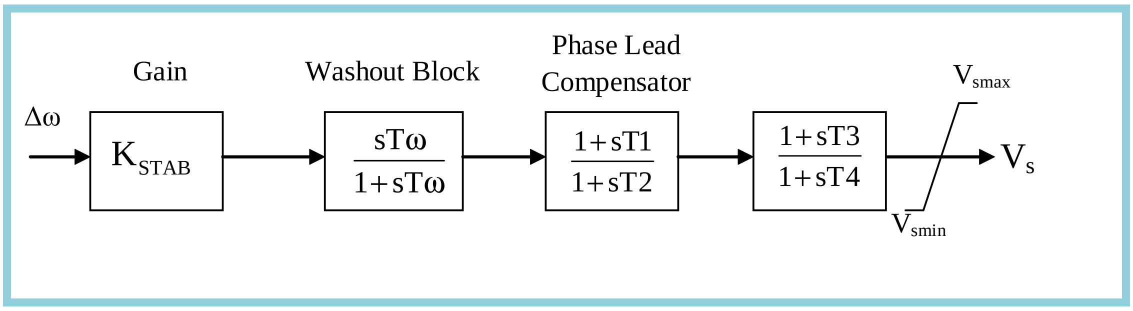

Fig. 2.1: Power System Stabilizer transfer function model

$$\frac{V_s(s)}{\Delta\omega(s)} = K_s\left[\frac{sT_w}{1+sT_w}\right]\left[\frac{1+sT_1}{1+sT_2}\right]\left[\frac{1+sT_3}{1+sT_4}\right] \tag{2.1}$$

Where K_S is Stabilizer gain, T_W is Washout time constant and T_1, T_2, T_3, T_4 are time constants of the lag lead networks.

To present an extensive literature review on theory, procedure, practice and implementation of PSS in various environments is the major fulcrum of this chapter. Literature review revolves around following parameters and basics of small signal stability investigations.

(i) Different methods for identification of suitable sites for PSSs locations in power system.

(ii) Conventional eigenvalue based objective functions

(iii) PSSs tuning methods and chronological developments in the sector.

(iv) Applications of evolutionary techniques in PSS design.

The key parameters of the review are evolutionary algorithms, which are stochastic search methods and mimic the metaphor of natural biological evolution of the social species [105]-[109]. Their chronological development in the past few decades is discussed. How bio inspired algorithms are fruitful to deal with complex optimization problems, their advantages and limitations are pointed out in this section.

The review also revolves around the trajectory sensitivity calculations [92]-[99] and their application in PSS parameters estimation [83]. Much work in this regard is reported by M.A. Pai *et al.* [94], [96] & [98] on the power system application of trajectory sensitivities. Trajectory sensitivity analysis provides a deep insight into the security of power system and often treated as substitution of simulation, as simulation provides only behaviour of the system at particular operating condition. However, parametric influence can't be judged by nonlinear simulation.

2.3 PSS LOCATION IDENTIFICATION

PSS location selection problem has been studied for a long time by researchers [6], [7], [9]-[12], [16], [31], [32]. While selecting PSS locations, the control effect of the PSS and choice of input signal should be considered. PSS is employed to improve damping of the system.

Arcidiacono *et al.* [5] used the sensitivity of mechanical-mode (swing) damping with respect to gain of the stabilizer to locate the most effective location for outfitting PSS for damping enhancement. Later, T. Hiyama [6] presented an approach using the concept of coherent groups. This technique was based on coherent identification method and proved extremely useful in transient studies. According to the author, the major disadvantage of this method was associated with the arbitrary behavior of generator under different variety of disturbances i.e. for small and large disturbance. Secondly the author also proposed that selection of the site for PSS was quite arbitrary in nature in a coherent group. The most universally used approach for stabilizer location determination was the eigenvector method proposed by DeMello *et al.* [7]. Although this method had been successfully applied to the systems having same generators, it might fail in certain systems with generators of different rated capacities.

In fact, it was reported in the study [8] that the eigenvector (generator speed) itself may lead to undesirable stabilizer location. In order to get better results it was proposed that, generator momenta, which are the generator speeds weighted by their moments of inertia, must be employed as the criterion for choosing suitable stabilizer locations.

In 1989 Martin *et al.* [9] presented efficient algorithms for penetrating the locations of PSS and Static VAR Compensators (SVC) in multi machine power systems. The proposed algorithm suggested the most suitable generators and buses for placement of PSS and SVC in order to damp the critical modes. The algorithm involves the calculation of transfer function residues [5]-[10].

Many approaches or indices based on the open-loop system model have been proposed and successfully used for selecting the optimum PSS sites, such as the modal analysis approach [10], Relative Gain Arrays (RGA) [11] and different sensitivity coefficients [12]. Relationships between sensitivity, residue and participation factors have also been discussed in [33]. To consider more machines and state variables in a large-scale system, some indices were derived from the reduced-order modal analysis [25]-[27]. A comparative study was presented in [12] and the most popular techniques or indices were found to be the residue method and the damping torque analysis. However, all of these techniques [5]-[12] were based on a deterministic condition with constant system parameters and a particular load level.

E.Z. Zhou *et al.* [32] presented a new concept of allocating PSS in multi machine by using Sensitivity of PSS effect (SPE). In this paper author formulated an index which was function of Automatic Voltage Regulator (AVR) gains and time constant. Although author demonstrated and validated the proposed approach through non linear simulation, yet the paper left unabated dilemma of what will happen if different configuration(s) of AVRs were employed.

Yuan-Yih Hsu *et al.* [16] presented a method based on participation factor to identify the best location of PSS to provide adequate damping. Authors presented a momentous analysis over single machine infinite bus (SMIB) system and extended that analogy over two multi machine systems. It was reported that swing modes are the main culprits and introduced oscillatory instability in the system. In the very first part, author calculated participation factors for various states of SMIB system and concluded that the value of participation factors is significantly higher for δ (rotor angle) and ω (rotor speed). Summation of the participation factors of most associated states are calculated and used as the perfect location identification mark.

Critical Review

- All these indexes are based on the calculation of eigenvalues or indirectly related to them. The most ironical thing observed in these analyses is that all these investigations are addressed with a particular operating condition and the values of these indices are changed when the operating scenario is changed. There is an acute shortage of indices which indicate the proper site of PSS and that indication too, holds good in almost all operating conditions.

- The major assumption in the calculation of Participation Factor (PF) is that often effect of PSS is considered as the effect of damping coefficient of machine which holds good when system is small *i.e.* SMIB. However, approach is not suitable for a large multi machine power system.

- SPE is the function of AVR gain and time constant. For different configuration(s) of AVRs, the values of SPEs end up with ambiguous results.

The hypotheses arrived at, from this literature survey are informative and provide a solid foundation for the investigations of new indices for identifying effective locations of PSS in multi machine Networks.

2.4 DESIGN OF CONVENTIONAL PSS

In this section, technical literature of designing PSS through linear methods is discussed in brief.

2.4.1 Pole placement

Controllers obtained from simultaneous stabilization techniques had fixed gain constants as compared to adaptive controllers. These reasons induced Othman *et al.* [17] to apply a pole-placement procedure to design non-switching controllers for systems with multiple operating conditions. A set of gains were separately designed. Then, a special root locus technique was used to adjust the gains and only dominant modes were used in the controller design. The new stabilizer performs better than the traditional one especially if a machine outage occurs. On the other hand, a new and more efficient pole placement PSS design method was proposed by Yu and Li [18]. In this method, participation factors [16] were used to select the sites and number of stabilizers in a multi-machine system. Further Julio C.R. Ferraz *et al.* [87] presented an approach based on least square method. The problem of PSS gain scheduling for 36 stabilizers, considering 11 operating conditions, are described for a model of the Brazilian South-Southeast system. The problem was addressed with nonlinear least squares through Newton method. However the method was based on phase compensation parameters for the individual PSSs from the Generator Exciter Plant (GEP) [19]-[23] phase compensation requirements. The PSS gains were object of coordination, which was the only lacking part of this research [87].

A classical well written approach was presented by Pal [24]. In this work, merits of a robust low-order pole-placement method of damping-control design over a conventional root-locus method were discussed. The design was based on a Weighted and Normalized Eigen value Distance Minimization (WNEDM) method, to model damping controllers employing Superconducting Magnetic Energy Storage (SMES) devices in a study system. The WNEDM-based control guarantees adequate damping in the pre-fault and post-fault cases. The damping performance of the controllers is compared with that obtained by the root-locus technique. Author also found that classical techniques like Linear optimal control did not address the objective of the closed loop damping directly.

2.4.2 Linear Matrix Inequalities (LMI)

Phase compensation method and the root-locus method [24] are most classical methods used in literature. Recently, modem control methods have been used by several researchers to take advantage of optimal control techniques [25], [26] & [28]. These methods utilize a state-space representation of the power-system model to calculate a gain matrix which, when applied as a state feedback control, will minimize a given prescribed objective function. The feedback gain matrix is obtained through solving a family of linear matrix inequalities [25]-[28].

R. Gupta *et al.* [29] presented an approach in 2003, for designing a power system stabilizer for single machine system using robust periodic output feedback controller. In this approach, authors linearized the nonlinear model of machine at different 16 points and created 16 different plant models. For each of these plants, an output injection gain was obtained using the Linear Quadratic Regulator (LQR) technique. A robust periodic output feedback gain which realized these output gain, is obtained using LMI approach [30]. This robust periodic output control was applied to a non-linear plant model of the machine at different operating (equilibrium) points. Further author added that the proposed approach had an upper edge over the conventional static output feedback control.

P. Shrikant Rao *et al.* [30] presented an approach by which placement of the system poles in an acceptable region, in the complex plane for a given set of operating and system conditions was accomplished. It guaranteed appropriately damped system response over the entire set of operating conditions. The proposed controller used full state feedback. The feedback gain matrix was obtained as the solution of a LMI expressing the pole region constraints for polytrophic plants. The technique was illustrated with applications for the design of stabilizers for single machine and 3 machine power systems.

2.4.3 Eigen Value sensitivity analysis

In Chung *et al.* [31] proposed PSS design based on eigen value sensitivity analysis, where the statistical attributes were given to the real part of the eigen value to encapsulate various operating conditions. Various approaches based on eigen property analysis is reported in literature [32]-[40].

The probabilistic approach for power system dynamic studies began in 1978 [34]. The probabilistic property of an eigenvalue in a 2-machine test system was determined from the known statistical attributes variations of system parameters namely, the rotor angle and mechanical damping [35]. Uncertainties considered were stemmed from measurement, estimation, and forecast errors for a particular load level. The concept of stochastic stability was employed to study the stability problem based on dynamic stability limit curves of single-machine system [35]. Variation of system operating conditions in multimachine system was first considered in [37]. Second order eigenvalue analysis was presented in [39]. This work was based on simulation of lightly loaded hydro generator, which was equipped with a stabilizer and connected to a local non-linear load. The dependency of sub-synchronous resonance on system parameters was predicted for the case of a thermal generating unit feeding a large induction motor load through a compensated transmission line.

2.4.4 Adaptive Control

To improve the damping torque applied by PSS, researchers came forward with nonlinear methods of design. Adaptive control methods [41]-[73] for designing PSS came in picture for two reasons:

a. Extremely fast processing facility.

b. Ability of schemes to realize complicated nonlinear mapping from the input space to the output space.

Kamal Sadan *et al.* [43] developed a controller, based on a novel methodology that was a hybrid controller with two algorithms, namely, a neural-network (NN) based controller with explicit neuro identifier and an adaptive controller that evolved from a model reference adaptive controller. Much work was reported by O.P.Malik *et al.* [45], [48], [49], [50], [54], [56], [57], [61], [62], [64], [67], [71] & [72] in adaptive control. Adaptive tuning scheme based on back propagation with multilayer perceptron was developed in [48]. The concept associated with the work was that during tuning, ANN memorized the control strategy and provided damping torque under different operating conditions. Kothari *et al.* [53] proposed a self tuning procedure of PSS. The controller used a state-feedback law, whose gains were evaluated from the pole-shifting factor. The proposed method was simple and computationally efficient. The problem with this ANN controller was that, training of neural network was based on nonlinear optimization. The parameters estimated through nonlinear optimization have a great probability to get trapped in local minima [59].

2.5 CONVENTIONAL OBJECTIVE FUNCTIONS IN PSS DESIGN

Power system is subjected to different disturbances; the duration of oscillation in the time domain is determined by several eigenvalues at the most right sides on the s-plane. Objective functions are currently formed with the help of damping ratios and damping factor [74]-[81], as the swing mode excited by a specific contingency introduce negative damping in the system. Abido *et al.* [74], [75] & [80] used an eigen value based objective function which employed real part of the swing modes in objective function. The shifting of the eigen part in rectangular zone towards left half of the plain was achieved. Further the work reported in [77] & [78] concerned with the construction of multi objective function which not only shifted eigen value's real part in left plane but also simultaneously improved the damping. However, this is worthwhile mentioning here that objective(s) was not conflicting in nature. In literature single objective function with damping ratio was constructed in the works [74] & [80]. Table 2.1 shows the critical comparison of the approaches in terms of convergence, shape and component(s) involved in objective function(s) along with the disadvantages associated with it.

Table 2.1: Comparison of Objective Functions

Objective function	Component	Convergence region	Limit Oscillation Frequencies?	Limit Damping Factors?	Disadvantage
J1 [74],[75],[77]	σ	rectangle	No	Yes	Higher frequency modes
J2 [74],[81],[80]	ξ	Fan shaped with the tip at the origin	Yes	No	Low frequency inferior damped modes
J3 [77], [78]	σ, ξ	D-shaped	Slight	Yes	High frequency modes
J4 [81]	χ	Fan-shaped with the tip at the	Yes	Yes	Slightly difficult to converge
J5 [82]	ω	D shaped	Yes	Yes	Difficult to converge

Fig. 2.2 shows the convergence region of all the four objective functions. Out of these objective functions, the most effective function based on damping scale was created by S.K.Wang [82].The work was based on creation of a novel objective function and application of a novel algorithm called Gradual Self Tuning Hybrid

Differential Evolution (GSTHDE), for designing PSS. It was proposed and applied on 5 area multimachine system.

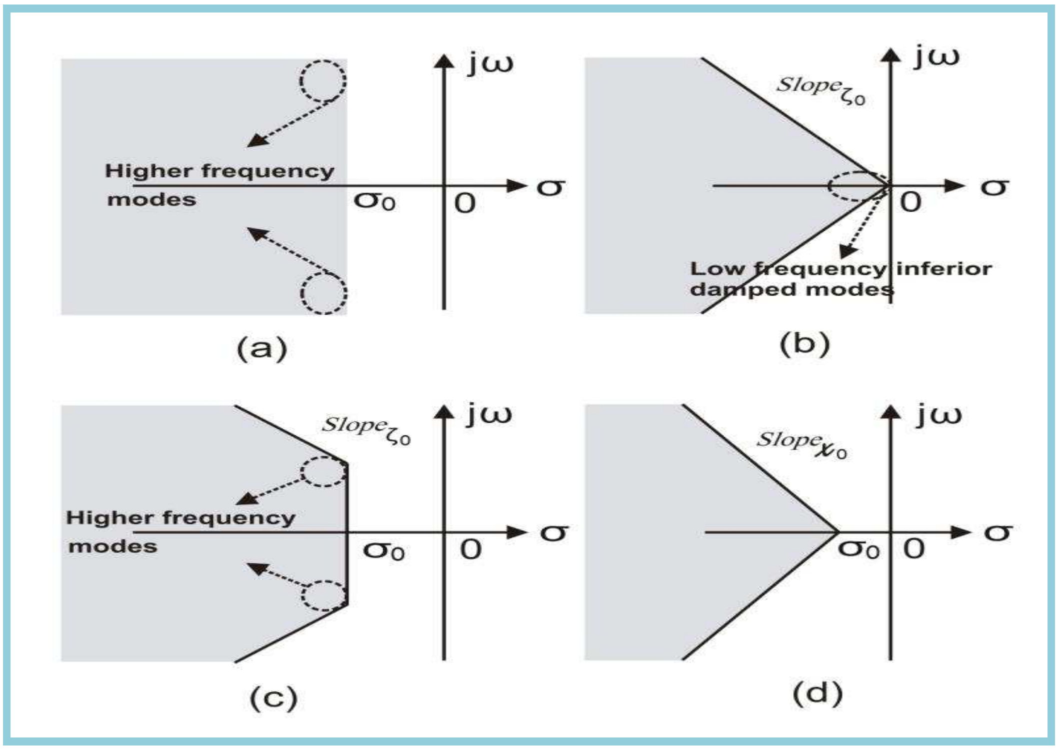

Fig. 2.2: Comaparison of Objective functions

From Fig. 2.2, it can be concluded that the most effective objective functions which don't contain higher frequency and lower frequency inferior modes are damping scale and speed deviation based objective functions. Higher frequency modes cause numerous up/down oscillations which reduce the life time of system devices. Similarly low frequency modes are also dangerous for the life of equipment. This problem was reported with all three objective functions, which was removed in the objective functions based on speed deviations & damping scale [82]. The problem associated with the speed deviations based objective function is that, when the system is large it increases the computational burden and may be unable to determine the global optimum while solving the optimization with the conventional approaches [79], [83], [84], [88]. This postulate gives motivation to solve the above said optimization process with the latest evolutionary algorithm.

2.6 TRAJECTORY SENSITIVITY APPROACH

Trajectory sensitivity approach [83]-[104] is an analytical tool to determine parametric influence of PSS on objective function. In real power system trajectories are used to determine the behaviour of the power system under stressed conditions. In literature trajectory sensitivity analysis is not only limited to transient stability studies but also employed with small signal stability cases [85]-[89].

Baek *et al.* [85] proposed a method based on differential algebraic impulsive switched (DAIS), in this approach the damping performance of system was judged just after a large disturbance. Further in this work it was exhibited that the non linear smooth parameters such as the saturation limits of the PSS couldn't be tuned by the conventional methods based on linear approaches.

D.Z.Fang *et al.* [86] proposed a computation technique based on trajectory sensitivity of power system. These trajectories were calculated with respect to PSS parameters. Trajectory sensitivities of PSS offered a deep insight into influence of each PSS parameter on damping system oscillation. The method was tested over SMIB systems, however the more interesting studies could be carried out for large multi machine system where inter area oscillations are excited with the interaction of various generators.

M.A.Pai *et al.* [96] presented a trajectory sensitivity analysis for hybrid systems .A hybrid system model which had a differential algebraic discrete structure was taken. In this study authors illustrated the efficacy of trajectories to demonstrate the system behaviour which could not be obtained from traditional simulation. Sanchez *et al.* [103] presented a method based on trajectory sensitivity for determining the reactance of synchronous machine and excitation system time constants. In this paper generator was modelled in great detail to provide an accurate reference model. M.A. Pai *et al.* [94] investigated transient stability by using trajectory sensitivity functions of the post fault system with respect to system parameters.

Critical Review

Optimization process is complex, when the problems associated with the real worlds are solved. PSSs parameter estimation is an example of such optimization problem. In this problem, the behaviour of the objective function is predicted through the eigenvalue sensitivity analysis. However, interestingly PSS parameters are not explicitly included in the conventional objective function(s). There is an earnest need of sensitivity analysis to understand the behaviour and impact of PSS parameters on objective function(s). Literature reported different sensitivity based schemes for PSS parameter estimation in [83].

However, the work [83] left an unabated dilemma regarding sequential tuning scheme, how the sequence of optimization of the candidate(s) was decided in this work. This thesis not only presents a comparative analysis of conventional schemes but also presents modified versions existing schemes.

2.7 PSS DESIGN BASED ON EVOLUTIONARY ALGORITHM

Evolutionary algorithms [105]-[152] are examples of imitation of life, in designs. Evolutionary algorithms are a class of optimization problems, which hail inspiration from the social behaviour of swarms, species and the theory of natural evolutions [105]. All evolutionary algorithms are characterized by their different operators and their behavioural differences, but common attributes in the algorithms are the stochastic behaviour, random search and selection [106]. The behaviour of natural species like ants & their virtue of finding the shortest route to a source of food, and birds able to migrate to remote places & find their destination give inspiration for establishing mathematical framework for algorithms [107]. The behaviour of such species is guided by learning, adaptation and evolution, which was later termed as social intelligence [108] & [109].

To mimic the efficient behaviour of these species, various researchers have developed computational systems that seek fast and robust solutions to complex optimization problems. The first evolutionary-based technique introduced in the literature, was Genetic Algorithm (GA) [110] & [111]. GA was based on the Darwinian principle of ‘survival of the fittest’ and the natural process of evolution through reproduction. GA may require long processing time for a near optimum solution to evolve [74] & [80]. All problems lend themselves well, to a solution with GA [110]. An attempt is made to improve the performance of GA in terms of processing time and solution quality and those are reported in the literature [111] & [112]. Wong *et al.* [113] used genetic/ simulated annealing approach for solving the economic load dispatch problem. Chanan Singh *et al.* [114] used two functions death penalty and penalty function to fight with premature convergence and large processing time, this procedure was named as atavistic genetic algorithm. In addition, to the experiments with GA in 1995, Particle Swarm Optimization (PSO) algorithm was developed by Kennedy and Eberhart [115], which depicted social behaviour of flocks of birds and schools of fish. Similar to GA, PSO is also an optimization technique based on population. GA is employed in PSS design [77], [79] & [116]-[119].

In [119] a systematic and automated approach based on GA was proposed. It gave rise to selection of optimal performance weights without any trial and error attempt. The resulting H^{∞} PSS performed quite satisfactorily under a wide range of turbo generator operating conditions and was found robust against un-modeled low-damped torsional modes. Further PSO was employed in the design of PSS in [74] & [120-125].

Stative *et al.* [123] proposed an approach in which MATLAB [154] and Dig SILENT [155] were employed and linked together in a genuine automatic data exchange procedure. Consequently, the test system and the controllers were modeled in Dig SILENT and PSO algorithm was implemented in MATLAB. Gravitational Search Algorithm (GSA) was applied in modified form in [124], where it was called Oppositional based Gravitational Search Algorithm (OGSA). The most important issue for applying oppositional based GSA was to reach the optimal value in less time. This scheme enabled the process to reach the desired value in smaller search space [125]. Computation results illustrated that the proposed technique was more effective in improving the dynamic performance by damping the low frequency oscillations.

Abido *et al.* [76] employed Tabu Search (TS) algorithm in the PSS design. The parameters of the proposed stabilizers were selected using TS. This TS tuned PSS was used to shift; the system poorly damped electromechanical modes at several loading conditions and system configurations simultaneously.

Incorporation of TS as a derivative-free optimization technique in PSS design significantly reduced the computational burden. In addition, the quality of the optimal solution does not rely on the initial guess. Further approaches for obtaining designs based on optimization process through evolutionary algorithms can be found in the literature [126]-[131].

Critical Review

It is quite obvious that gradient methods are applied only to the objective functions which are differentiable [156] & [157]. It is to worth mention here that if the shape and behavior of the objective function is unknown due to limited knowledge, which often occurs in real world, the choice left is evolutionary design. Multi point search strategies and randomization are the main postulates of the evolutionary algorithms [105]-[111]. These features help the designer to prevent from being trapped in local minima.

Although different design strategies were proposed in past for evaluation of PSS parameters yet the comparison based on the solution quality, time elapsed and convergence is not presented effectively. Many of the optimization processes were reported as time taking exercises in literature [76], [77], [80] & [82]. There is an acute need of an optimization paradigm, which not only solves optimization process in less time but also gives the better solution quality. A decisive evaluation of different algorithms will provide a better insight to different attributes and features of the algorithms.

2.8 RESEARCH OBJECTIVES OF THESIS

On the basis of critical review, following objectives have been formulated for the research work:

1. To present a comparative analysis and evaluate the accuracy of existing methods for identifying effective locations of PSS in IEEE standard multimachine system [153].

2. To propose a methodology to inculcate statistical attributes in real part of eigenvalues and overshoots under different operating conditions, and propose a set of location identification indexes for outfitting PSS in multimachine power system.

3. To perform sensitivity studies on a standard IEEE multimachine system to know the parametric influence of PSS on conventional eigenvalue based objective function.

4. To present efficient Trajectory sensitivity based schemes and decisive evaluations of the schemes for optimal tuning of PSS parameters.

5. To solve PSS parameter estimation problem with latest evolutionary algorithm. Draw a momentous comparison with the conventional optimization approaches on the base of solution quality and standard deviations in objective function values.

6. To present the comparative analysis between overshoot and settling time of speed deviation curves based on the response obtained under different operating conditions, system configurations and different perturbations.

In the following chapter, PSs location identification problem is solved by using existing methods (PF & SPE). These existing approaches are compared with two new proposed indexes namely Eigen Value Sensitivity Index (ESI) & Overshoot Sensitivity Index (OSI), for identifying efficient locations of PSS in multimachine system.

Chapter 3
PSS Location Identification Index

Stability investigations of a large electric power system exhibit a formidable challenge to a system analyst as the system size and complexity are major parameters. Power system faces the problem of bothersome dynamic oscillations in the range of 0.2 to 2.5 Hz, which are associated with poorly damped oscillation modes [1]. The important objective of oscillatory instability is to identify the poorly damped modes which embed the instability in the system. Power System Stabilizers (PSSs) are the effective solutions for enhancing system damping [2]-[8].There are several indices introduced in the past for finding out the effective locations of PSS in power system. These indices were based on eigenvalue [32], residue [21]-[23], [34]-[35] and Participation Factor (PF) calculations [16]. Eigenvalue calculations are time taking for multimachine systems hence, it is pragmatic to discuss an acute necessity of the fast acting methodologies for computing eigenvalues analysis of the system [38]-[40].

The existing indices have some limitations [16], [32], [34]-[37] & [89]. Considering these limitations, this chapter proposes two new indexes to penetrate the suitable locations of PSSs in multi machine networks. Proposed indexes are based on probabilistic distributions of eigenvalues and overshoot of swing modes [27], [38]-[40] & [89]. Probabilistic distribution of the real part of the eigenvalues and overshoot is done to make the replica of real power systems operating conditions. The performance of proposed indexes is tested on standard IEEE 39 and 68 bus test systems [153] & [160].

3.1 INTRODUCTION

PSSs offer a cost effective control for damping requirements. High gain Automatic Voltage Regulators (AVRs) are required to achieve transient stability but these devices inculcate negative damping in the network. In this way PSS is dynamically interlinked with the AVR. In early 80's the approaches like coherent group identification [6], sensitivity calculation of mechanical damping modes with respect to stabiliser gains were established for penetrating suitable locations of PSS in power networks. Most of these approaches were based upon eigen property analysis [32]-[40]. These approaches gained wide acceptance initially but finally took over by the residue and PF methods [16] & [33].

It is well reported in literature that approach based on only right eigenvector gave erroneous results as the right eigenvector is only associated with the measurement of the activity of the associated variable [32].

Yuan Yi Hsu *et al*. [8] & [16] presented a beautiful comparison of two methods namely PF and right eigenvector method, the variation in real part of swing mode was observed while PSS gain was varied in a wide range. It was observed in the studies that for location suggested by right eigenvector method observes small amount of variation in the real part of the eigenvalue for large changes in PSS gain. However, the location suggested by PF observed a significant amount of variation for the small change in PSS gain. The previous approach was highly undesirable since high stabilizer gain would result in severe deviation in the voltage profile under fault conditions. E.V. Larsen *et al.* [14]-[15] mentioned some cases, where the stabilizer may even cause leading power factor generator operation [21]. As a matter of fact, being liable to cause unsatisfactory deviation in the voltage profile is the major disadvantage of a PSS [14]. As a result, it is essential to keep the gain of the stabilizer as small as possible as long as the desired damping can be achieved satisfactorily [13]-[14].

T.Hiyama [6] presented a method based on residues. In this work, the identification of states influencing the modes of oscillation was obtained by employing right and left eigenvectors. Thus a measure of the relative participation of the j^{th} state variable in the i^{th} mode could be calculated. The modes of concern (inter-area modes) were poorly damped. These modes were selected to carry out this analysis sequentially. Using input-output relationships, those excitation systems mainly influencing states with an important content of the oscillating mode of concern were detected. This result was verified using the eigenvalues' sensitivity to changes in the damping factor $D_{i.}$

Y.Hsu *et al*. [8] & [16] presented an extension of the analysis from Single Machine Infinite Bus (SMIB) to multi machine system .In this work authors calculated the value of PFs for different swing modes for different variables. On the basis of the values of PFs most affecting states were identified and for extension the analysis on multi machine network summation of the δ and ω were obtained. Section 3.2.1 shows this analysis for SMIB. The problem with this analysis is that in PF calculation, often the effect of PF is assumed to be equivalent of damping effect of PSS. This analysis holds good for small networks but not suitable for multi machine networks [21].

A conventional index which was based on the calculation of the right and left eigenvalues was presented by O.P.Malik *et al*. [32]. In this work emphasis was given to calculate right eigenvalues & left eigenvalues simultaneously. It was demonstrated by authors that whereas the right eigenvector gives the mode shape by describing the activity of the variables when that particular mode was excited, the left eigenvector gives the mode composition by describing what weighted combination of state variables is needed to construct the mode. Further authors introduced an index which was based on AVR gain and time constant and corresponding entries of eigenvectors for swing modes. This indice was named as Sensitivity of PSS effect (SPE).

Stochastic probability analysis of dynamic stability limit curves is presented [6] however, it was for SMIB. The state of art analysis based on reduced order eigenvalues was presented by Ignacio J. Perez Azziagra *et al*. [33].It was based on a physically motivated framework and reported as selective modal approach. For considering different operating conditions the nodal voltage injections was selected by K.W.Wang *et al*. [36] .These voltages were found as a suitable agents for introducing the uncertainty quotient in the system studies, this frame work was based on successive calculation of load flow where each eigen value was obtained from the probabilistic attributes of the nodal voltages. Following are the points of considerations while proposing new indexes based on sensitivity and probabilistic distribution of the eigenvalues.

- All these indexes are based on the calculation of eigenvalues or indirectly related to that, which are addressed with particular operating conditions. The values of these indices are changed when the operating scenario is changed. There is an acute shortage of an indice which indicate the proper site of PSS.

- The major assumption in the calculation of PF is that often effect of PSS is considered as the effect of damping coefficient of the machine. It is considerable for small networks but loose the relevance when multi machine systems are considered.

- Change in the value of SPE with AVR gain and time constant makes this indice less efficient, for different configuration of AVRs.

This chapter proposes a set of new location identification indexes based on statistical attributes for outfitting PSS in multi machine systems. Eigenvalue and overshoot sensitivity indices are calculated and the comparison of the same was done with the conventional indice SPE & PF. The statistical attribute in form of standard deviations and mean is given to the real part of the eigenvalue and overshoot of the damping modes to inculcate different operating conditions. The probabilistic distributions of these parameters are a replica of different contingencies and give a more realistic approach to the analysis.

3.2 EXISTING PSS LOCATION IDENTIFICATION INDEX

Several indices are defined in the literature for identify the effective location of PSS in power system [9], [11], [12], [21], [23] & [33]. In the following sections some of these indices are mentioned and calculated to appreciate the proposed overshoot and eigenvalue sensitivity indexes.

3.2.1 Participation Factor (PF)

The PF is a dimensionless real number which is invariable with the change of the scale of state variables [1], [16]. The participation factor P_{ij} can be also interpreted as the sensitivity of the eigenvalue λ_i with respect to the diagonal element a_{jj} of A. To form a better understanding firstly the calculation of participation factor is done on SMIB system.

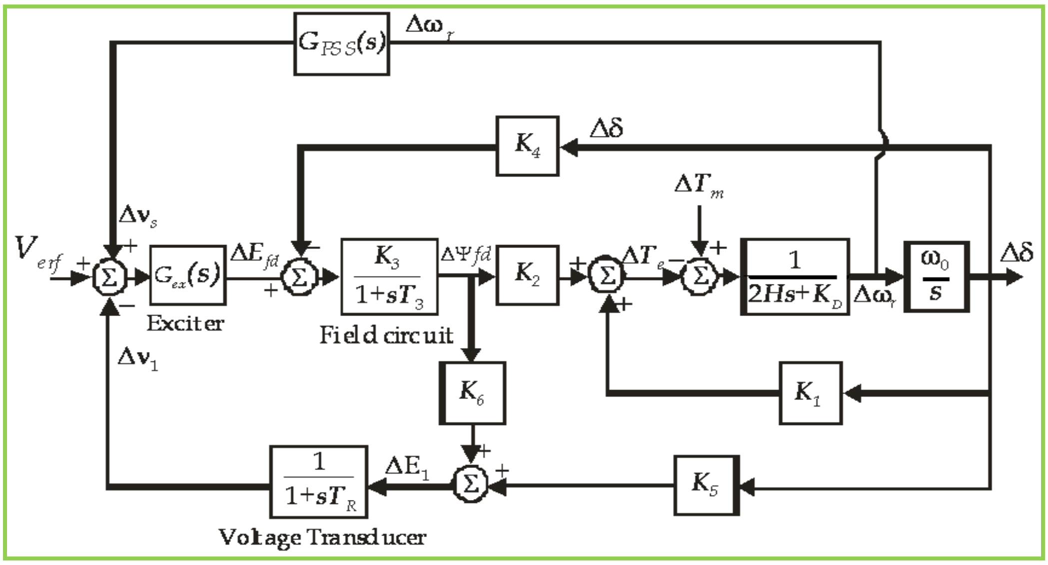

Fig. 3.1: SMIB system with AVR and PSS

Fig.3.1 shows a SMIB system with AVR and PSS. The initial operating condition for this system is given as $K_1 = 1.0755, K_2 = 1.2578, K_3 = 0.3072, K_4 = 1.7124,$ $K_5 = -0.0409, K_6 = 0.4971, K_A = 400, T_A = 0.05, E_{fd\,\mathbf{min}} = -7.3, U_{\mathbf{max}} = 0.12, U_{\mathbf{min}} = -0.12$. These operating conditions excited some of the swing modes, the detail values of eigen and participation factors for different states are shown in Table 3.1.Brief description of the eigen property analysis and PF is included in Appendix-A.

Table 3.1: Participation factor associated with different states

Eigen values	Δδ	Δω	ΔE'q	ΔE_{fd}	ΔV_f
-217.8	0	0	-0.01433	0.07836	0.9631
-0.0138±j9.22	**1.004**	**1.004**	-0.00646	0.00686	-0.00858
-1.8522±j0.0382	-0.00409	-0.00409	1.0208	0.9148	0.0725

From Table 3.1 following conclusions can be drawn:

- It can be observed that torque-angle deviation and speed deviation (*Δδ, Δω*) are the state variables which have significant participation factors for the poorly damped electro mechanical mode.
- Only negligible participation factors have been found for other state variables as far as the mechanical mode is concerned.
- This is as expected since the variables (*Δω, Δδ*) are related directly to rotor oscillations. These characteristics are described by the mechanical-mode eigenvalues.
- As a result, only the sum of the participation factors of Δδ and Δω of each generator, associated with the swing modes will be examined in preceding section.

3.2.2 Sensitivity of PSS Effect (SPE)

This conventional index first proposed by E.Z.Zhou *et al*. [32] and named as sensitivity of PSS Effect (SPE). According to this index when a machine is selected for PSS installation, for best affect first the amplitude of PSS input (measured by right-eigenvector) should be relatively large, and second the control effect of PSS is considered as a left eigenvector entry.

SPE is defined as per equation for any machine *j:*

$$SPE_J = \mu_{\Delta\omega j} V_{\Delta E_{fdj}} \frac{k_{ej}}{t_{ej}} \Delta \quad (j = 1, 2, ..., m) \tag{3.1}$$

Where:

$\mu_{\Delta\omega j}$: Right eigenvector entry corresponding to $\Delta\omega j$

$V_{\Delta E_{fdj}}$: Left eigenvector entry corresponding to ΔE_{fdj}

k_{ej} : AVR Gain

t_{ej} : Time Constant

3.3 PROBABILISTIC SENSITIVITY INDICES

State space equation for Multimachine system can be simply described by equation (3.2). For a particular mode *'m'* the residue calculation is based on the controllability and observability factor as mentioned in (3.3).

$$\begin{Bmatrix} \dot{X} = AX + BQ \\ Y = CX \end{Bmatrix} \tag{3.2}$$

$$R_m = CU_m V_m{}^T B \tag{3.3}$$

Where, U_m, V_m are the right and left eigenvectors of system matrix R_m is the residue matrix. Eigenvalue for this mode $Z_m = \alpha_m + j\beta_m$ sensitivity of this eigenvalue with respect to any system parameter(s) will be given as equation (3.4).

$$\frac{\partial Z_m}{\partial K_i} = V_m{}^T \frac{\partial A}{\partial K_i} U_m \tag{3.4}$$

Where K_i and K_j are the system parameters.

$$\frac{\partial^2 Z_m}{\partial K_i \partial K_j} = V_m{}^T \frac{\partial^2 A}{\partial K_i \partial K_j} U_m + \frac{\partial V_m{}^T}{\partial K_i} \frac{\partial A}{\partial K_j} U_m + \frac{\partial V_m{}^T}{\partial K_j} \frac{\partial A}{\partial K_i} U_m \tag{3.5}$$

Equation (3.4) and (3.5) are the expressions for first order and second order eigenvalue analysis. In probabilistic eigenvalue analysis covariance matrix C_v of the nodal voltages is solved from successsive load flow runs for different voltage injections. Covariance matrix is formulated in [34]-[37] & [89] and given as expression (3.6).

$$C_{\lambda m,\eta m} = \sum_{a,b=1}^{N} \frac{\partial Z_m}{\partial V_i} \frac{\partial \eta_m}{\partial V_j} Cv_{ij} \tag{3.6}$$

Probabilistic index for damping ratios and probabilistic index for real part of the eigenvalues were derived in the state of art work [34].

3.3.1 Probabilistic eigenvalues calculation

Eigenvalues obtained from probabilistic eigenvalues calculation are regarded as random variables described by their probabilistic density function, for a particular eigenvalue $Z_m = \alpha_m + j\beta_m$, in oscillatory studies computing and identification of poorly damped mode and fixing a control strategy for the modes is a daunting task to perform. Dynamic scenario of the power system leaves a choice to consider an eigen value as a random variable as it is mostly effected by system conditions configurations and other system parameters [38]-[40]. Hence with standard deviation and expected value of the eigens are spreaded in form of probabilistic distributed function. Sensitivities of overshoot with respect to PSSs gain is demonstrated in this work further sensitivity reflects that which PSSs location is able to bound the envelope of overshoot of speed deviation curve in moderate range.

$\alpha_m = \overline{\alpha_m} \pm 4\sigma_{\alpha m}$, $\beta'_m = \overline{\beta_m} \pm 4\sigma_{\beta m}$ where α_m and β'_m are the distributed vector envelope between upper and lower range of eigen’s real and imaginary parts $\overline{\alpha_m}$, $\overline{\beta_m}$ are the expected values of $\sigma_{\alpha m}\,\sigma_{\beta m}$ are the standard deviations [34]-[37].

3.3.1.1 Probabilistic sensitivity representation of the Eigen Value real part

For a system of n eigenvalues, the derivative of left eigen vector is a linear combination of all eigenvectors [34].

$$\frac{\partial V_m{}^T}{\partial K_i} = \sum_{k=1}^{n} \left(\frac{1}{\lambda_m - \lambda_k}\right) V_m{}^T \frac{\partial A}{\partial K_i} U_k V_k{}^T \tag{3.7}$$

Probabilistic sensitivity index for eigenvalue m (ESI) with respect to k^{th} PSS gain as per equation (3.8) can be formulated as

$$ESI_{mk} = \frac{\partial \alpha'_m}{\partial K_{pss_k}} = \frac{\partial \overline{\alpha_m}}{\partial K_{pss_k}} + 4\frac{\partial \sigma_{\alpha m}}{\partial K_{pss_k}} \tag{3.8}$$

3.3.1.2 Probabilistic sensitivity representation of the Damping ratio

Damping ratio of any eigenvalue m is given by equation (3.9)

$$\xi_m = -\frac{\alpha_m}{\sqrt{\alpha_m{}^2 + \beta_m{}^2}} \tag{3.9}$$

By performing linearization of (3.9) at the expectation point

Where

$$D_{am} = \frac{-\overline{\beta_m}}{\left|Z_m\right|^3}, \quad D_{bm} = \frac{-\overline{\alpha_m}\,\overline{\beta_m}}{\left|Z_m\right|^3}$$

The sensitivity of the variance of damping ratio with respect to the kth PSS gain will be given by following equation

$$C_{\xi m} = D^2{}_{am} C_{\alpha m,\alpha m} + D^2{}_{bm} C_{\beta m,\beta m} + 2 D_{am} D_{bm} C_{\alpha m,\beta m} \tag{3.10}$$

$$\begin{aligned} \frac{\partial C_{\xi m}}{\partial Kpss_k} &= D^2{}_{am} \frac{\partial C_{\alpha m,\alpha m}}{\partial Kpss_k} + D^2{}_{bm,bm} \frac{\partial C_{\beta m,\beta m}}{\partial Kpss_k} + D_{am} D_{bm} \frac{\partial C_{\alpha m,\beta m}}{\partial Kpss_k} \\ &+ 2(D_{am} C_{\alpha m,\alpha m} + D_{bm} C_{\alpha m,\beta m}) \frac{\partial D_{ak}}{\partial Kpss_k} + 2(D_{bm} C_{bm,bm} + D_{am} C_{\alpha m,\beta m}) \frac{\partial D_{bm}}{\partial Kpss_k} \end{aligned} \tag{3.11}$$

Here

$$\frac{\partial D_{am}}{\partial Kpss_k} = -\frac{3}{\overline{\overline{\alpha_m}}} D_{am} \xi_m{}^{-2} \frac{\partial \overline{\alpha_m}}{\partial Kpss_k} - \left[\frac{2}{\overline{\overline{\alpha_m}}} - \frac{3}{\xi_m} D_{am} \right] D_{bm} \frac{\partial \overline{\beta_m}}{\partial Kpss_k} \tag{3.12}$$

$$\frac{\partial D_{bm}}{\partial Kpss_k} = \left[1 - 3\xi_m{}^2\right] \frac{D_{\beta m}}{\overline{\overline{\alpha_m}}} \frac{\partial \overline{\alpha_m}}{\partial Kpss_k} + \left[\frac{1}{\beta_m} + \frac{3}{\xi_m} D_{bm} \right] D_{bm} \frac{\partial \overline{\beta_m}}{\partial Kpss_k} \tag{3.13}$$

$$PSI_{\xi m} = \frac{\partial \overline{\xi_m}}{\partial Kpss_k} - 4 \frac{\partial \sigma_{\xi m}}{\partial Kpss_k} \tag{3.14}$$

3.3.1.3 Probabilistic sensitivity representation of the Eigen value’s overshoots

Damping ratio ξ_m and overshoot of the signal ζ_m is given for any eigenvalues $Z_m = \alpha_m + j\beta_m$ mode is given by expression (3.8) and (3.14). Of concern of this work the PSSs gain (K_{pss}) is a parameter over which the sensitivity analysis of the overshoot will be performed.

$$\zeta_m = \mathbf{exp}\left(-\frac{\xi_m}{\sqrt{1 - \xi_m{}^2}} \right) \tag{3.15}$$

$$\frac{\partial \zeta_m}{\partial K_{pss}} = \frac{\partial \zeta_m}{\partial \xi_m} \frac{\partial \xi_m}{\partial K_{pss}} \tag{3.16}$$

$$\frac{\partial \zeta_m}{\partial K_{pss}} = -e^{\frac{-\xi_m}{\sqrt{1-\xi_m{}^2}}} \frac{(1+\xi_m{}^4 - 2\xi_m{}^2) + (\xi_m / 2)}{((1-\xi_m{}^2)^{\frac{5}{2}}} \frac{\partial \xi_m}{\partial K_{pss}} \tag{3.17}$$

$$\frac{\partial \xi_m}{\partial K_{pss}} = D_{am} \frac{\partial \overline{\alpha_m}}{\partial K_{pss}} + D_{bm} \frac{\partial \overline{\beta_m}}{\partial K_{pss}} \tag{3.18}$$

Where $D_{am} = \frac{-\overline{\beta_m}}{|Z_m|^3}, D_{bm} = \frac{-\overline{\alpha_m}\overline{\beta_m}}{|Z_m|^3}$, $\overline{\alpha_m}$ and $\overline{\beta_m}$ are the expected values of the real and imaginary parts. Overshoot Sensitivity Indice (OSI) is proposed as per equation 3.20.

$$OSI_{mk} = \frac{\partial \zeta'_m}{\partial K_{pss_k}} = \frac{\partial \overline{\zeta_m}}{\partial K_{pss_k}} + 4 \frac{\partial \sigma_{\zeta m}}{\partial K_{pss_k}} \tag{3.19}$$

Based on the work reported in [34]-[37] statistical attributes are given to the overshoot and real part of the eigenvalues of the poorly damped modes. Simulation results on two IEEE standard test systems are presented in preceding section.

3.4 SIMULATION AND RESULTS

The PSSs location identification problem is investigated on standard IEEE-39 [153] and IEEE-68 bus systems [160]. Standard indices, which are based on the eigenvalue analysis, are carried out for the sake of comparison, as discussed in previous section.

Table 3.2: Table Eigen Property analysis (New England)

Modes	Eigen Values	Damping Ratio
18	0.2848 - 6.6998i	-0.0424
19	0.2848 + 6.6998i	-0.0424
20	0.5728 - 7.2201i	-0.079
21	0.5728 + 7.2201i	-0.079
22	0.13506 - 7.7029i	-0.017
23	0.13506+ 7.7029i	-0.017
26	0.03581 - 8.2562i	-0.0043
27	0.03581 + 8.2562i	-0.0043
31	0.01936- 9.0723i	-0.0021
32	0.01936-+9.0723i	-0.0021

In stability studies ample importance is given to the initial operating condition. In this study nonconforming loads (10% constant current 10% constant power and 60%

constant impedance for active power) are assigned on New England System. Constant impedance loads on each load bus for 16 generator 68 bus system are considered. According [82] System is observed in such a stressed condition that a small perturbation make it unstable. To perform this simulation study 2.5 GB ram 2.5 GHz icore-7 processing unit is used. Power System Toolbox (PST) [158] of Matlab [154] is used for simulation studies.

It can be observed from the eigenvalue analysis that some of the modes are poorly damped and system is observing negative damping. Few poorer modes are shown in Table 3.2 for New England System. Similarly eigenvalue analysis is carried out on 68 bus systems. Poorly damped modes are shown in Table 3.3. To provide a solution for this condition, PSSs should be located for enhance system damping.

Table 3.3: Table Eigen Property analysis (16 Machine)

Modes	Eigenvalues	Damping
31	0.3745-6.8347i	-0.00409
32	0.3745+6.8347i	-0.00409
33	0.01432- 6.904i	-0.00207
34	0.01432 + 6.904i	-0.00207
35	-0.04981 + 7.346i	0.0067
36	-0.04981 + 7.346i	0.0067
40	-0.01368 - 8.077i	0.00169
41	-0.01368 + 8.077i	0.00169
42	-0.04616 - 8.102i	0.00569
43	-0.04616 + 8.102i	0.00569

Conventional indices PF and SPE are calculated as per approach reported [16] & [32]. For calculating SPE, Automatic Voltage Regulator (AVR) configurations are shown in Appendix-D. In this study AVR gain =100 and time constant of 0.01 is used. Table 3.4 & 3.5 show the values of PFs for both power networks. As mentioned in section 3.2.1, it is quite imperative to mention here that states associated with the swing modes are generator's rotor speed deviation and rotor angle of the generator. Values of participation factors for these two state variables are much higher as compared with others. In following analysis the summation of participation factor for these two states are exhibited, efficacy of the proposed index is confirmed through eigenvalue analysis.

3.4.1 Calculation of Participation Factors

New England 10 generator 39 Bus- PF method

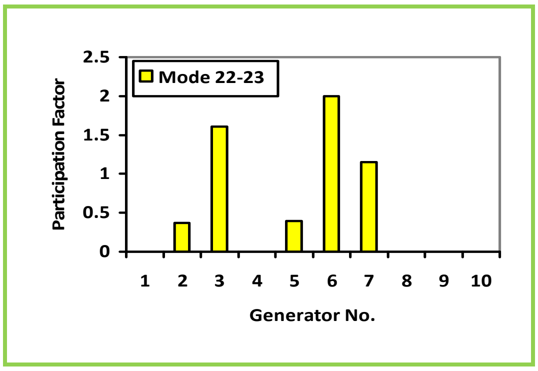

Fig.3.2: PF Calculation for mode 14-15

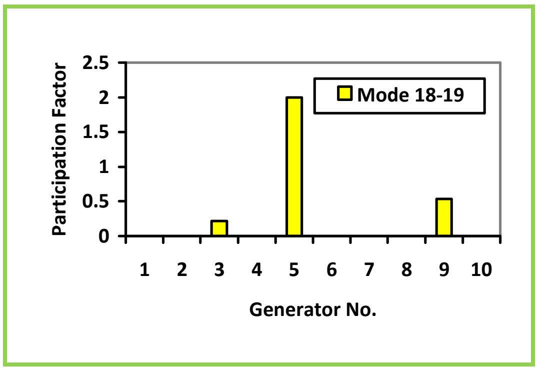

Fig.3.3: PF Calculation for mode 18-19

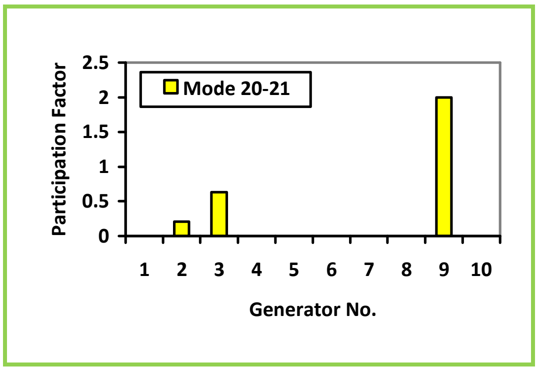

Fig.3.4: PF Calculation for mode 20-21

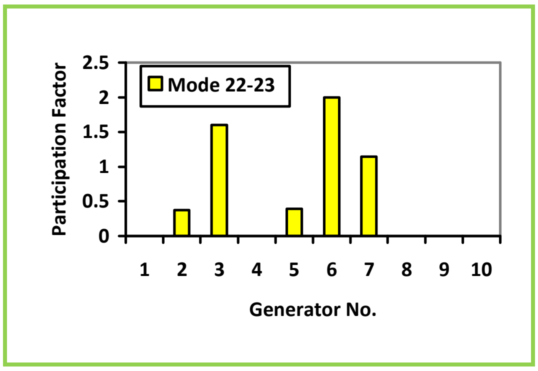

Fig.3.5: PF Calculation for mode 22-23

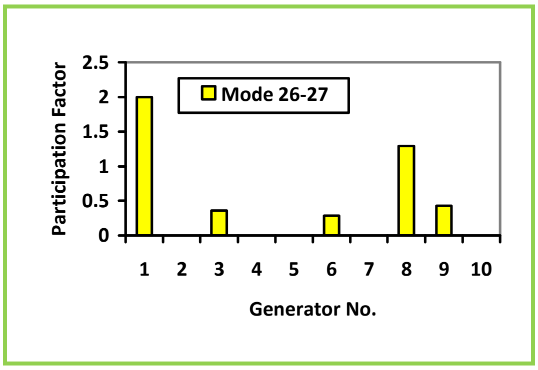

Fig.3.6: PF Calculation for mode 26-27

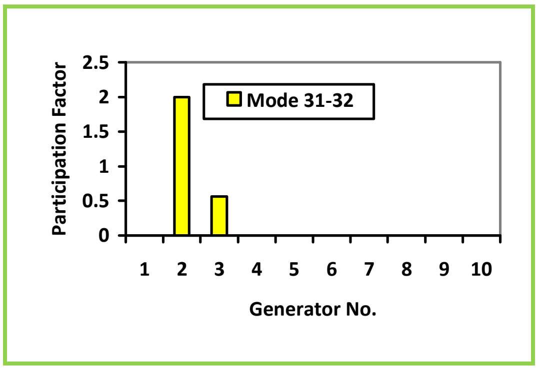

Fig.3.7: PF Calculation for mode 31-32

It can be concluded from Figs. 3.2-3.7 that value of PFs for different generating unit is the measurement of the participation of the generator in that particular damping mode .As shown in Fig. 3.2 generator no. 10 is the most suitable location for outfitting PSS. For mode 31-32 the effective location of PSS is on generator no. 2. Table 3.4 & 3.5 shows the calculation of PF for both power networks.

16 Machine 68 Bus System PF method

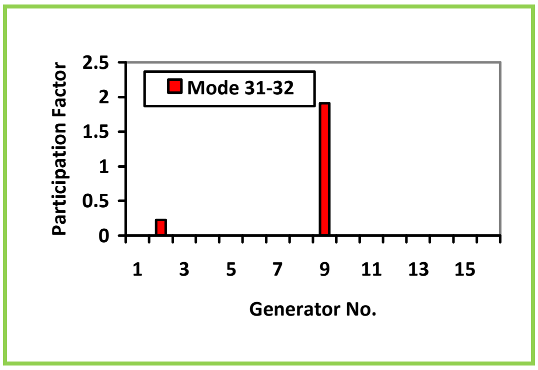

Fig.3.8: PF Calculation for mode 31-32

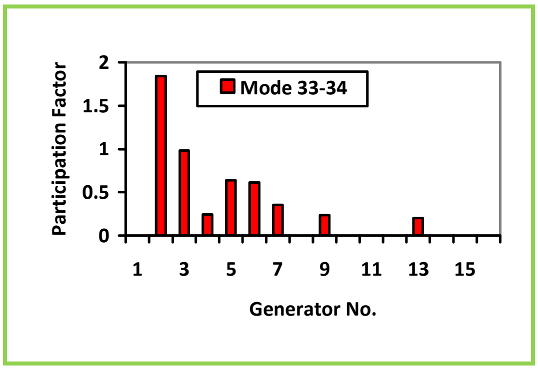

Fig.3.9: PF Calculation for mode 33-34

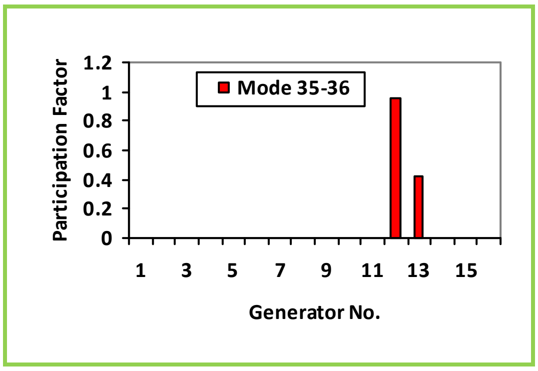

Fig.3.10: PF Calculation for mode 35-36

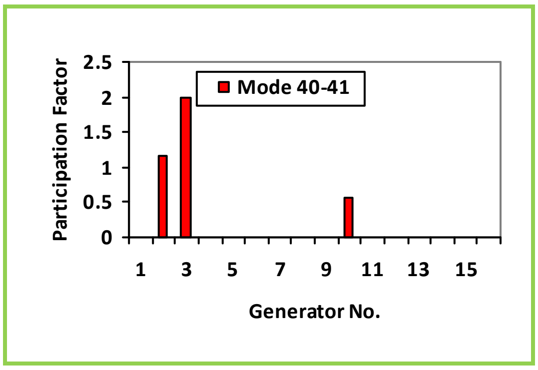

Fig.3.11: PF Calculation for mode 40-41

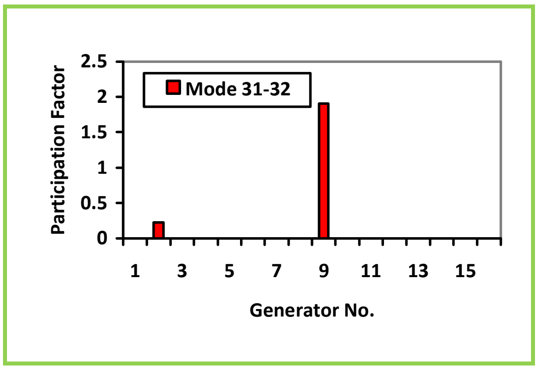

Fig.3.12: PF Calculation for mode 42-43

Similar analogy is found in the calculation of the participation factor for 16 generator and 68 buses. It is quite empirical to judge that participation of generator no. 3 is highest. Similarly effective location of PSSs for mode 42-43 is on generator 10 as per Fig. 3.12. In this study the calculations are carried out only for swing modes or those modes which are inferior and poorly damped.

Table 3.4: Eigen Value Analysis & PF Calculation (New England Power System)

Mode	Eigen Value	Damping Ratio	G1	G2	G3	G4	G5	G6	G7	G8	G9	G10
14-15	-0.0325± 4.3465i	0.0075	0.244	0	0.2718	0.466	0.8144	0.595	0.2256	0	0.4466	2
18-19	0.2844 ± 6.6974i	-0.0424	0	0	0.2164	0	2	0	0	0	0.5328	0
20-21	0.5700± 7.2228i	-0.0787	0	0.207	0.6298	0	0	0	0	0	2	0
22-23	0.0993 ± 7.7128i	-0.0129	0	0.3726	1.603	0	0.3922	2	1.146	0	0	0
26-27	0.03004± 8.24225i	-0.0036	2	0	0.357	0	0	0.2856	0	1.2928	0.4272	0
31-32	0.0185 ± 9.0714i	-0.002	0	2	0.5628	0	0	0	0	0	0	0

Table 3.5: Eigen Value Analysis & PF Calculation (16 Machine Power System)

Mode	Eigen Value	Damping Ratio	G1	G2	G3	G4	G5	G6	G7	G8	G9	G10	G11	G12	G13	G14	G15	G16
31-32	0.3628 ± 6.8657i	-0.0528	0	0.2244	0	0	0	0	0	0	1.91	0	0	0	0	0	0	0
33-34	0.0047 ± 6.9158i	-0.0007	0	1.8406	0.9831	0.2449	0.6409	0.6153	0.3523	0	0.2347	0	0	0	0.2041	0	0	0
35-36	-0.0443 ± 7.3468i	0.006	0	0	0	0	0	0	0	0	0	0	0	0.9579	0.4285	0	0	0
40-41	-0.0133 ± 8.0775i	0.0016	0	1.16	1.98	0	0	0	0	0	0	0.556	0	0	0	0	0	0
42-43	-0.0479 ± 8.1037i	0.0059	0	0.2564	0.349	0	0	0	0	0	0	1.83	0	0.1224	0	0	0	0

3.4.2 SPE Method

Similarly SPE is calculated for the both system Table 3.6 and 3.7 shows the calculation of the SPE [32].

Table 3.6: Eigen Value Analysis & SPE Calculation for different Modes (New England Power System)

Mode	14-15	18-19	20-21	22-23	26-27	28-29	31-32	33-34	36-37	38-39
G1	0.00250	0.00165	0.00032	0.00033	0.01352	0.00032	0.00033	0.00014	0.01490	0.00010
G2	0.00284	0.00277	0.00517	0.00475	0.00010	0.00265	0.05881	0.00064	0.00007	0.00003
G3	0.00461	0.00844	0.02239	0.03608	0.01024	0.01253	0.02878	0.00003	0.00004	0.00001
G4	0.00997	0.00499	0.00123	0.00229	0.00007	0.03455	0.00047	0.15220	0.00034	0.01280
G5	0.01558	0.08252	0.00763	0.00895	0.00006	0.01843	0.00005	0.01124	0.00001	0.00052
G6	0.00933	0.00119	0.00400	0.03502	0.00653	0.00925	0.00034	0.01197	0.00032	0.05965
G7	0.00681	0.00087	0.00334	0.02625	0.00493	0.04407	0.00038	0.01588	0.00075	0.11106
G8	0.00326	0.00429	0.00256	0.00137	0.04727	0.00283	0.00139	0.00040	0.10528	0.00060
G9	0.00983	0.02786	0.10131	0.00441	0.01889	0.00945	0.00004	0.00009	0.00016	0.00001

The noteworthy feature of this analysis is that SPE is a function of right as well as left eigen vector calculation. It is combination of the activity of state variable(s) and control effect of control signals. In PSS location identification, major state variables, which are associated with the in oscillatory stability are angle and speed deviation of the generator. In Table 3.6 & 3.7 SPE is calculated, SPE is function of right eigen values of speed deviation ($\Delta\omega$) & change in reference excitation voltage (ΔE_{fd}).

It is to worth mention here that the location identified by this index should be such that the PSS input should be comparatively large for observing the effect of the input [40]. Conventional PSS takes speed deviation as input signal. Right eigenvalue correspond to speed deviation measures the activity of input signal and change in excitation voltage gives the measure of the control signal [5], [27] & [38]. SPE has one disadvantage that it is also function of AVR gains and time constants. The value of indices observes a change when configuration of AVR is changed. The problems of growing interarea oscillations are more prominent in multimachine networks. SPE provides the best locations when many machines participate in a particular mode [32]. For the ease of understanding SPE calculations are presented in tabular as well as pictorial form. PSS is installed on the generator which has higher value of SPE.

Table 3.7: Eigen Value Analysis & SPE Calculation for different Modes (16 Machine Power System)

Mode	17-18	19-20	24-25	27-28	31-32	33-34	35-36	37-38	40-41	42-43	44-45	47-48	50-51	53-54	55-56	58-59	60-61	62-63
G1	0.00076	0.00008	0.00085	0	0.00014	0.00023	0.00002	0.00002	0.00019	0.00077	0.00505	0.00006	0.00007	0.06968	0.00049	0.00034	0	0.00038
G2	0.00168	0.00017	0.00247	0	0.00676	0.03532	0.00186	0.00044	0.04512	0.01174	0.00081	0.00002	0.00006	0.00007	0.00008	0.00005	0.00001	0.00264
G3	0.00185	0.0002	0.00329	0	0.00632	0.02402	0.00114	0.00019	0.09076	0.01908	0.00155	0.00012	0.00023	0.00013	0.00009	0.00003	0.00001	0.00428
G4	0.00214	0.00029	0.00753	0.00001	0.00153	0.0059	0.00002	0.01458	0.00012	0.00012	0.00021	0.01037	0.13808	0.00028	0.00004	0.0594	0.00009	0.02196
G5	0.00233	0.00035	0.00936	0.00002	0.00222	0.01133	0.00004	0.06051	0.00022	0.00018	0.00125	0.0062	0.03869	0.00003	0	0.0914	0.00009	0.02163
G6	0.00238	0.00034	0.00887	0.00001	0.00229	0.00932	0.00006	0.03162	0.00049	0.00044	0.00205	0.04631	0.00101	0.00005	0.00001	0.00836	0.00003	0.00641
G7	0.00145	0.00021	0.00594	0.00001	0.00186	0.00664	0.00004	0.01745	0.00041	0.00038	0.00058	0.08984	0.01365	0.00006	0.00001	0.04292	0.00008	0.01967
G8	0.0016	0.0002	0.00271	0.00001	0.00226	0.00131	0.00006	0.00016	0.00194	0.00709	0.12134	0.0015	0.00142	0.01185	0.00034	0.02015	0.00001	0.00473
G9	0.00227	0.00032	0.00678	0.00001	0.09886	0.00761	0.00027	0.00036	0.00124	0.00371	0.00936	0.00003	0.00009	0.00027	0.00003	0.5559	0.00006	0.02927
G10	0.00033	0.00002	0.00008	0.00003	0.00012	0.00079	0.00117	0.00003	0.01398	0.06863	0.00507	0.00001	0.00001	0.00014	0.00238	0.00002	0.00001	0.00005
G11	0.00056	0.00002	0.00014	0.00001	0.00004	0.00033	0.00073	0.00001	0.00115	0.00521	0.00036	0	0.00001	0.00117	0.24108	0.0029	0.00377	0.04947
G12	0.00318	0.00007	0.00276	0.00001	0.0001	0.00087	0.06985	0.00002	0.00129	0.00496	0.00008	0	0	0.00002	0.00072	0.00001	0.00001	0.00001
G13	0.01117	0.00024	0.01357	0.00016	0.00006	0.00119	0.00838	0	0.0001	0.00036	0.00002	0	0	0.00002	0.00057	0.00022	0.00043	0.00206
G14	0.00348	0.0099	0.00013	0.00908	0	0.00002	0.00001	0	0.00002	0.00008	0	0	0	0	0.00002	0.00001	0	0.00001
G15	0.00303	0.00032	0.00004	0.01229	0	0	0	0	0	0	0	0	0	0	0	0	0.00107	0
G16	0.00257	0.01913	0.00043	0.00426	0	0.00001	0.00002	0	0.00002	0.00008	0	0	0	0	0.00005	0.00002	0.0541	0.00007

New England 10 generator 39 Bus SPE method

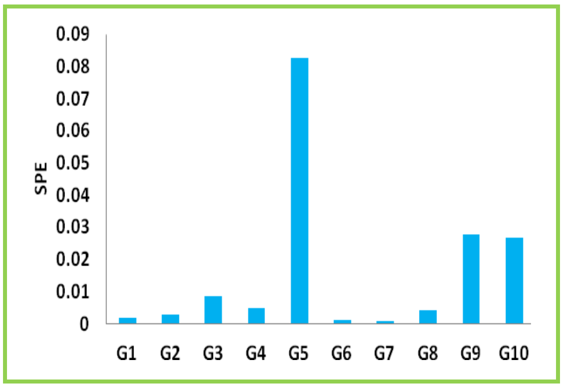

Fig.3.13: SPE Calculation for mode 18-19

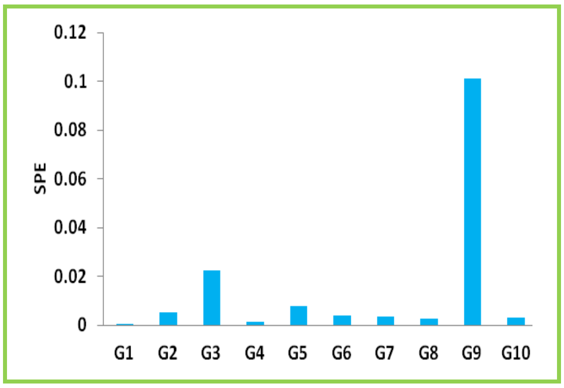

Fig.3.14: SPE Calculation for mode 20-21

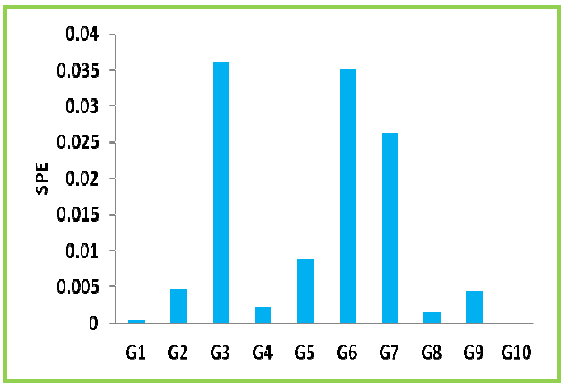

Fig.3.15: SPE Calculation for mode 22-23

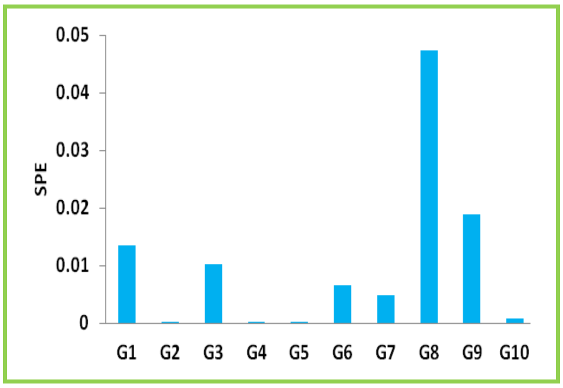

Fig.3.16: SPE Calculation for mode 26-27

16 generator 68 Bus- SPE method

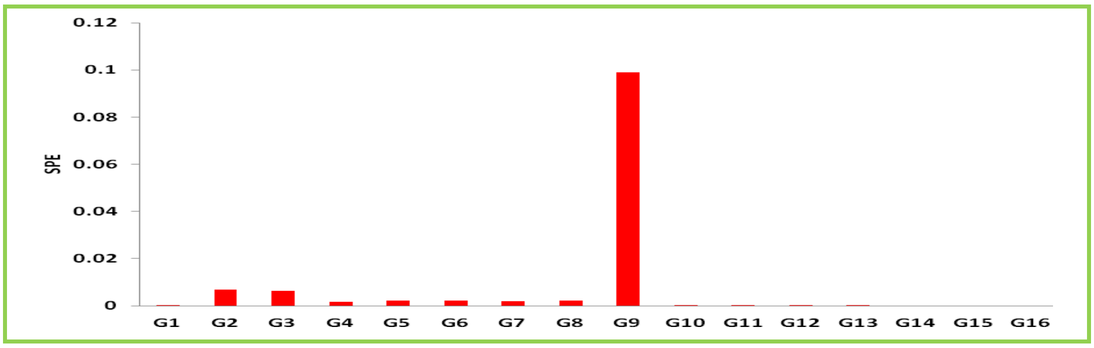

Fig.3.17: SPE Calculation for mode 31-32

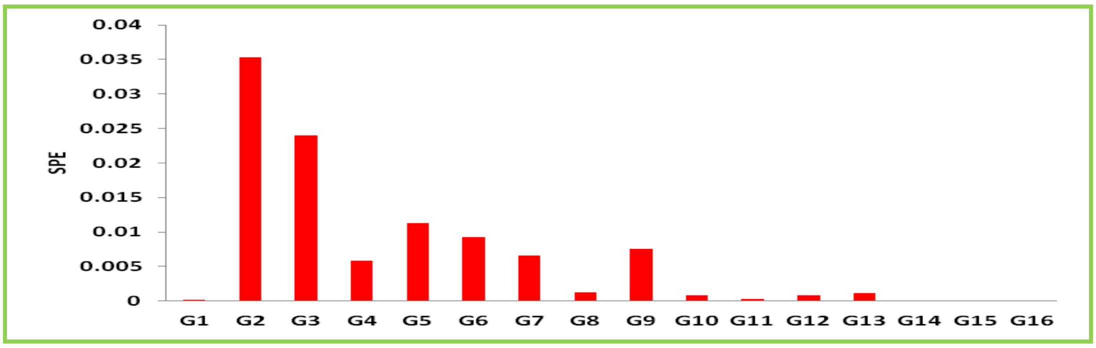

Fig.3.18: SPE Calculation for mode 33-34

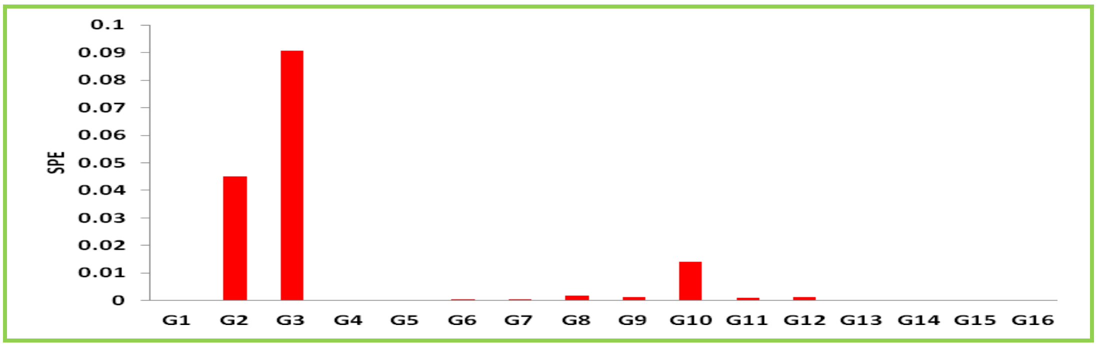

Fig.3.19: SPE Calculation for mode 40-41

It can be observed from the analysis of New England System, that according to SPE, locations for nullify negative damping for mode 18-19 a PSS should be located on generator no.5. Simlarly for 16 generator 68 system, for mode 31-32 ideal location of PSS is on generator no.9, for mode 40-41 the location is on generator no.3.The low values of SPE indicate that if the AVR configurations are not considered, the values of multiplication of right and left eigen's will be very low and determination of PSS location will be troublesome task to do.

3.4.3 Calculation of Probabilistic distribution based indices

The normal distribution (Gaussian distribution) is a family of distributions recognized as being symmetrical, unimodal, and bell-shaped [37]. The normal distribution is characterized by two parameters: μ and σ. The mean (μ) determines the distribution's location. The standard deviation σ of a particular normal distribution determines its spread. Table 3.8 shows the statistics related with the proposed index as per equation (3.8).

Table 3.8: Probabilistic distribution of Real part of eigenvalues

System	Mode	*Real part of eigen value*	*Expectation(s) As per [89]*	*Standard deviation σ*	*Upper Range*	*Lower Range*	*PDF*
10 Generator 39 Bus	18-19	0.2848	-0.5	1.255	5.3048	-4.732	0.29546
	20-21	0.57	-0.75	1.495	6.55	-4.51	0.2345
	22-23	0.135	-0.4	0.985	4.075	-3.08	0.25457
	26-27	0.03	-0.34	0.955	3.85	-3.79	0.38909
	31-32	0.01	-0.25	0.955	3.83	-3.81	0.40476
16 Generator 68 Bus	31-32	0.368	-0.67	0.952	5.45	-3.96	0.3789
	33-34	0.0047	-0.43	0.915	4.21	-3.65	0.254
	40-41	-0.013	-0.35	0.965	3.78	-2.96	0.365

Tables 3.8 & 3.9 show the probabilistic distribution of real part of the eigenvalues and overshoots for both systems. Following points will throw special light on the analysis carried out in these Tables.

1. Highest positive real part of eigenvalue is of mode 20-21 for New England system. According to eigenvalue analysis the real part indicates the amplitude of oscillations. Value of standard deviation is kept maximum for this mode, as the probability of exciting this mode can be hazardous for the system stability.
2. Spread of eigenvalue is between $(\overline{\alpha_k}+4\sigma_k, \overline{\alpha_k}-4\sigma_k)$ where $\overline{\alpha_k}$ is the expectation value for k^{th} mode and σ_k standard deviation. This spread is replica of the swing of real part of eigenvalue between upper and lower limit. Standard deviation decides the spread of probability distribution curve.
3. The advantage of this analysis is that the value of indices calculated as per equation (3.8) & (3.19) will hold good for all operating cases in which the real part of eigen fall in this range.
4. Table 3.9 shows that minimum spread is assigned to the real part which is nearby to origin. In case of New England system the minimum spread is assigned to mode 31-32. In case of 16 generator 68 bus system the minimum spread is given to the mode 40-41.

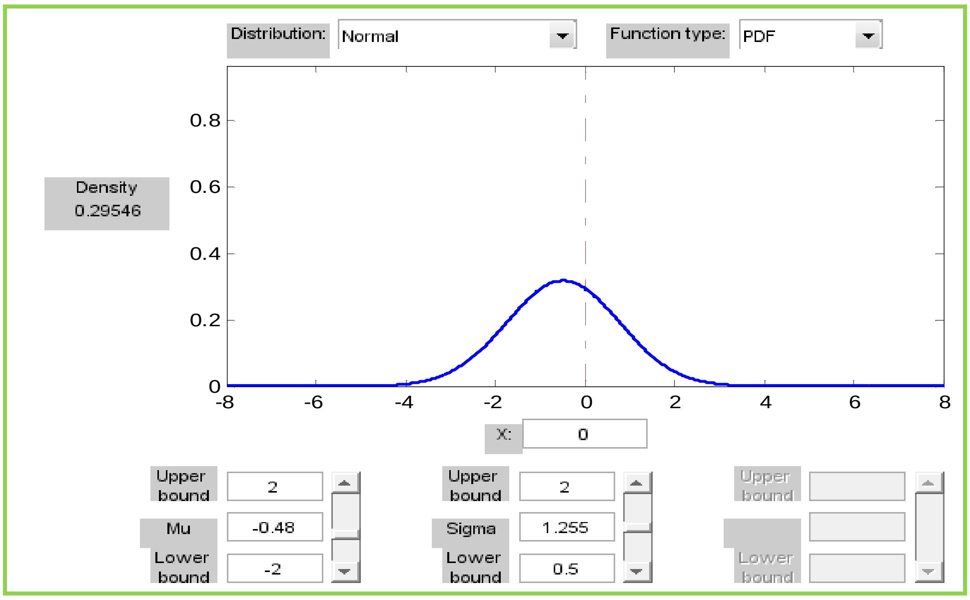

Fig.3.20: Probabilistic distribution of real part of eigen 18-19

Fig. 3.20 shows the Probabilistic distribution of the real part of eigenvalue of mode 18-19 for New England system. Fig. 3.21 shows the probabilistic distribution of the overshoot of mode 22-23.

Table 3.9: Probabilistic distribution of overshoot of swing modes

System	Mode	*Overshoot of Swing mode*	*Expectation(s)*	*Standard deviation σ*	*Upper Range*	*Lower Range*	*PDF*
New England	18-19	0.9584	0.0384	1.18	5.67	-3.761	0.4714
	20-21	0.9238	-0.0016	1.08	5.24	-3.396	0.3389
	22-23	0.9831	0.1184	1.3	6.183	-4.216	0.30561
	26-27	0.9957	0.1589	1.305	6.2517	-4.221	0.3040
	31-32	0.9979	0.198	1.315	6.257	-4.262	0.2994
16 Generator 68 Bus	31-32	0.9959	0.159	1.2952	6.1767	-4.184	0.3040
	33-34	0.9979	0.198	1.305	6.217	-4.221	0.2994
	40-41	1.0017	0.2	1.105	5.4217	-3.418	0.254

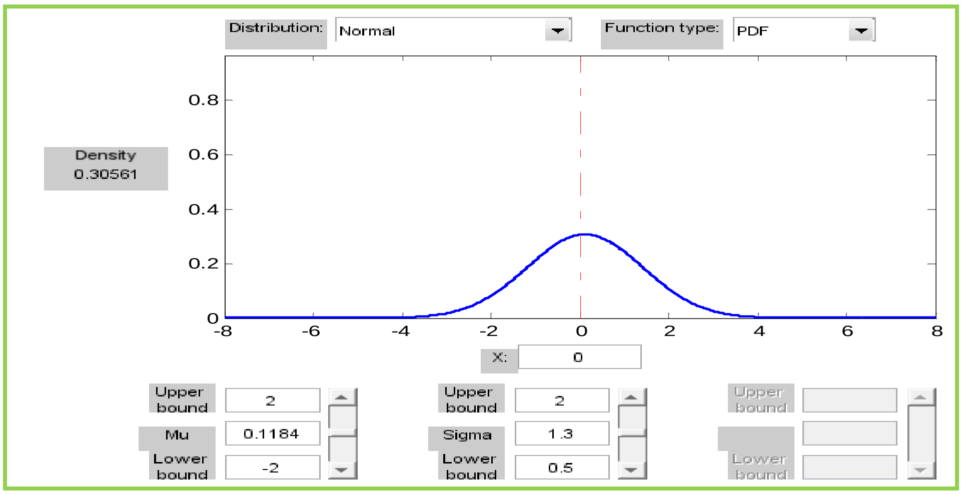

Fig.3.21: Probabilistic distribution of overshoot of mode 22-23

3.4.3.1 Results of Proposed Indexes (16 Machine Power System)

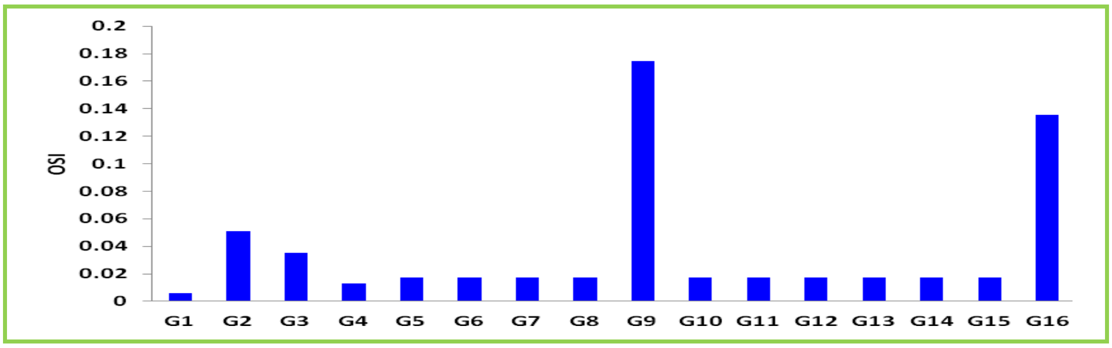

Fig.3.22: OSI Calculation for mode 31-32

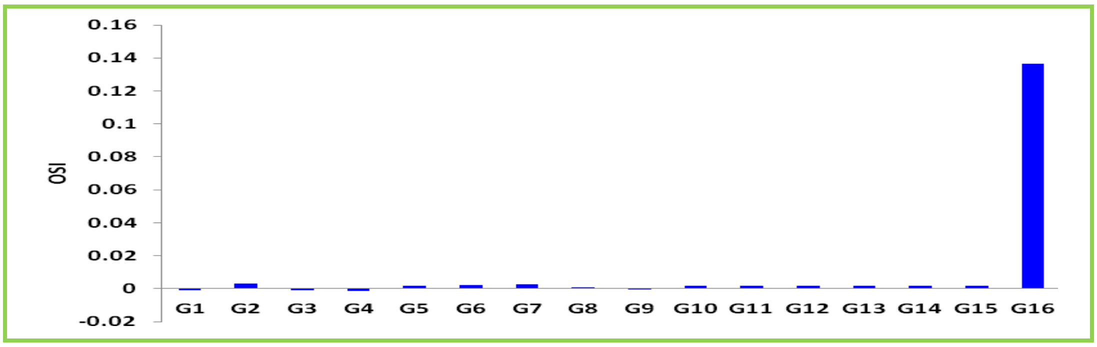

Fig.3.23: OSI Calculation for mode 33-34

Fig.3.24: ESI Calculation for mode 33-34

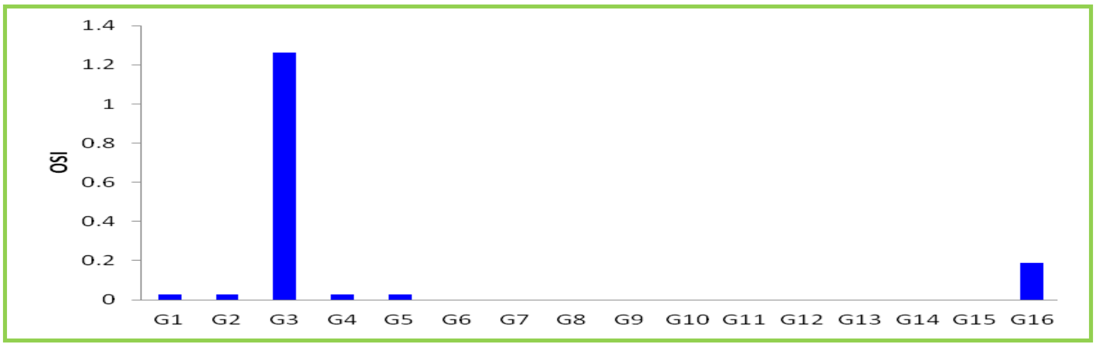

Fig.3.25: OSI Calculation for mode 40-41

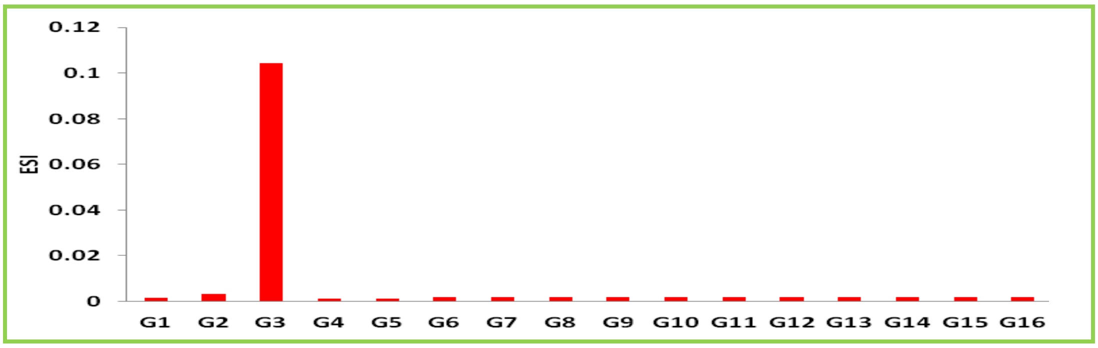

Fig.3.26: ESI Calculation for mode 40-41

3.4.3.2 Results of Proposed Indexes (New England Power System)

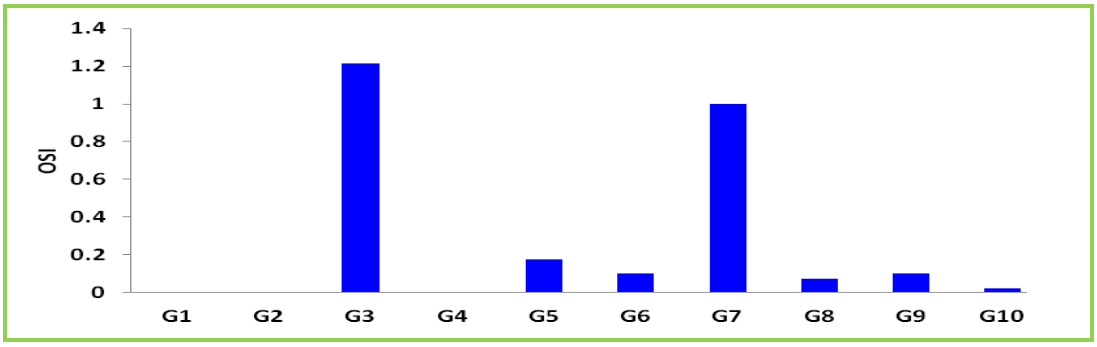

Fig.3.27: OSI Calculation for mode 22-23

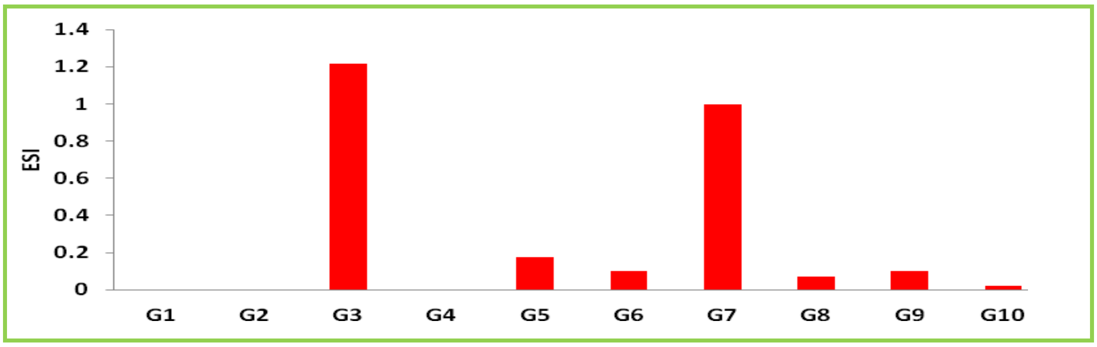

Fig.3.28: ESI Calculation for mode 22-23

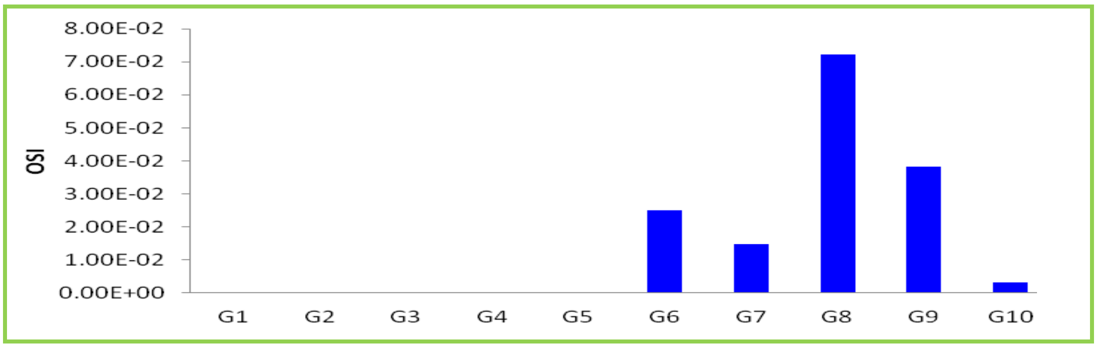

Fig.3.29: OSI Calculation for mode 26-27

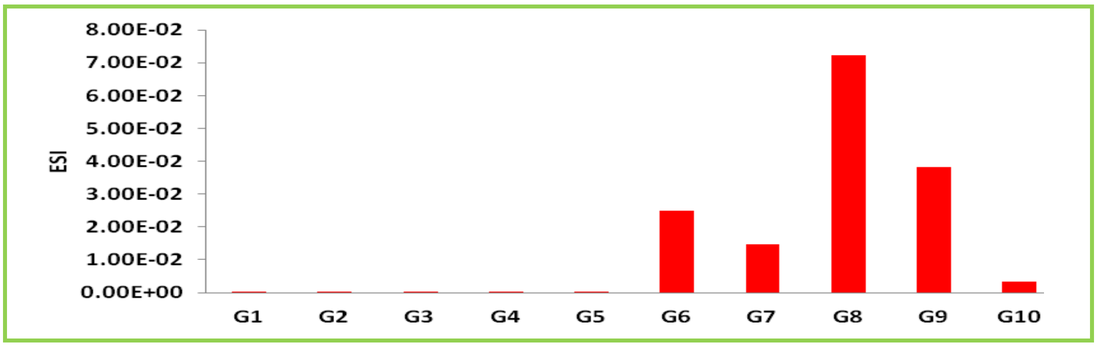

Fig.3.30: ESI Calculation for mode 26-27

Tables 3.10 & 3.11 show the values of all indices cumulatively for New England System. According to the methods the PSSs will be outfitted on those locations which will have higher values of the indice. As per Table 3.10 for mode 18-19 PSS should be outfitted on generator 5. For the ease of understanding and observations higher values are shown in bold. Similarly cumulative indice calculations for 16 Generator 68 bus system are shown in Table 3.12

Table 3.10: Indice Values for New England

INDEX	MODE 18-19				MODE 20-21			
	SPE[32]	P F[16]	O S I	E S I	SPE[32]	P F[16]	O S I	E S I
G1	0.00165	0	0.08105	0.0055	0.00032	0	-0.0064	-0.0005
G2	0.00277	0	0.16182	0.01086	0.00517	0.207	0.04824	0.00363
G3	0.00844	0.2164	0.27143	0.0179	0.02239	0.6298	0.92295	0.0755
G4	0.00499	0	0.04445	0.00301	0.00123	0	0.00414	0.00029
G5	**0.08252**	**2**	**1.39787**	**0.1034**	0.00763	0	0.03348	0.0024
G6	0.00119	0	-0.013	-0.0008	0.004	0	0.11	0.0073
G7	0.00087	0	-0.0074	-0.0005	0.00334	0	0.1175	0.00785
G8	0.00429	0	0.02	0.00121	0.00256	0	0.0684	0.00471
G9	0.02786	0.5328	0.6024	0.03899	**0.10131**	**2**	**1.4123**	**0.10228**
G10	0.02657	0	0.6886	0.04	0.0032	0	0.72	0.05

Table 3.11: Indice Values for New England

INDEX	MODE 22-23				MODE 26-27			
	SPE[32]	P F[16]	O S I	E S I	SPE[32]	P F[16]	O S I	E S I
G1	0.00033	0	0	-0.0007	0.01352	**2**	4.58E-08	-0.002
G2	0.00475	0.3726	0	-0.0031	0.0001	0	4.51E-08	-0.0021
G3	0.03608	1.603	1.21656	0.13315	0.01024	0.357	4.35E-08	-0.0019
G4	0.00229	0	0	-0.0014	7.00E-05	0	4.98E-08	-0.0026
G5	0.00895	0.3922	0.17545	0.1216	6.00E-05	0	3.80E-08	-0.002
G6	**0.03502**	**2**	**0.101**	**0.0066**	0.00653	0.2856	0.025	0.0021
G7	0.02625	1.146	0.9991	0.00695	0.00493	0	0.0148	0.00121
G8	0.00137	0	0.0727	0.00511	**0.04727**	1.2928	**0.0722**	**0.00601**
G9	0.00441	0	0.0997	0.01664	0.01889	0.4272	0.0383	0.00315
G10	0	0	0.023	0.03	0.00087	0	0.00323	0.0005

Table 3.12: Indice Values for 16 Machine 68 Bus

INDEX	MODE 31-32				MODE 33-34				MODE 40-41			
	SPE[32]	P F[16]	O S I	E S I	SPE[32]	P F[16]	O S I	E S I	SPE[32]	P F[16]	O S I	E S I
G1	0.00014	0	0.006	1.00172	0.00023	0	-0.001	-0.0154	0.00019	0	0.02728	0.0014
G2	0.00676	0.2244	0.051	0.96135	**0.03532**	**1.841**	0.00302	0.05296	0.04512	1.16	0.02755	0.00319
G3	0.00632	0	0.03505	0.97201	0.02402	0.983	-0.0009	-0.0124	**0.09076**	**1.98**	**1.26336**	**0.10429**
G4	0.00153	0	0.0131	0.99322	0.0059	0.245	-0.00129	-0.0156	0.00012	0	0.02634	0.00134
G5	0.00222	0	0.0175	0	0.01133	0.641	0.0017	0.028336	0.00022	0	0.026401	0.0013
G6	0.00229	0	0.0175	0	0.00932	0.615	0.0022	0.036	0.00049	0	0	0.002
G7	0.00186	0	0.01746	0	0.00664	0.352	0.00273	0.0427	0.00041	0	0	0.00177
G8	0.00226	0	0.01749	0	0.00131	0	0.00065	0.0137	0.00194	0	0	0.00198
G9	**0.09886**	**1.91**	**0.1745**	**1.8785**	0.00761	0.235	-0.0001	0	0.00124	0	0	0.00195
G10	0.00012	0	0.017087	0	0.00079	0	0.001657	0.027828	0.01398	0.556	0	0.001996
G11	0.00004	0	0.017451	0	0.00033	0	0.001698	0.028427	0.00115	0	0	0.001994
G12	0.0001	0	0.017368	0	0.00087	0	0.001773	0.029505	0.00129	0	0	0.001995
G13	0.00006	0	0.017444	0	0.00119	0.204	0.001656	0.027593	0.0001	0	0	0.001994
G14	0	0	0.017458	0	0.00002	0	0.001744	0.029078	0.00002	0	0	0.001995
G15	0	0	0.017456	0	0	0	0.001742	0.029042	0	0	0	0.001995
G16	0	0	0.1355	1.79	0.00001	0	**0.1365**	**2.74**	0.00002	0	0.19	0.10089

3.4.3.3 Validation of the proposed method by eigenvalue analysis

To investigate the effect of proposed methods initially PSSs are outfitted on1, 5, 6, 8th and 9th generator in New England System and 2,3,9,7 and 16th generator for 16 Generator 68 bus system. Damping observed after installation of PSS is shown in Table 3.13.

Table 3.13: Eigen Values and damping for critical swing modes with high AVR gains and PSS (New England)

Mode	AVR gain=100		AVR gain=150	
	Eigen Value	Damping	Eigen Value	Damping
17	-1.416 - 0.027i	0.999812	-1.407 - 0.026i	0.999817
18	-1.416 + 0.027i	0.999812	-1.407 + 0.026i	0.999817
30	-0.830 - 9.364i	0.08835	-1.115 - 9.1953i	0.120409
31	-0.830 + 9.364i	0.08835	-1.115 + 9.1953i	0.120409
41	-1.723 - 12.716i	0.134341	-1.151 - 12.022i	0.095332
42	-1.723 + 12.716i	0.134341	-1.151 + 12.022i	0.095332
43	-1.636 - 12.867i	0.126187	-1.273 - 12.251i	0.103417
44	-1.636 + 12.867i	0.126187	-1.273 + 12.251i	0.103417

Table 3.14: Eigen Values and damping for critical swing modes with low AVR gains and PSS (16 Generator 68 Bus)

Mode	AVR gain=100		AVR gain=150	
	Eigen Value	Damping	Eigen Value	Damping
29	-0.125 - 4.078i	0.030866926	-0.315 - 7.559i	0.041677036
30	-0.125 + 4.078i	0.030866926	-0.315 + 7.559i	0.041677036
33	-0.159 - 6.714i	0.023766445	-0.220 - 8.231i	0.026736357
34	-0.159 + 6.714i	0.023766445	-0.220 + 8.231i	0.026736357
36	-0.245 - 7.372i	0.033303319	-0.464 - 8.618i	0.053778808
37	-0.245 + 7.372i	0.033303319	-0.464 + 8.618i	0.053778808
42	-0.287 - 9.020i	0.031802575	-0.235 - 9.931i	0.023675384
43	-0.287 + 9.020i	0.031802575	-0.235 + 9.931i	0.023675384
44	-0.445 - 9.414i	0.047274777	-0.558 - 10.912i	0.051124361
45	-0.445 + 9.414i	0.047274777	-0.558 + 10.912i	0.051124361
46	-0.400 - 9.612i	0.041624211	-0.574 - 11.022i	0.052061421
47	-0.400 + 9.612i	0.041624211	-0.574 + 11.022i	0.052061421
48	-0.632 - 9.699i	0.065062023	-0.627 - 11.247i	0.055712769
49	-0.632 + 9.699i	0.065062023	-0.627 + 11.247i	0.055712769

PSS gain is kept constant and the values of time constants for lead lag loop are also constant. However AVR gains are varied in a wide range to show the importance of adequate tuning of PSS. It is worth mention here that during eigenvalue analysis

PSS includes three states in modal analysis. The positions of the modes have been shifted due to the presence of PSS in system. As before installation of PSS New England system was having 49 states and after installing PSS it became 76 and for 16 generator 68 bus system before PSS it was 112 and after installing PSS it has become 160. For carrying out meaningful evaluations it is empirical to judge the involvement of the state variables with particular mode.

Following are the noteworthy points from this analysis:

1. It is observed that significant amount of increase in damping is observed for critical swing modes when PSS is added on the locations specified by the indexes.
2. Due to high AVR gains in Table 3.14, it is quite pragmatic to observe that due to high AVR gains significant amount of reduction in damping is also observed, for example mode 43-44 the damping is reduced when AVR gain is increased, without changing the PSS setting.
3. It is also worth mention here that if tuning of PSS for a particular AVR setting is done, it is also possible that the same may not be able to provide significant amount of damping for all different configurations of AVR. This postulate shows the inefficiency of SPE [32].
4. It is also concluded that if different configurations of AVRs (change in time constants and AVRs gains) are employed, the setting of PSSs is also required to be altered. This alteration is to be done in such a manner so that system will be having an adequate damping.

Further in this section validity of the proposed indexes (OSI, ESI) is presented through eigenvalue analysis. It is observed that in all cases the location identified by the OSI and ESI are same.

Table 3.15: Critical Observations on mode 26-27 (New England System)

K stab	AVR Gain=200		AVR Gain=100	
	G1	G8	G1	G8
10	0.02760	0.0278	-8.686	-8.6862
20	0.02740	0.0277	-8.686	-8.6864
30	0.02720	-1.4265	-8.686	-8.6866
40	0.02700	-9.737	-8.686	-8.6867
50	0.02690	-9.737	-8.6859	-8.6869
60	0.02680	-9.737	-8.6859	-8.6871
70	0.02670	-9.737	-8.6859	-8.6873
80	0.02660	-9.737	-8.6859	-8.6874
90	0.02660	-9.737	-8.6859	-8.6876
100	0.02650	-9.737	-8.6858	-8.6878

For New England system all indexes give same results for mode 18-19, 20-21 and mode 22-23. However, for mode 26-27 as per PF method the ideal location for the PSS site is on generator 1, proposed indexes indicates that it should be on generator 8. To show efficacy of the proposed index the AVR gains (K_a) are modulated between 100 - 200.

Following points can be concluded from Table 3.15

1. It is observed that when PSS is outfitted at location 1 with AVR gain 200, real part of eigenvalue for mode 26-27 will remain positive. However, the real part of Eigen becomes negative when PSS is outfitted on generator 8. It indicates that the location identified by proposed indexes hold good. It is interesting to observe that with AVR gain 100, outfitting of PSS on both locations give adequate damping and same effect.
2. It is also a noteworthy observation that when, PSS is outfitted at location 8, It is not able to give proper damping till the PSS gain exceeds to a specific value in this case 30. This fact establishes the need of proper PSS gain tuning.
3. Table 3.15 also shows that under different operating conditions the conventional methods can give false prediction as in this case. However, the location identified by OSI and ESI in both cases provides adequate damping.

Table 3.16: Critical Observations on mode 33-34 (16 Generator 68 Bus)

PSS Gain	AVR Gain=50		AVR Gain=100		AVR Gain=150		AVR Gain=200	
	G2	G16	G2	G16	G2	G16	G2	G16
10	-8.67188	-8.095	0.027712	-7.03326	0.109688	-8.45632	0.027646	-9.52734
20	-8.67188	-8.095	0.027766	-7.03229	0.109684	-8.4771	0.027437	-9.52723
30	-8.67175	-8.095	0.02782	-7.03133	0.109705	-8.4987	0.027253	-9.52712
40	-8.67169	-8.096	0.027871	-7.03036	0.109744	-8.52125	0.027092	-9.52701
50	-8.67162	-8.096	0.027922	-7.0294	0.109798	-8.54492	0.026952	-9.52689
60	-8.67156	-8.096	0.027971	-7.02845	0.109863	-8.56993	0.026831	-9.52677
70	-8.6715	-8.096	0.02802	-7.0275	0.109937	-8.59657	0.026725	-9.52665
80	-8.67144	-8.097	0.028066	-7.02656	0.110016	-8.62523	0.026634	-9.52653
90	-8.67138	-8.097	0.028112	-7.02562	0.1101	-8.65652	0.026554	-9.5264
100	-8.67132	-8.097	0.028157	-7.02469	0.110187	-8.69136	0.026484	-9.52627

Table 3.16 shows the eigenvalue analysis for 16 generator 68 bus system it is observed that according to SPE and PF, effective location of PSS installation is on generator 2. However, according to OSI and ESI the effective location of PSS is on generator 16. In this analysis both AVR gain and PSS gain both are modulated in a stepwise manner. It is observed that for low AVR gains both identified locations give adequate amount of damping. However, slight modulations in AVR gain introduce negative damping. Effective damping is achieved by outfitting PSS on location 16, which is identified by ESI and OSI. This fact further validates the efficacy of the proposed indexes.

3.5 SUMMARY

This chapter proposes two indexes based on probabilistic distribution of real part and overshoot of the swing modes. Following are the noteworthy features of the indexes.

1. A probabilistic approach for penetrating optimum locations of PSS in Multi machine power system is introduced in this chapter. Under multi operating conditions of a power system, Variations of the eigenvalues are described by the normal distribution. Normal distributions of the eigenvalues are defined by the expectations and variance. Sensitivity analysis of the overshoot with respect to the PSSs gain is presented. Modal analysis is performed to identify the poorly damped modes and effect on the mode’s behavior is judged by outfitting PSSs at different locations as suggested by proposed indexes. The proposed indexes results are compared with the residue and participation factor methods.

2. An eigenvalue can be expressed by its expectation and variance under the assumption of normal distribution. PSSs improve both expectations and variances for all concerned eigenvalues.

3. The proposed method is more realistic as it takes load variations and nodal voltage injections as important parameters for probabilistic distribution.

4. Eigenvalue sensitivity analysis and comparison of the results with conventional indexes ensures the effectiveness of the proposed method.

5. Variation in the real part of the eigenvalue is observed with different stabilizer gain, from this analysis it is concluded that the indexes are able to locate the perfect candidate locations in multimachine power system. However, if PSS is placed on the location suggested by the index and it is not tuned properly, than it is as equal as the absence of the same, from this analysis importance of parameter estimation is emerged very strongly.

It is worth to mention here that although PSS provide damping for power networks yet improper tuned PSS will not be able to serve the purpose, even if it is properly placed. Following chapter presents a trajectory sensitivity approach to know the parametric influence of PSS parameters on the conventional eigenvalue based objective function and later proposes PSS parameter estimation scheme for robust operations.

Chapter 4

Robust PSS Design by Trajectory Sensitivity Approach

Many physical systems demonstrate dynamic behavior which is governed by many attributes like discrete-time and event dynamics, switching action and jump phenomenon [94]. Most of the time amalgamation of these attributes makes the system more complicated. It is quite indispensable to study dynamics of the system .As it is observed all the above said inequalities is often seen in power system ,the behavior of power systems is governed by the nonlinear dynamics of machines, loads, Flexible AC Transmission Systems (FACTS) devices, and their associated control equipment [95].

Dynamic behavior of any system is constrained by physical laws: some examples are quoted in literature to demonstrate the constrained physical laws: current balance must be maintained at all nodes; in each transformation the energy should be conserved. Furthermore, protection relays, controller limits, and discrete devices, such as on-load tap changing transformers and switched shunt capacitors, introduce discrete events, switching action, and state resetting into the system [94], [98], [103] & [104]. Power system behavior can therefore be quite complicated, yet system integrity is reliant on a thorough understanding of that behavior. This requires effective and insightful analysis of the system. To judge the system behavior nonlinear simulation is performed, many advantages associated with simulation studies are shown here [96]:

a) It gives information of the system behavior (unexpected phenomenon) without actually building it.

b) The simulation studies are based on “What if” analysis.

c) It is applicable for arbitrarily complicated models.

The disadvantage of nonlinear simulation is that it always gives information about only one scenario it is not possible to extrapolate the results for other scenarios or even small changes in the system parameters [98]. For many systems iterations of simulation works, but for large systems, like power system computational cost and time associated with the process becomes a tedious issue.

To overcome this troublesome process of performing simulation over repeated time, trajectory sensitivity analysis is a suitable approach.[94] Preceding section presents a mathematical frame work for trajectory sensitivity approach. The process related with the sensitivity analysis is to make system linearize the whole system to a nominal trajectory point rather than an equilibrium point. It is possible to determine the change in trajectory directly with respect to system parameters [100]. Trajectory sensitivities provide valuable insights into the influence of parameters on the dynamic behavior of systems. Properties which are not obvious from the actual system response are often evident in the sensitivities studies [98]-[103].

4.1 MATHEMATICAL FRAME WORK

Sensitivity approach is originally applied in system control and parameter estimation. Approach for PSS parameter design is reported in these works in literature [88]. A trajectory sensitive mapping technique is developed to evaluate the gradient of the objective function with respect to PSS parameters and for coordinately tuning of those [83]. To give an insight on the concept following description is inculcated in this work:

$$\dot{x} = f(x), \quad x(t_0) = x_0 \tag{4.1}$$

Parameter β can be incorporated through trivial differential equations

$$\dot{\lambda} = 0 \qquad \lambda(t) = \lambda_0 \tag{4.2}$$

Conveniently flow of x is defined as (4.3) the trajectory of anything is nothing but the visualization of the parametric influence on any variable for this model the same is demonstrated by calculating the flow of variable x.

$$x(t) = \phi(x_0, t) \tag{4.3}$$

$$\phi(x_0, t_0) = x_0 \tag{4.4}$$

$$\Delta x(t) = \frac{\partial \phi}{\partial x_0}\Delta x_0 + \dots High\ order\ terms \tag{4.5}$$

$$\approx \frac{\partial x(t)}{\partial x_0}\Delta x_0 \equiv x_{x0}(t)\Delta x_0 \tag{4.6}$$

Term shown in (4.6) is a partial derivative and also known as trajectory Sensitivity. Following points are worth mention here for underlying the importance of trajectory analysis in a dynamic scenario of the power system.

1. Trajectories behaviour is early indication impending system instability.

2. Trajectory sensitivities provide gradient information that motivates the number of inverse problems (parameter estimation, boundary value problem) and optimal control.

3. Analysis of any disturbance on power system is contingent of time domain simulation analysis; however the effect of parameters can't be easily deduced by such simulations.

The quantum of sensitivity indices depict that a parameter has a significant effect on behaviour of the system. These insights are useful while analyzing the underlying influences on system dynamics and for assessing the implication of parameter uncertainty [101].

Preface: An application of classical optimization method gives us a canvas to explore and predict the trajectory and behaviour of an eigenvalue based objective function [156]. It is quite pragmatic to state that in most real power system problem the size and shape of objective function prediction is an unabated dilemma. To predict the PSSs parameters influence and to understand behaviour and trajectories of objective function with respect to PSSs parameter three schemes are proposed in this work and further shortcoming of the schemes reported in literature [83] is modified and validated through non linear simulation.

4.2 CLASSICAL OPTIMIZATION METHODS

One of the simplest methods of finding minima and maxima of the function is the equal interval search method [127], [129] & [156]-[157]. For understanding the scheme based on golden section and golden ratio, let's consider a function *f(x)*, where the minima exist between points [a, b]. Let's choose an interval of ε over which it is assumed that the minimum occurs. Fig. 4.1 shows the function flow with x.

1. Optimization process started with the calculation of function at two points $f\left(\frac{a+b}{2}+\frac{\varepsilon}{2}\right)$ and $f\left(\frac{a+b}{2}-\frac{\varepsilon}{2}\right)$

2. If $f\left(\frac{a+b}{2}+\frac{\varepsilon}{2}\right) \le f\left(\frac{a+b}{2}-\frac{\varepsilon}{2}\right)$ than the search space is limited in interval $\left(\frac{a+b}{2}-\frac{\varepsilon}{2}, b\right)$ otherwise it would be change $\left(a, \frac{a+b}{2}+\frac{\varepsilon}{2}\right)$

3. This reduces the search space of the algorithm, and easily locates the minima for the function.

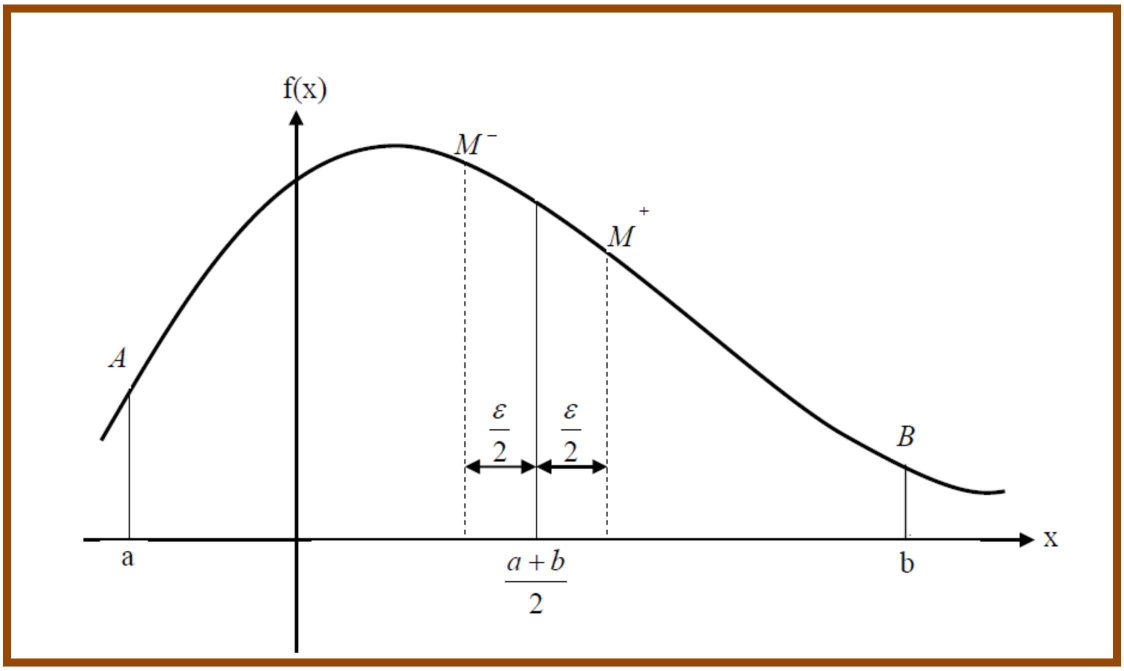

Fig. 4.1: Equal interval search method

This paradigm is based on the reduction of the search space and it can take a long time if ε is very small number, to remove this shortcoming golden section method is introduced [157].

4.2.1 Golden Section Search

Golden section search optimization is a conventional optimization process normally used for unimodal functions [156]. The term unimodal is defined for any function *f(x)*, which has only one minimum in a given value of parametric range. Let there are three points exist such as $x_1 < x_2 < x_3$ along x axis corresponding values of objective functions are $f(x_1), f(x_2)$ and $f(x_3)$ and the search of the algorithm is towards obtaining minima in the range (x_1, x_3). Fig. 4.2 shows the approach of golden section to find the maxima for a given function *f(x)*. It compares the value of function *f(x)* at $\left(\frac{x_1+x_3}{2}+\delta, \frac{x_1+x_3}{2}-\delta\right)$, further it aggregates the direction of search towards the section, where minima lies. Upper bound and lower bound of the search is change to $\left(\frac{x_1+x_3}{2}-\delta, x_3\right)$ Henceforth the iterative procedure terminates at point x_2.

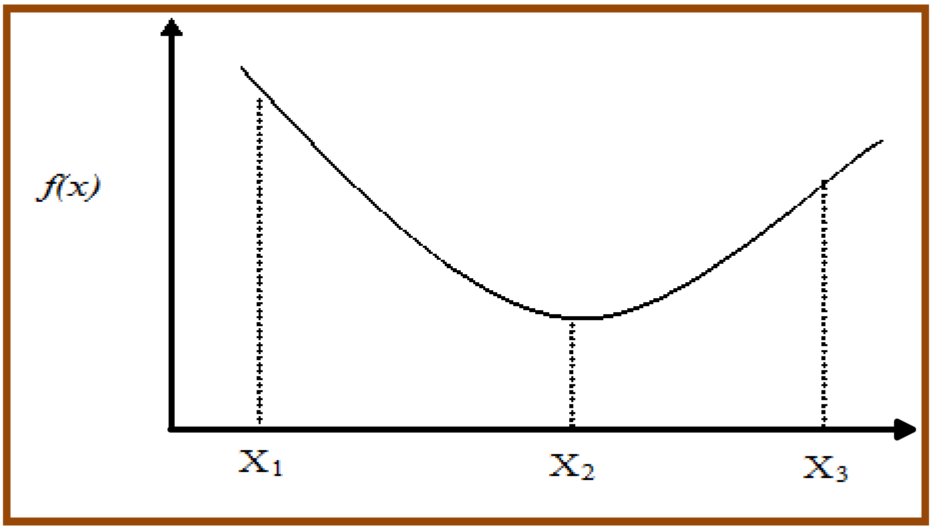

Fig. 4.2: Golden section search Method

The beauty of golden section lies in that it compares the value of objective functions at different point and further extends the search in that section where it obtain the minimum value of the function. Normally this approach is applicable and also suitable for unimodal functions. Since the exact shape of the objective function is not known in the PSS parameter estimation case, it is quite empirical to investigate the optimization problems with this conventional technique [157].

4.2.2 Objective function

To perform this study conventional eigenvalue based objective function is formed [74]-[75] & [77]. Eigen property analysis is carried out on PST tool box [158]. Equation (4.7) shows the conventional objective function and constraints used for optimization process.

$$J = \sum \left(\alpha_0 - \alpha_{ij}\right)^2$$

$$s.t. \quad \left.\begin{array}{l} K_{si}^{\mathbf{min}} \le K_{si} \le K_{si}^{\mathbf{max}} \\ T_{1i}^{\mathbf{min}} \le T_{1i} \le T_{1i}^{\mathbf{max}} \\ T_{3i}^{\mathbf{min}} \le T_{3i} \le T_{3i}^{\mathbf{max}} \end{array}\right\} \tag{4.7}$$

Where α_0 is a negative no. in this case it is considered as *-1*. α_{ij} is the real part of i^{th} eigen value of j^{th} operating point. Normally the values of T_w, T_2 and T_4 are pre specified [73]-[77], [79], [121]. In this work parameters K_{si}, T_{1i} and T_{3i} are optimized. In preceding section sensitivity based schemes for PSS parameter estimation is presented.

4.2.3 PSS design through Scheme I and II

PSS parameter estimation problem is a classical optimization problem with certain set of operating constraints consisting of lower and upper bound of PSS parameters [57]-[89]. Details of different objective function is already given in section (2.5), for developing the parameter estimation schemes an eigen value based objective function is used [74], [75] &[77]. Two schemes based on gradient descent search are developed [83]. Comparison of the schemes is done with conventional golden section search method [156]. These two schemes are developed for New England power system [153]. Some special features of schemes are exhibited here:

1. Search is started with the middle point and effect of parameters on objective function is judged. For this analysis wash out time constant and other lead time constants are kept constant.

2. Parameter T_1, T_3 and K_s is varied in between lower and upper bound as per Table 4.2.The upper and lower bound of the optimized parameters are taken from [77]-[82]. Total 30 parameters are optimized for New England system.

3. Scheme I is based on sequential optimization where parametric influence of PSSs are taken one by one and tuning of the PSSs are done in a sequence [83]. Scheme II is based on simultaneous tuning where parametric influences of PSSs are observed on objective function simultaneously. Pseudo codes for both schemes are presented in following section. Here W is the different operating conditions cases mentioned in preceding section.

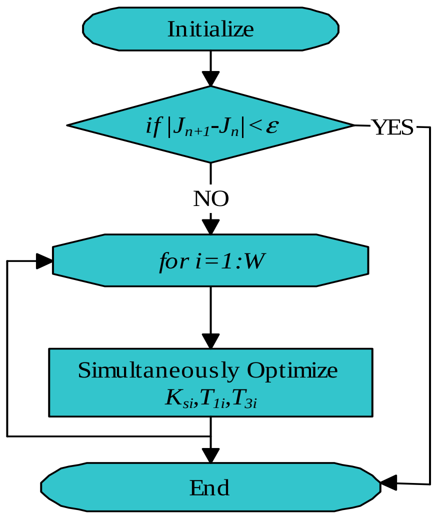

Fig. 4.3 Simultaneous Optimization (Scheme-II)

4.2.4 Pseudo Code for Schemes

In this subsection classical trajectory based schemes for PSS parameter estimation is described. The vector α is the matrix of PSS parameters. Where i is the subscript used for generator(s).

$$\alpha = \lfloor K_{si} \quad T_{1i} \quad T_{3i} \rfloor, i = 1:10$$

Step 1. Set the iteration counter $m = 0$, and assign the initial value of PSS parameters α^m Evaluate the initial gradient $g^{(0)} = \frac{(\partial J)}{(\partial \alpha)|_{\alpha(0)}}$.

Step 2. In the direction of $S^{(m)}$ golden section method [156] is adopted to search for an optimal step length parameter $\gamma^{(m)}$ to make the object function $J(\alpha^{(m+1)})$ minimum on condition that $\alpha^{(m+1)} = \alpha^{(m)} + \gamma^{(m)} S^{(m)}$ and that constraints are all satisfied.

As observed by S.Q.Yang *et al.* [83] Candidate range for one dimension studies may be too small that to reach effectively new PSS parameter setting. As described in work [83] it is noticed that a very negligible effect is observed of parameter *β*, this motivates the removal of the parameter from existing scheme.

Step 3. Evaluate the gradient $g^{(m+1)} = \left.\frac{(\partial J)}{(\partial \alpha)}\right|_{\alpha(m+1)}$. Calculate the coefficient and the new conjugate gradient vector $S^{(m+1)} = -g^{(m+1)} + S^{(m)}$.

Step 4. Set $m = m + 1$ and go back to step2.

Step 5. End

Figs. 4.3 & 4.4 exhibit the flow of iterative processes.

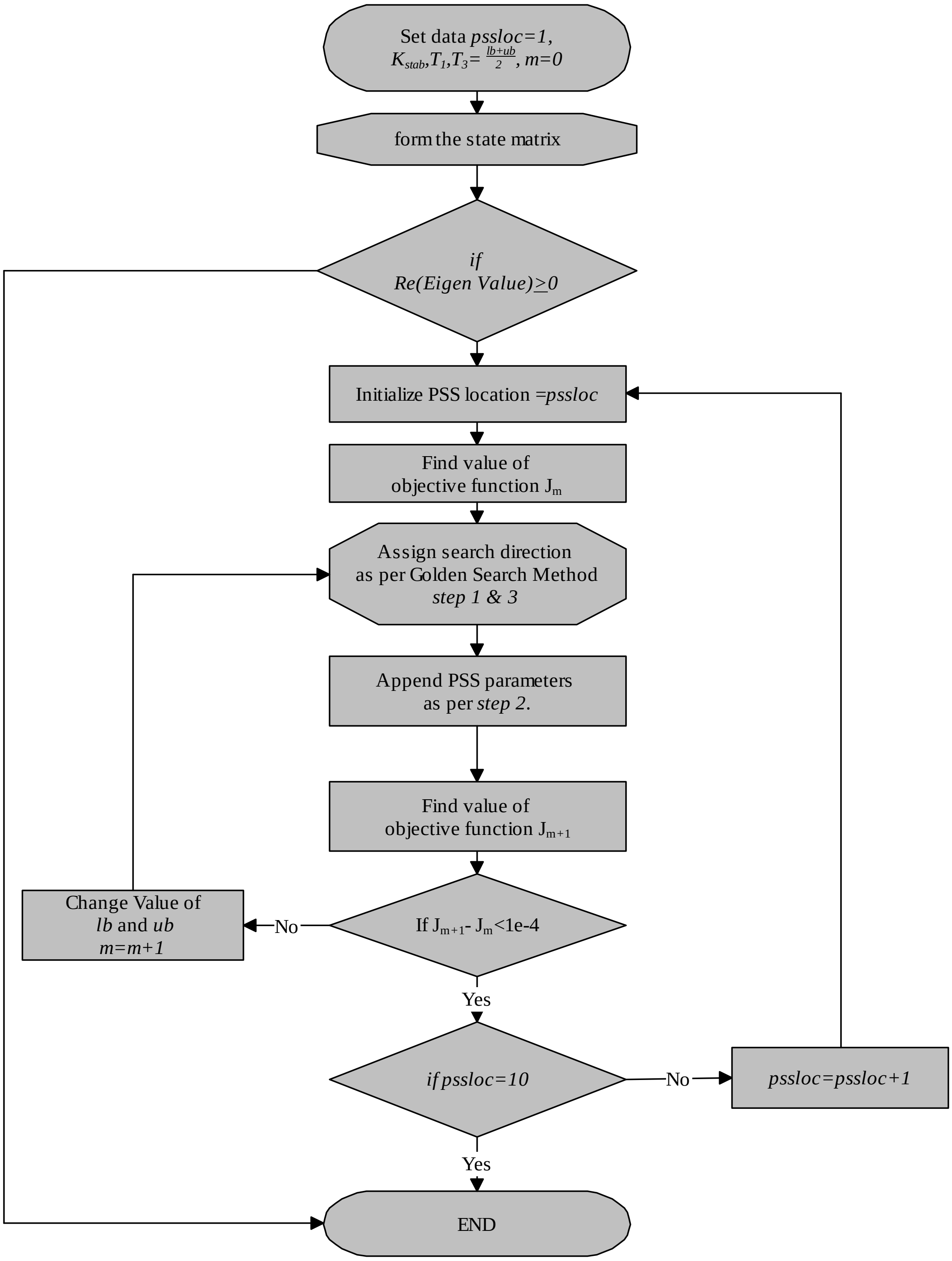

Fig.4.4: Sequential Optimization (Scheme-I)

4.3 SIMULATION AND RESULTS

The system considered for the verification of the scheme is New England system [153] (10 generators and 39 buses). Simulations are performed using program developed in the Matlab [154] by using Power System Tool box (PST) [158].The modeling of the system and schemes are performed over Intel ® core ™, i7, 2.9 GHz

4.00 GB ram Processor unit. Table 4.3 & 4.4 shows the sensitivity jacobian of PSSs parametric influence on objective function. New England power system has 10 generators and each generator is equipped with PSS. In this simulation work parameters are considered as $T_w = 10s$, $T_2 = 0.02s$, $T_4 = 0.02s$ Total 30 parameters K_{si} , T_{1i} and T_{3i} are optimized. To indicate the acute need of PSS, Eigen property analysis is carried out for this system without any PSS installed.

Table 4.1: Eigen property analysis of New England System

Modes	Eigen Values	Damping Ratio
18	0.2848 - 6.6998i	-0.0424
19	0.2848 + 6.6998i	-0.0424
20	0.5728 - 7.2201i	-0.079
21	0.5728 + 7.2201i	-0.079
22	0.13506 - 7.7029i	-0.017
23	0.13506+ 7.7029i	-0.017
26	0.03581 - 8.2562i	-0.0043
27	0.03581 + 8.2562i	-0.0043
31	0.01936- 9.0723i	-0.0021
32	0.01936-+9.0723i	-0.0021

Table 4.1 shows the some poorly damped modes while considering operating condition of base case. It is assumed that each load bus is containing nonconforming loads (constant impedance load). Eigen property analysis is carried out by using Matlab [154] on PST with the help of function *svm_mgen* [159]. Following are the points of considerations:

1. In this analysis it is assumed that due to high static exciter (AVR) gain 100, (Appendix-D) some of the poorly damped mode appears. Value of system damping is become negative. It is imperative to discuss here that system is in such state that even a small perturbation makes it unstable.

2. While observing system stability, it is quite pragmatic to discuss and indicate system's initial condition. Eigen property analysis shows that the system is on the verge of losing stability. As some of eigen's are having positive real part and the negative damping is reflected in mode 18-19, 20-21, 26-27 and 31-32.

3. These modes are associated with the states of machines. Mode 18-19 is associated with 3rd and 5th state i.e. (E'_q and E'_d) of generator 4. Similarly mode 26-27 refers to 1st and 2nd state (δ, ω) of generator 6. Mode 31-32 refers to 1st and 2nd state of generator 7; again state variable associated with this mode is (δ, ω). All in all these poorly damped states are connected with the generator and introduces oscillatory instability in the system [158]-[159].

4.3.1 Decisive Evaluation of Scheme(s)

Based on eigen property analysis, it is advisable to incorporate PSS in this power system to achieve effective damping and further stability of the power system. Table 4.3 & 4.4 show the intermediate calculations of Jacobian. It can be observed from the Table 4.3 that parameter length while search by golden section method decreased with the increment in the iteration, however major assumption in golden section lies in that function should be continuous in the range (parametric range) [83], [88] & [90]. For PSS at location 10, solution is converged in iteration 5-6 here J is the numerical replica of the given objective function. Stopping criterion used for this optimization is that the successive tolerance limit *1e-3* in solution obtained after each iteration [83]. Surprisingly in some locations solution converged in 5th iteration and other takes 10 iterations. Sensitivity analysis shows that each location has its own effect on the PSS settings, observing the overall effect of the PSS parameter on the objective function J the last two iterative results are shown in the Tables 4.3 and 4.4.

Table 4.2: Parameters, Initial Values and Bounds for the Original PSS Parameter Setting

$T_w(s)$	$T_2(s)$	$T_4(s)$	V_{smax}	$V_{s\,min}$
10	0.02	0.02	0.2	-0.05
$T_1(s)$	$T_{1max}(s)$	$T_{1min}(s)$	$T_3(s)$	$T_{3max}(s)$
0.2	100 T_1(s)	0.1 T_1(s)	0.2	100 T_3(s)
$T_{3min}(s)$	K_s	K_{smax}	K_{smin}	
0.1 T3(s)	10	5 K_S	0.2 K_S	

*s=Sec.

Table 4.3: Intermediate Data (Sensitivity Jacobian) during Iterative Process for Scheme I

PSS Location	Iteration	γT_1	γT_3	γK_S	$\frac{\partial J}{\partial K_s}$	$\frac{\partial J}{\partial T_1}$	$\frac{\partial J}{\partial T_3}$	J
1	9	0.000967	0.00105	0.023438	0.966945	1.03353	0.023198	2.991623
	10	0.000483	0.000525	0.011719	0.084596	0.072888	0.145455	2.99178
2	7	0.061875	0.067188	1.5	0.004666	0.003842	0.010184	3.024632
	8	0.030938	0.033594	0.75	-0.01091	-0.0122	-0.00021	3.024632
3	6	0.061875	0.067188	1.5	-5.27E-06	-5.81E-06	-1.06E-07	4.054499
	7	0.030938	0.033594	0.75	-7.71E-07	-6.44E-07	-1.58E-06	4.054499
4	9	0.000967	0.00105	0.023438	0.856934	0.928061	0.019047	4.16089
	10	0.000483	0.000525	0.011719	0.362652	0.308381	0.673016	4.161263
5	4	0.2475	0.26875	6	0.044393	0.048609	0.00093	3.122271
	5	0.12375	0.134375	3	-0.15466	-0.13007	-0.30446	3.123203
6	7	0.061875	0.067188	1.5	-0.05591	-0.05608	-0.00223	4.127455
	8	0.030938	0.033594	0.75	-0.02715	-0.02493	-0.02804	4.127661
7	4	0.2475	0.26875	6	4.42E-07	4.97E-07	8.11E-09	4.256329
	5	0.12375	0.134375	3	-1.62E-08	-1.33E-08	-3.65E-08	4.256329
8	3	0.495	0.5375	12	-0.02273	-0.02092	-0.02289	3.140486
	4	0.2475	0.26875	6	-0.02102	-0.02103	-0.00086	3.140652
9	5	0.12375	0.134375	3	-3.59E-06	-3.04E-06	-6.88E-06	4.106212
	6	0.061875	0.067188	1.5	-1.25E-05	-1.36E-05	-2.69E-07	4.106211
10	5	0.12375	0.134375	3	-0.00272	-0.00225	-0.00579	3.138765
	6	0.061875	0.067188	1.5	-0.01871	-0.02081	-0.00036	3.138793

Table 4.4: Intermediate Data (Sensitivity Jacobian) during Iterative Process for Scheme II

PSS Location	Iteration 1			Iteration 2		
	$\frac{\partial J}{\partial K_s}$	$\frac{\partial J}{\partial T_1}$	$\frac{\partial J}{\partial T_3}$	$\frac{\partial J}{\partial K_s}$	$\frac{\partial J}{\partial T_1}$	$\frac{\partial J}{\partial T_3}$
1	-0.04067	-20.5583	-17.9386	-0.00132	-0.47388	-0.47618
2	-0.05787	-18.1592	-10.2221	-0.00118	-0.45803	-0.45551
3	-0.03426	-14.9857	-15.6417	-0.00117	-0.46254	-0.46238
4	-0.04647	-19.9182	-21.2466	-0.00119	-0.45454	-0.46295
5	-0.06055	-10.8234	-10.3567	-0.00131	-0.45632	-0.4511
6	-0.03059	-20.9424	-9.83275	-0.00128	-0.45113	-0.45926
7	-0.03231	-20.0435	-15.4974	-0.00127	-0.45148	-0.45904
8	-0.04546	-21.6935	-23.8088	-0.00121	-0.46716	-0.45234
9	-0.04169	-19.9955	-19.1936	-0.00131	-0.45677	-0.45382
10	-0.04346	-15.5499	-16.0115	-0.0012	-0.47117	-0.4602
J		3.4472			3.440	

Following are the points worthwhile mentioning here:

1. PSS tuning is done sequentially, surprisingly the iterative process terminates within 10 iterations while having the tolerance *1e-3* as an aim. This tolerance is considered as the stopping criterion for the optimization process [83] & [98].

2. It is observed that PSS location at generator 4 and 1 is time consuming and observe the maximum iteration count, the difference between values of objective function in successive run is less that *1e-3*.

3. The value of objective functions for different locations of PSS is different and it is shown in the Table 4.3, it shows that each PSS unit has a relationship and profound effect on objective function. It is noteworthy to observe in this analysis that low value of jacobian sensitivity is found for time T_3 and significantly large values of jacobian sensitivities are obtained for PSS gain.

4. For scheme II it is observed that values of objective functions as obtained in iteration 1 and 2 are very close, fortunately iterative process ends in 2 iterations with the tolerance of *1e-3*.

5. It is also observed from the Table 4.4 that for iteration 1 the values of sensitivity jacobian is very large, it depicts that PSS parameters have an ample

amount of effect on objective function, however when parameters are appended in the search of golden section search soon the value of sensitivity jacobian observe significant amount of reduction in the numerical values. This effect was also observed in [83] & [98].

6. Pragmatically there is no substitute of simultaneous optimization as in sequential optimization; sequence of the candidate parameters for optimization is always a tight spot [157].

To validate the efficacy of the proposed schemes nonlinear simulations are performed, while considering three operating cases.

- ❖ **Base Case.** Constant Impedance on all load buses
- ❖ **Case (a).** Reduction in generation by 10% generator 5, Load Modulation on Bus 25, 27, 4 and 21, Non confirming Loads (50% constant impedance and 50 % constant current) else constant impedance on all Load buses.
- ❖ **Case (b).** Nonconforming loads on 8, 20, 24 and 28 and load modulation (50% constant impedance and 50 % constant current) else constant impedance on all load buses.

Disturbances are considered as three phase six cycles (3-φ6-cycles) at different locations mentioned in sub heading. The data for the New England system is taken from standard bench mark system IEEE [160] and also shown in Appendix-B. Figure of Demerit (FOD) is defined as the summation of square of overshoot and settling time of the speed deviation curves.

Following conditions with different operating scenarios are taken to validate the effectiveness of proposed approach.

a) 3-φ6-cycles disturbance at line -6-11

b) 3-φ6-cycles disturbance at line 17-27

c) 3-φ6-cycles disturbance at line 6-7

d) 3-φ6-cycles disturbance at line 22-23

e) 3-φ6-cycles disturbance on line 17-18

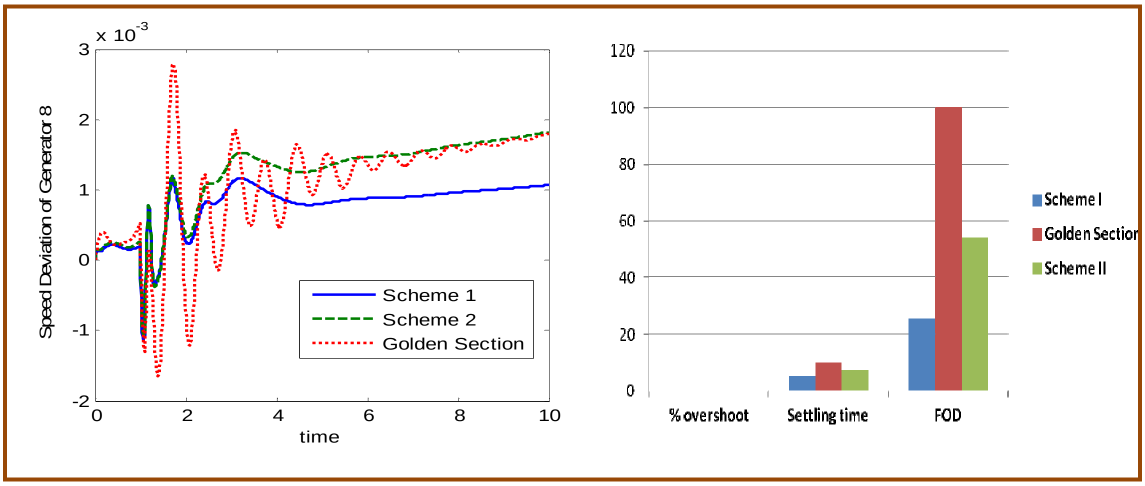

Fig. 4.5: Speed deviation curve of generator 8 for fault at line 6-11

Fig. 4.5 shows the speed deviation of the generator 8 when the system observes a 3-φ 6-cycles disturbance at line 6-11, it is observed from the curve that golden section and scheme 2 presents a poor design in this context. To understand the speed deviation curve in a more meaningful manner analysis of the same is presented in bar chart form in Fig. 4.5 and Table 4.5

Table 4.5: Statistics of speed deviation curve of generator 8

Fault on Line 6-11			
	% overshoot	Settling time	FOD
Scheme I	0.1171	5.05	25.5162124
Golden Section	0.28	10	100.0784
Scheme II	0.257	7.34	53.941649

Fig. 4.6 shows the speed deviation of generator 3 for base case, the values of overshoot, settling time and figure of demerit is shown in bar form validate the efficacy of the schemes.

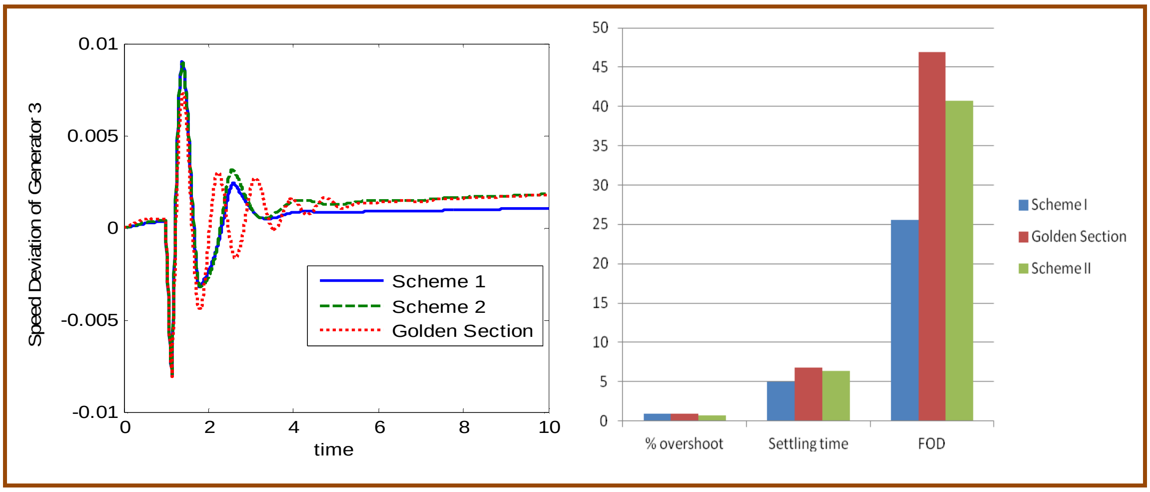

Fig. 4.6: Speed deviation curve of generator 3 for fault at line 6-11

Table 4.6 shows the statistics of this disturbance. It is observed that the numerical value of FOD is very high in case of golden section a method, which indicates the poor design.

Table 4.6: Statistics of speed deviation curve of generator 8

Fault on Line 6-11			
	% overshoot	Settling time	FOD
Scheme I	0.887	4.98	25.587169
Golden Section	0.88	6.79	46.8785
Scheme II	0.72	6.34	40.714

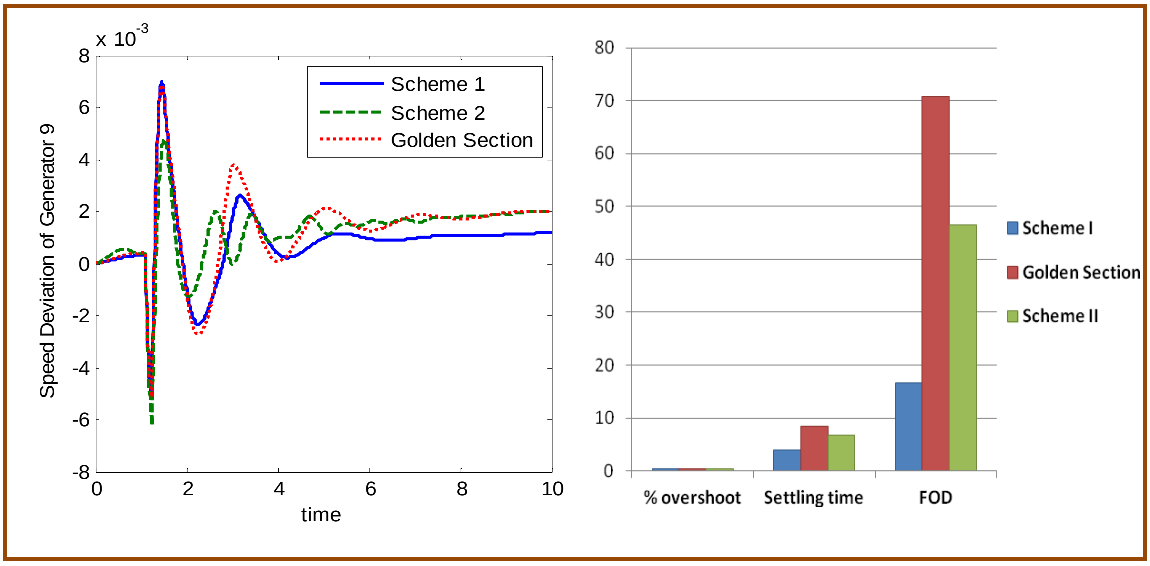

Fig. 4.7: Speed deviation curve of generator 9 for fault at line 17-27

Table 4.7 shows the statistics of this disturbance. It is observed that the numerical values of FOD are very high in case of golden section method and scheme II which indicate the poor design.

Table 4.7: Statistics of speed deviation curve of generator 9

Fault on Line 17-27 Case (a)			
	% overshoot	Settling time	FOD
Scheme I	0.49	4.05	16.6426
Golden Section	0.4936	8.4	70.803641
Scheme II	0.4944	6.8	46.4844314

Figs. 4.8-4.9 shows the speed deviation curves for generator 1 and 2 with operating condition b and a respectively.

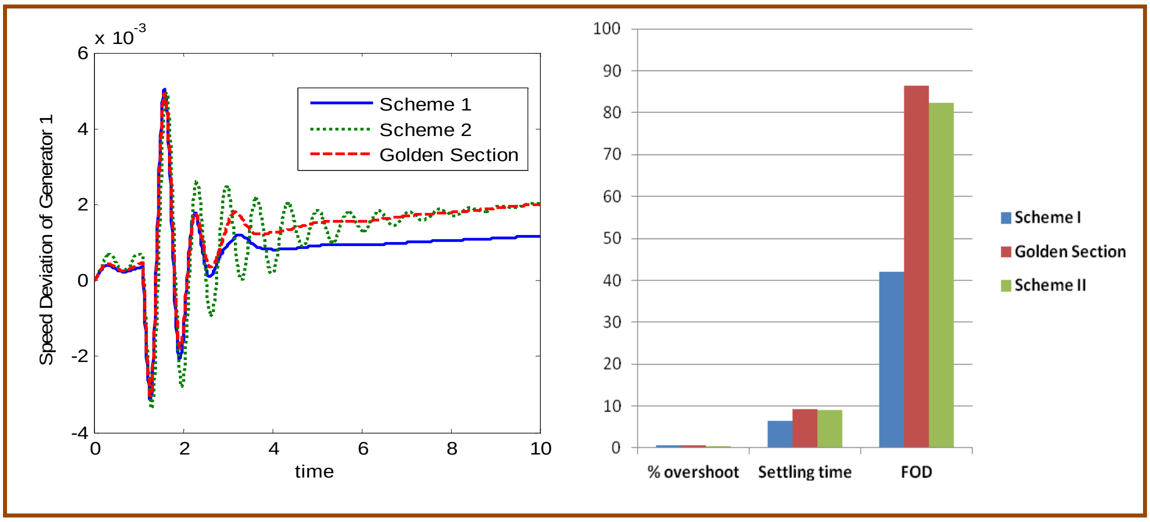

Fig. 4.8: Speed deviation curve of generator 1 for fault at line 17-27 (Case (b))

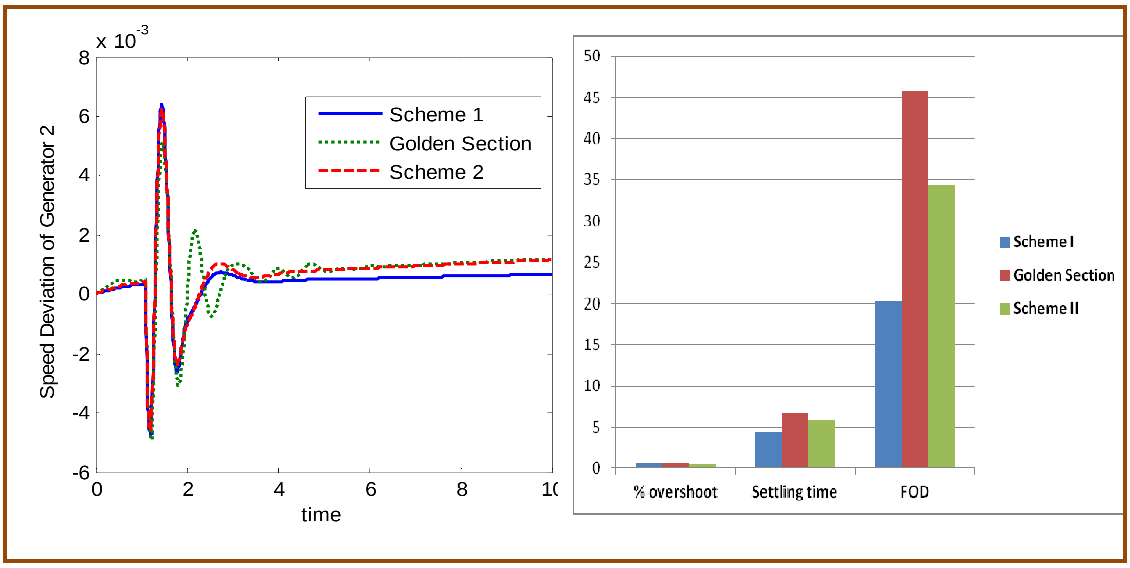

Fig. 4.9: Speed deviation curve of generator 2 for fault at line 6-7 (Case (a))

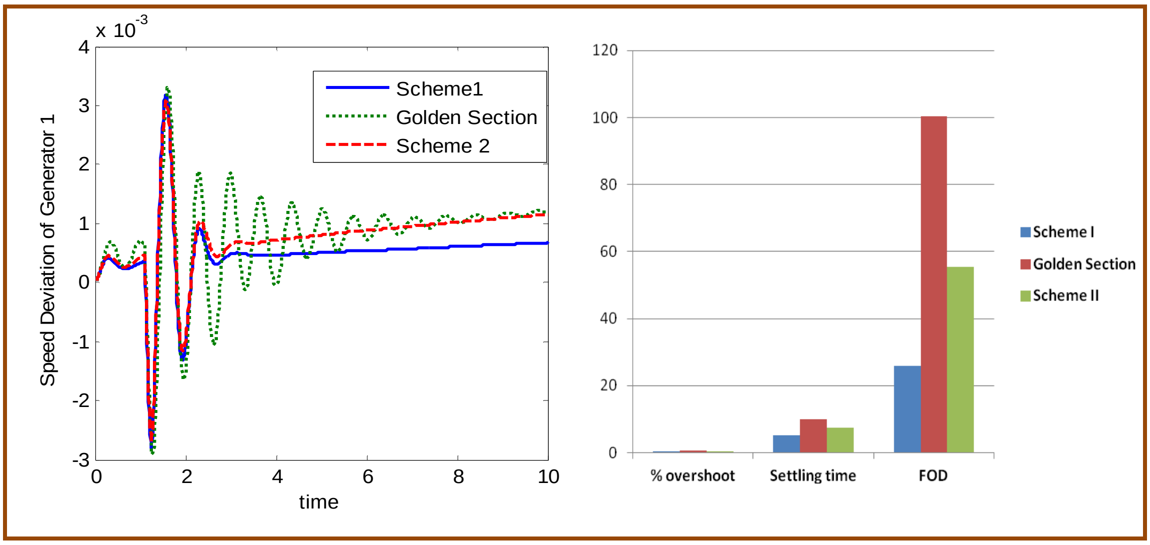

Fig.4.10: Speed deviation curve of generator 1 for fault at line 6-7 (Case (a))

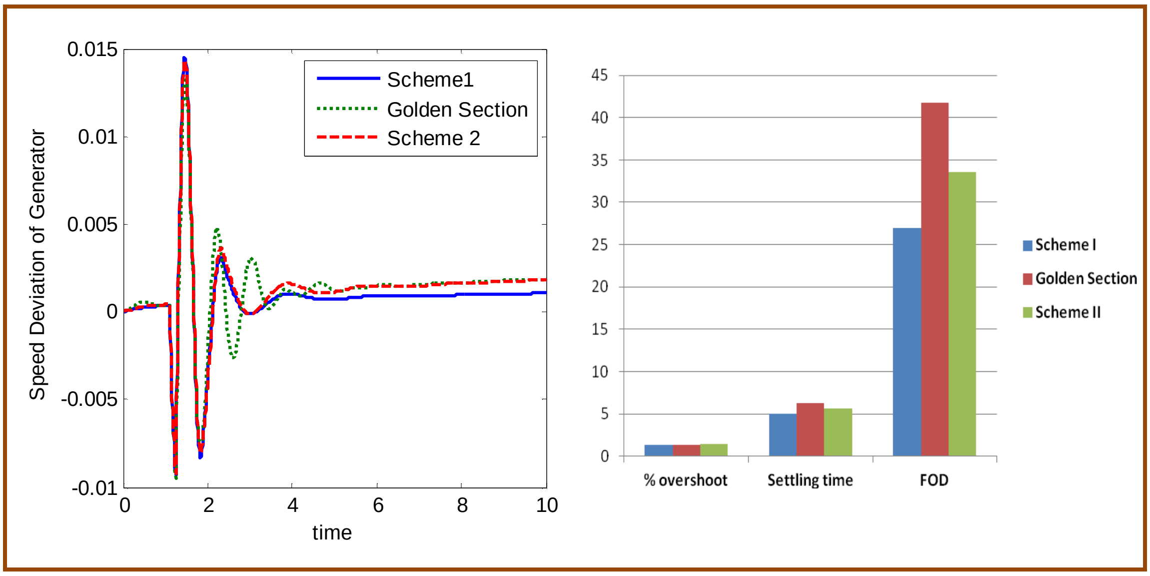

Fig. 4.11: Speed deviation curve of generator 6 for fault at line 22-23 (Case (b))

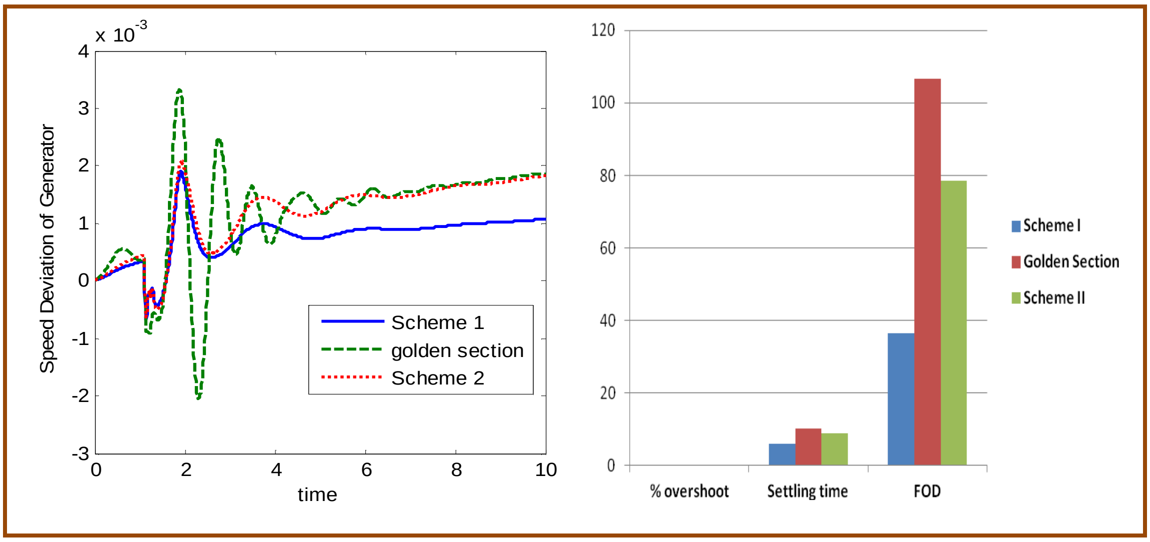

Fig. 4.12: Speed deviation curve of generator 7 for fault at line 22-23 (Case (b))

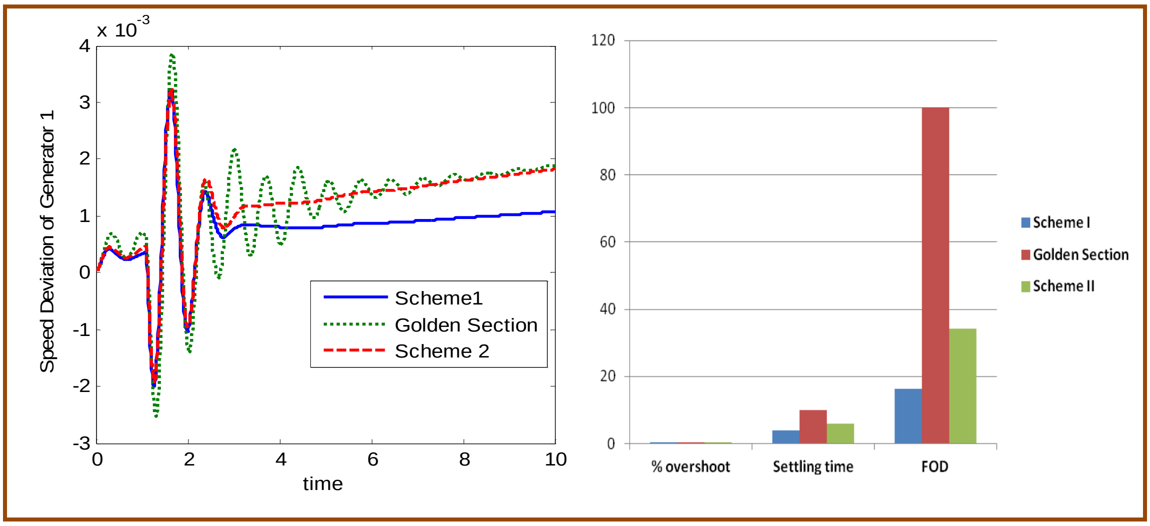

Fig. 4.13: Speed deviation curve of generator 1 for fault at line 22-23 (Case (b))

Figs. 4.10 – 4.13 show the speed deviation curves for generator 1, 6, 7 and 1 with different operating cases.

Table 4.8: Statistics of speed deviation curve of generator(s)

Contingencies	Methods	% overshoot	Settling time	FOD
Fault on Line 17-27 Case (b)	Scheme I	0.6986	6.45	42.090542
	Golden Section	0.6836	9.27	86.400209
	Scheme II	0.4744	9.06	82.308655
Fault on Line 6-7 Case (a)	Scheme I	0.63	4.46	20.2885
	Golden Section	0.62	6.74	45.812
	Scheme II	0.5	5.84	34.3556
Fault on Line 6-7 Case (a)	Scheme I	0.3122	5.09	26.005569
	Golden Section	0.62	10	100.3844
	Scheme II	0.35	7.44	55.4761
Fault on Line 22-23 Case (b)	Scheme I	1.3	5.03	26.9909
	Golden Section	1.34	6.32	41.738
	Scheme II	1.4	5.62	33.5444
Fault on Line 22-23 Case (b)	Scheme I	0.193	6.04	36.518849
	Golden Section	0.31	10.32	106.5985
	Scheme II	0.18	8.86	78.532
Fault on Line 22-23 Case (b)	Scheme I	0.3	4.03	16.3309
	Golden Section	0.34	10	100.1156
	Scheme II	0.32	5.84	34.208
Fault on Line 17-18 Case (b)	Scheme I	0.2042	3.71	13.805798
	Golden Section	0.2188	10	100.04787
	Scheme II	0.1744	9.06	82.114015
Fault on Line 17-18 Case (b)	Scheme I	0.3011	4.03	16.331561
	Golden Section	0.259	10	100.06708
	Scheme II	0.257	7.34	53.941649

As per Table 4.8, following points are emerged:

1. To test the robustness of the schemes extremely hard conditions are considered [82]. Scheme I gives over all good response in few cases however, in many cases respond obtained from all three schemes are pessimistic.
2. From Table 4.8 it can be observed that unanimously values of FOD are higher in case of golden section search method. For fault at 17-18 significant amount

of increment is observed in FOD values of golden section search and Scheme II. Increment of 83.03% and 6.98% is observed with respect to Scheme I in case of speed deviation curve of generator 8. For the same contingency speed deviation curves of generator 4 show increment of 87.07% and 13%.

3. Almost all cases formed show the significant amount of increment in FOD values for golden section search and Scheme II.

4.4 MODIFICATION OF THE EXISTING SCHEMES

Scheme I (Sequential Design) is only able to mitigate the frequency oscillation while other schemes are failed to present a good design under different operating conditions. Line search methods are prone to trapped in local minima, initial search point has an ample importance for these methods [156]-[157]. Sensitivity Jacobian elements for scheme I has larger amplitude that itself suggest that those corresponding parameters have leverage in altering the trajectory to better match. Due to lack of multi point search strategy, these methods (Scheme II and Golden Section) have high probability to be trapped in local minima [83]. However, point of consideration is that scheme I is merely a replica of multi point search technique, as it is following a sequence. Surprisingly in [83], it was not mentioned how the sequence of optimization was decided, or which candidate (PSS) was preferred for tuning first & how. Following modification are suggested in the existing schemes:

1. As line search methods have a tendency to be trapped in local minima, it is proposed that firstly optimization process should be solved by conventional algorithm like Genetic Algorithm (GA) [130] in this case, than these schemes should be employed for seeking robust design.
2. The sequence of optimization in Scheme I should be determined by the values of jacobians sensitivity.

As per modification proposed, optimization process is first solved by GA by using eigenvalue based objective function [77]. The parameters obtained from GA are shown in Table 4.9.

Table 4.9: Initialization of Parameters by Conventional method (GA)

PSS location	K_s	T_1	T_3
1	32.94649	0.030578	0.057717
2	31.14555	0.075816	0.086446
3	19.99965	0.19416	0.039005
4	12.85038	0.119074	0.199867
5	18.77145	0.121632	0.11377
6	19.55481	0.18124	0.047255
7	16.29244	0.115894	0.080831
8	16.2249	0.123892	0.086243
9	17.71532	0.102687	0.029209
10	18.77145	0.121632	0.11377

Iterative processes are repeated and after plotting the values of jacobian sensitivity, it is concluded that the location of PSS at generator 8 is most sensitive as the values of jacobians are higher for PSS gain and T_1. These analyses give the sequence of the tuning as 8, 4, 9, 1, 7, 10, 3, 6, 2, and 5. Abscissa axis contains generator no. and jacobian sensitivity on Ordinate axis in Fig. 4.14.

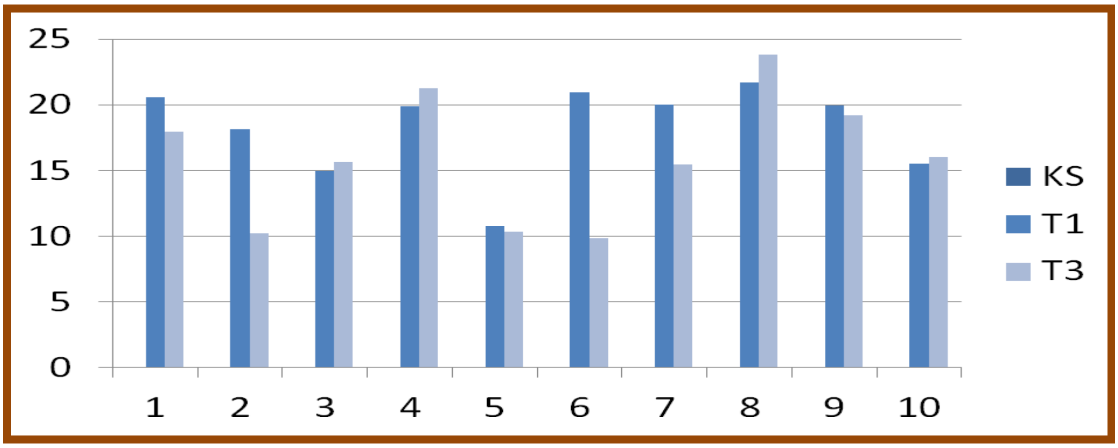

Fig. 4.14: Jacobian Sensitivity of PSS parameters

Fig. 4.14 shows the jacobian sensitivities of objective function with respect to PSS parameters. It is observed that the value of sensitivity jacobian is observable in case of T_1 and T_3 as the indice has a large impact on the objective function. In previous section it was observed that value of sensitivity indices for PSS gain was more and not a significant amount of change in observed in case of PSS time constants. This reflects the effect of initialization of the optimization process. Scheme I (old) [83] refers to the sequential optimization process without adopting above said methodology.

Table 4.10: Jacobian for Scheme I

Sequence	PSS Location	Iteration (J) 1	2	3	$\frac{\partial J}{\partial K_S}$	$\frac{\partial J}{\partial T_1}$	$\frac{\partial J}{\partial T_3}$
1	8	3.156171	3.156144		-0.00047	-0.04731	-0.04731
2	4	2.102668	2.049283	2.049286	-0.002	-0.20024	-0.20024
3	9	3.117089	3.117062		0.000126	0.012611	0.012611
4	1	3.152152	3.152139		-0.00049	-0.04869	-0.04869
5	7	2.183911	2.180456		-0.00655	-0.65454	-0.65454
6	10	3.160793	3.160945		-0.00015	-0.0152	-0.0152
7	3	4.297112	2.705634	2.705346	-0.00571	-0.57119	-0.57119
8	6	2.778421	2.778253		-0.00411	-0.4114	-0.4114
9	2	3.128139	3.128763		-0.00274	-0.27373	-0.27373
10	5	2.552979	2.552534		0.007639	0.763909	0.763909

Table 4.11: Jacobian for Scheme II

Iteration	1	2	3	4
J	1.086065	1.0747559	1.070059	1.070013
$\frac{\partial J}{\partial K_S}$		0.338506	-0.3525	-0.00132
$\frac{\partial J}{\partial T_1}$		33.85057	-35.25	-0.13218
$\frac{\partial J}{\partial T_3}$		33.85057	-35.25	-0.13218

Table 4.10 and 4.11 shows the mathematical details of intermediate process of jacobian calculations. It is observed from the Table 4.11 that iterative process for Scheme II (simultaneous optimization) converges in 4 iterations. The values of jacobians in first iteration is very high for T_1 & T_3. The values of jacobian become negative and possess small values. Similarly for sequential tuning scheme I PSS at location 8 tuned in two iterations, tuning of PSS at 4 and 3 takes three iteration, however as per stopping criterion optimization process terminates maximum in 3

iterations. PSS parameters obtained from both modified schemes are shown in Table 4.12.

Table 4.12: Parameters of PSS for Both Schemes

Scheme I(modified)				*Scheme II(modified)*			
PSS location	*Ks*	*T1*	*T3*	*PSS location*	*Ks*	*T1*	*T3*
8	16.2259	0.123892	0.086243	1	32.54649	0.0357	0.0571
4	12.8538	0.11974	0.19867	2	30.64555	0.0781	0.0844
9	18.81532	0.112687	0.039209	3	19.89965	0.1916	0.030
1	32.95649	0.032578	0.0657717	4	12.35038	0.1174	0.186
7	16.29244	0.115894	0.080831	5	18.67145	0.1263	0.117
10	18.77145	0.121632	0.11377	6	19.35481	0.112	0.047
3	19.79965	0.18416	0.029005	7	16.19244	0.159	0.0831
6	19.55481	0.18124	0.047255	8	16.7249	0.129	0.0243
2	30.14555	0.075816	0.086446	9	17.1532	0.1028	0.0209
5	18.67145	0.111632	0.10377	10	18.7145	0.1162	0.137

Preceding section contains the simulation results of the proposed modified schemes.

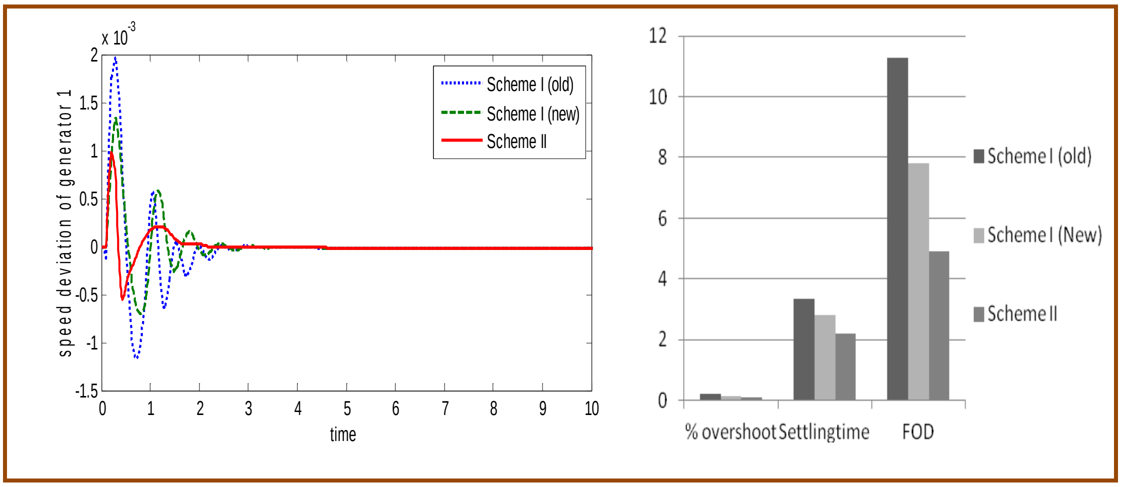

Fig. 4.15: Speed deviation curve of generator 1 for fault at line 2-25 (Case (a))

Fig. 4.15 shows the speed deviation curves for generator 1 with operating Case (a). It is observed from the Fig. 4.15 that the scheme II presents a substantial design as the overshoot and settling time of the curve is well bound. Table 4.13 shows the statistics of the curve. FOD values are much lower for Scheme II in this case. However, old scheme with modified initialization also gives the low values of FOD which was much higher in previous cases.

Table 4.13: Statistics of speed deviation curve of generator1

Three phase 6 cycle disturbance on line 2-25 (Case (a))			
	% overshoot	Settling time	FOD
Scheme I (old) [83]	0.1965	3.35	11.2611
Scheme I (New)	0.13	2.79	7.801
Scheme II	0.09	2.21	4.8922

Speed deviation curve is plotted for the same contingency with different operating case gives the response as per Fig. 4.15. Statistics related with the speed deviations curve is shown in Table 4.14.

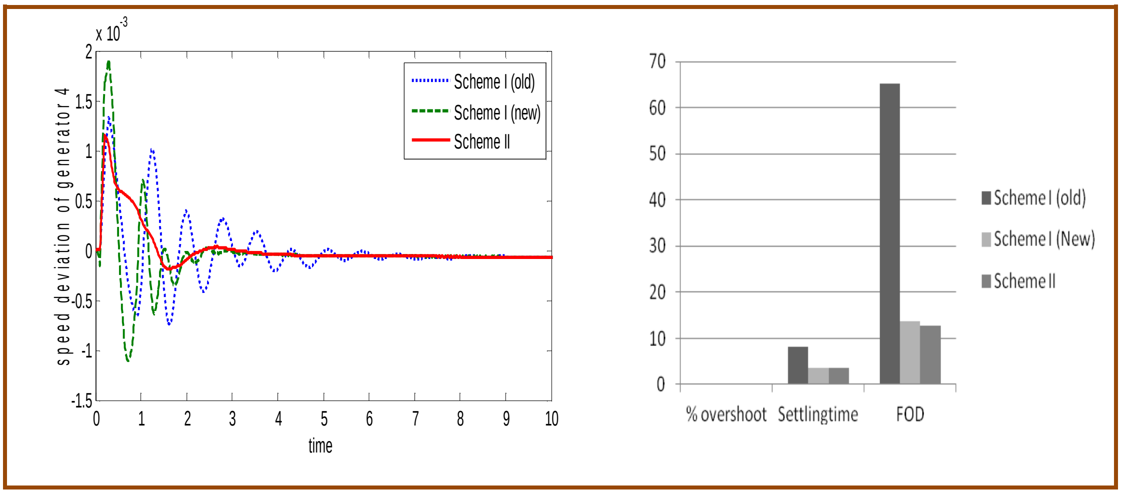

Fig. 4.16: Speed deviation curve of generator 1 for fault at line 2-25 (Case (b))

Table 4.14: Statistics of speed deviation curve of generator 1

Disturbance on line 2-25 Case (b)			
	% overshoot	Settling time	FOD
Scheme I (old) [83]	0.133	8.07	65.142589
Scheme I (New)	0.19	3.69	13.6522
Scheme II	0.115	3.58	12.829625

Similarly in preceding Case (a) 3-φ 6-cycles fault is considered with operating Case (a). It is observed from the Fig. 4.16 that Scheme I old gives oscillatory response which is bad for instrument health however a bounded response is obtained from scheme II. Here Scheme I (old) is referred as the sequential tuning without sequencing the PSS as per the values of jacobians.

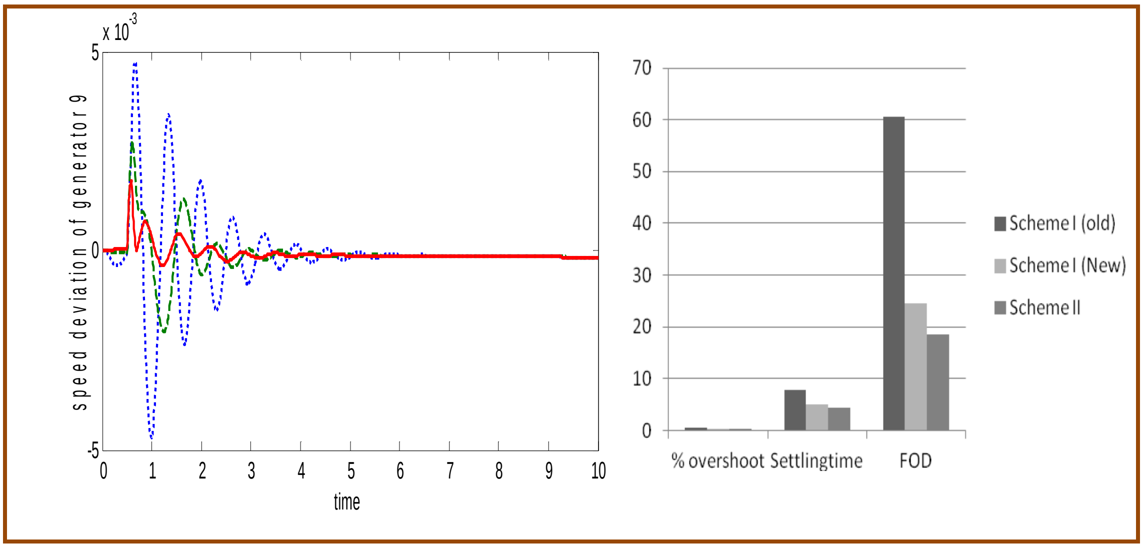

Fig. 4.17: Speed deviation curve of generator 9 for fault at line 12-13 (Case (a))

Statistics of the speed deviation curve is shown in Table 4.15. It is significant to observe that high value of FOD depicts a poor design with scheme I (old)[83].

Table 4.15: Statistics of speed deviation curve of generator 9

Disturbance on line 12-13 Case (a)			
	% overshoot	Settling time	FOD
Scheme I (old) [83]	0.4732	7.77	60.596818
Scheme I (New)	0.2745	4.95	24.57785
Scheme II	0.176	4.3	18.520976

Similar analogy is observed when the operating scenario b is taken. Speed deviation curve of generator 5 is shown in Fig. 4.18 it is observed that values of FODs are almost nearby to each other.

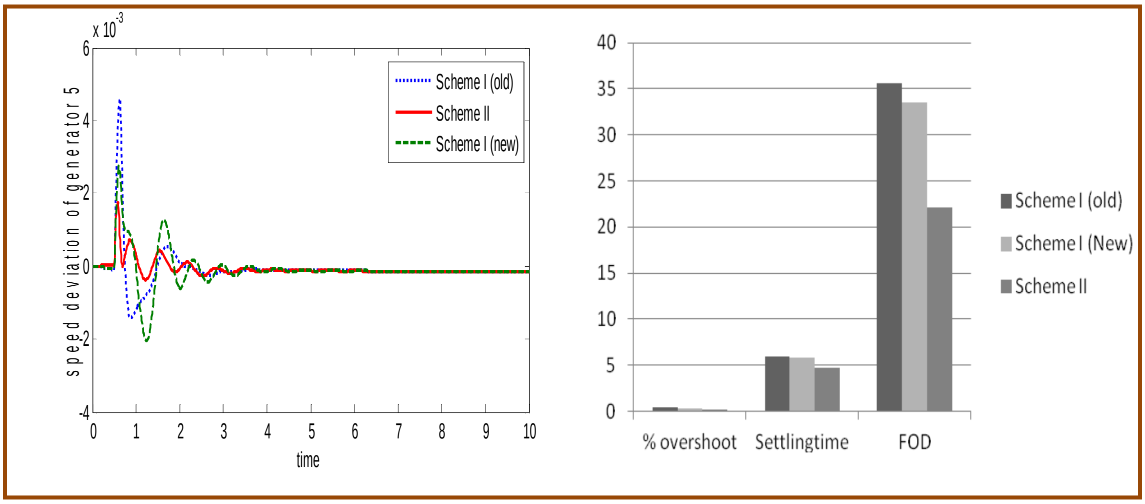

Fig. 4.18: Speed deviation curve of generator 5 for fault at line 12-13 (Case (b))

Table 4.16 shows the statistics of speed deviation curve of generator 5. Deviations in FOD values are much lower in this particular contingency.

Table 4.16: Statistics of speed deviation curve of generator 5

Disturbance on line 12-13 Case (b)			
	% overshoot	Settling time	FOD
Scheme I (old)[83]	0.4612	5.95	35.615205
Scheme I (New)	0.2745	5.78	33.48375
Scheme II	0.176	4.7	22.120976

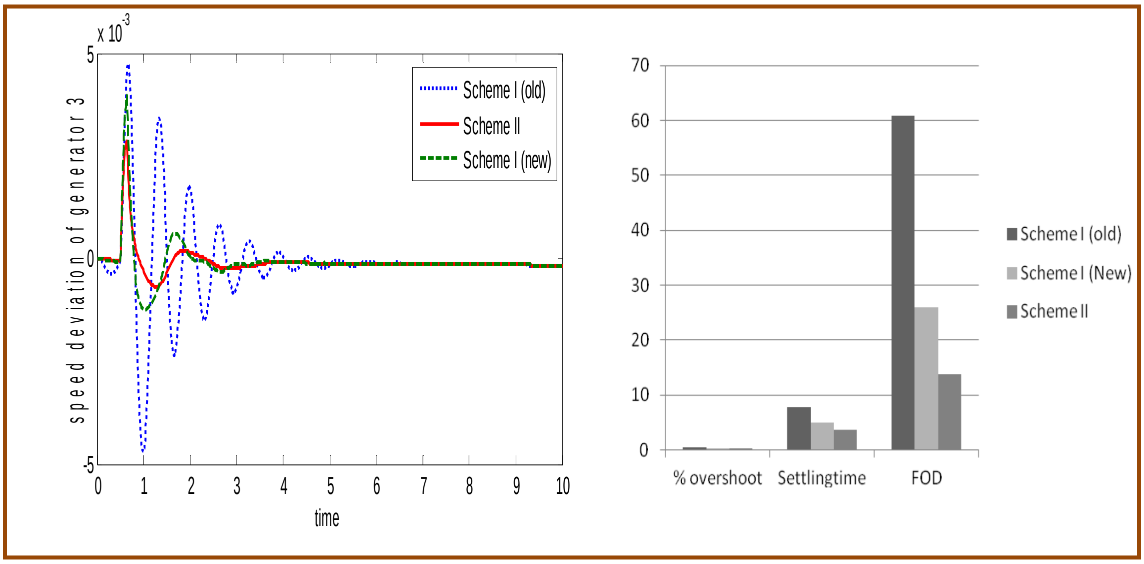

Fig. 4.19: Speed deviation curve of generator 3 for fault at line 14-15 (Case (a))

Table 4.17 shows the statistics of speed deviation curve of generator 3. The same analogy can be derived from the results. In each speed deviation curves Scheme II with modification is outperforming over Scheme I old [83] and Scheme II.

Table 4.17: Statistics of speed deviation curve of generator 3

Disturbance on line 14-15 Case (a)			
	% overshoot	Settling time	FOD
Scheme I (old)[83]	0.473	7.78	60.752129
Scheme I (New)	0.3946	5.08	25.962109
Scheme II	0.2864	3.7	13.772025

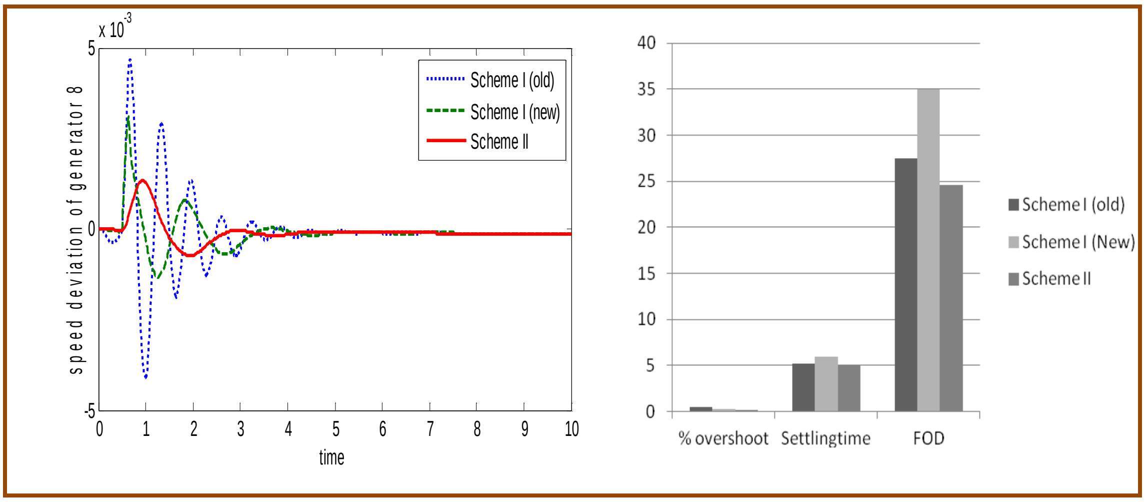

Fig. 4.20: Speed deviation curve of generator 9 for fault at line 10-13 (Case (b))

Table 4.18 shows the statistics of speed deviation curve of generator 8. Deviations in FOD values are much lower in this particular contingency. Scheme II outperformed over Scheme I

Table 4.18: Statistics of speed deviation curve of generator 8

Disturbance on line 10-13 Case (b)			
	% overshoot	Settling time	FOD
Scheme I (old) [83]	0.4675	5.22	27.466956
Scheme I (New)	0.3091	5.91	35.023643
Scheme II	0.1326	4.96	24.619183

Following conclusions can be drawn from the comparison of these three schemes:

1. Line search methods are traditional and successful methods for solving the constrained optimization problems. As in real power system nature and shape of the objective function is unknown, line search methods based on conjugate gradient descent provides an insight to nature of objective function.
2. Each iteration produces a decrease in the objective function, which can be observed from the Table 4.3 and 4.4. Every m^{th} iteration is a steepest descent step with step length chosen by step 2 and step 3, as shown in iterative process.
3. Line search methods are suitable for unimodal objective functions. However, for function used in real power systems has a high probability to be trapped in local minima. In some times the quality of solution and probability of obtaining global minima is dependent on the initial search point.

4. Scheme I addresses the sequential optimization approach [83].Modification of the Scheme I and Scheme II is implemented, as in some cases the both schemes are exhibiting pessimistic results.

4.5 SUMMARY

In this chapter three schemes based on trajectory sensitivity is applied for PSS parameter estimation problem. This chapter unfolds the difficulty related with eigenvalue based objective function and proposes a modification in scheme based on simultaneous optimization [83]. Following are the salient features of the proposed work.

1. Decisive evaluation of conventional optimization method with scheme(s) (based on trajectory sensitivity) is carried out [83] & [156]. It is concluded that golden section and scheme II (simultaneous optimization) present a poor design. This gives the direction that PSS parameter estimation objective functions are multimodal in nature. Hence the probability of getting trapped in local minima is enhanced.
2. Scheme II gives satisfactory response under all contingencies. It is worth to mention here that in first part of the observations, all schemes start their initial search with the midpoint of the parametric range.
3. Modification in terms of initialization is inculcated with the optimization schemes. A special light is thrown to the fact, that initial search point has a paramount importance for gradient based methods. In gradient based optimization process results can be improved with proper initialization.
4. Scheme I [83] was based on sequential optimization. However, methodology for determination of the sequence was not clearly described in optimization [83]. Hence the modification in scheme I is proposed and according to the values of sensitivity jacobian most sensitive PSS location is optimized first. However it is pragmatic to say from the results observed after modification that simultaneous optimization has an upper edge over the sequential optimization.
5. Effectiveness of the proposed schemes is tested over New England Power System. To present a robust design hard initial operating conditions are considered [77] & [82]. The comprehensive application of the schemes on New England System show that proposed schemes may serve as a promising tool for PSS parameter estimation.

Chapter 5

PSS design through Evolutionary Algorithm

The difficulties associated with conventional optimization processes are major motivation behind the development of alternative solutions. Researchers came forward with different creative analogies and similes to inculcate the nature's mimicry into the mathematical paradigms [105]-[109]. Conventional optimization methods like linear and dynamic programming are lacking in finding the global optima, problems related with real power system require attention and better design [156]. Compromise in design quality may be ended up with hazardous results as large networks are interconnected with each other. Evolutionary algorithms are scholastic search methods that mimic metaphor of natural biological evolution of the species [106]. The objective of this chapter is to present an evolutionary design based approach for PSS parameter estimation problem. In previous chapter the major findings extended the direction of research through evolutionary design, as the design presented in previous chapter observes severe alteration when the initial point of search is changed.

5.1 INTRODUCTION

Most of the conventional or classic algorithms are deterministic [157]. For example, the simplex method in linear programming is deterministic. Some of this algorithms are used gradient information for finding out the optima, these algorithms can further bifurcated into two main categories where the search direction is set to the negative of the gradient, than the search methods are known as gradient descent methods and vice versa also known as gradient ascent methods [156]. These algorithms works well in case of unimodal continuous functions but failed to find global optima in case multi modal function or discontinuous functions. Non gradient based algorithms are applied in the case discontinuous objective function, these objective functions are treated with stochastic approaches with the aim to find best results rather than good results.

These algorithms are come in the picture in early 80's, basically these are categorised into two subcategories [108]:

1. Heuristic algorithms

2. Meta-heuristic algorithms

Heuristic approach is nothing but based on trial error method, lateral meaning of heuristic is to discover by trial and error. Quality solutions can be obtained by these approaches but none of these approaches ensure global minima. Further development was metaheuristic algorithm “meta” means beyond or higher level. Recent trends are to name all algorithms with randomization and local search as meta-heuristic algorithms [107]. In literature no clear bifurcation is given for both these names however randomization is an important process as it helps algorithm not to be trapped in local minima. In previous chapter it is worth mention here that the design is poorly trapped in local minima as the initialization was not proper however metaheuristic algorithms don’t require initialization, randomisation is an inherent characteristic of these algorithms[106]-[108].

All evolutionary algorithms are based on learning processes. The most important aspect of such learning processes is the development of implicit and explicit techniques to accurately estimate the probability of the future events. The scientific method is an iterative process that facilitates gaining new knowledge about the underlying processes of an observed environment by forecasting as yet unknown aspects of that environment.

Fig. 5.1 shows the scientific method for propagation and adaption of the knowledge.

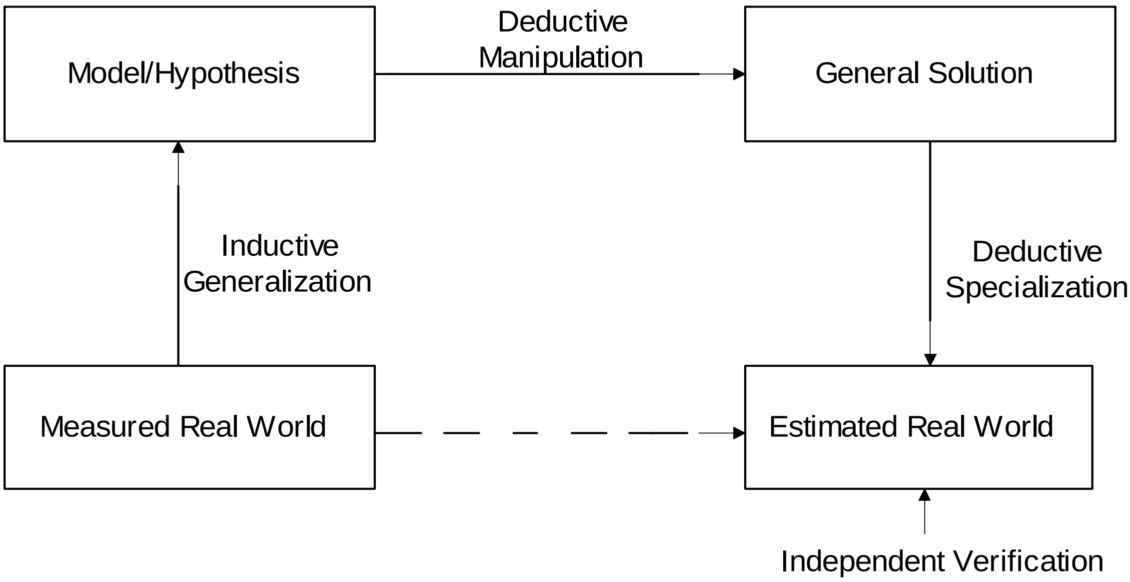

Fig. 5.1: Anatomy of Scientific method

Evolutionary computation must act on data structures that represent candidate solutions to the problems at hand. Essential gradient is evolution: population based search with random variation and selection. A population is required because single point to point searches are generally in-sufficiently robust to overcome local pathologies. Fig. 5.2 shows Flow of evolutionary algorithms [109]-[152].

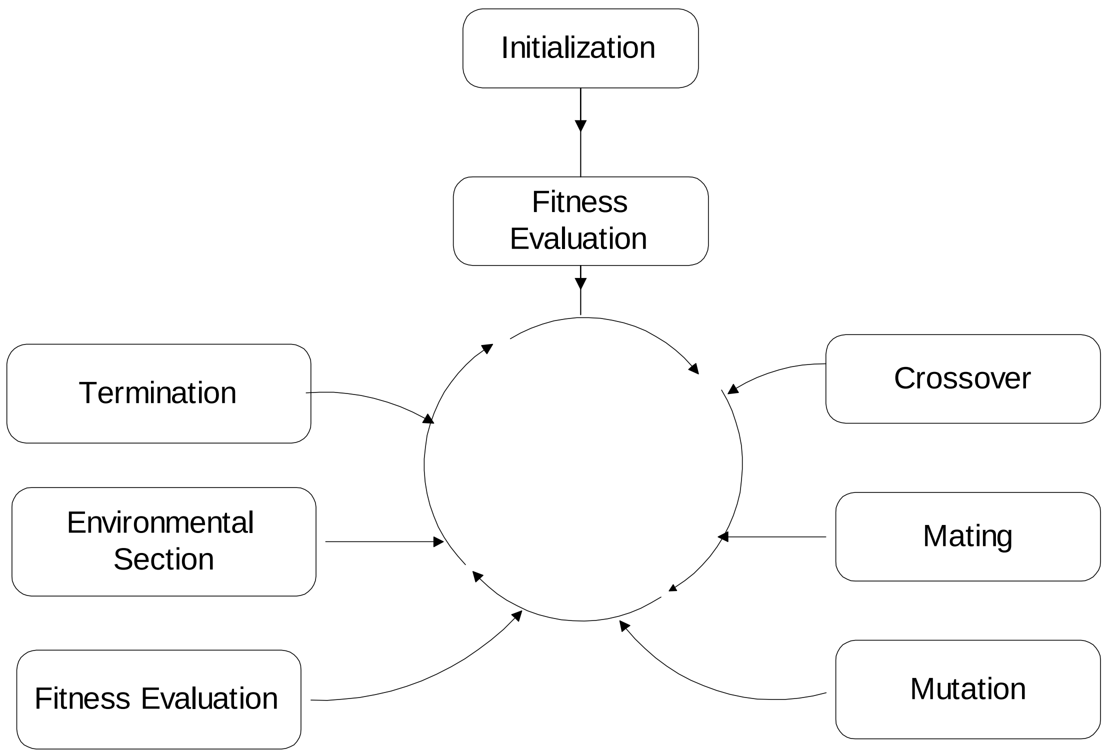

Fig.5.2: Flow of evolutionary algorithms

The beauty of these algorithms exists in multi point search strategy. Two major components of any metaheuristic algorithms are intensification and diversification in other words exploitation and exploration. Diversification is the term which is related with generation of the diverse solutions so as to explore the search space on global scale and a very efficient manner, while intensification is all about search in a local region by exploiting the information that a current good solution is found in the region [128]. The good combination of these two major components will usually ensure that the global optimally is achievable. Metaheuristic techniques can be classified as trajectory and population based algorithms. Genetic Algorithm (GA) [110], [112] & [133] and Particle Swarm Optimization (PSO) [115] are population based algorithms which incorporates strings and multiple no of agents for effective search. On the other hand, simulated annealing uses a single agent of solution. Single agent moves though the search space in a piecewise style. A better move is always accepted, while not so good move is accepted with a certain probability.

This chapter presents a comparative analysis of application of four population based algorithms namely genetic algorithm (GA), Particle Swarm optimization (PSO), Gravitational Search Algorithm (GSA) [132] and Cuckoo Search Algorithm (CSA) [127]-[129] in PSS parameter estimation problem [73]-[77], [116]-[124] & [135]-[136].

5.2 OVERVIEW OF GENETIC ALGORITHM

GA is a global search and optimization technique which is based on natural selection and genetics [110]-[111]. Development of GA is mostly attributed to the work of Goldberg and Holland [112]. The beauty of algorithm is lies in multipoint search i.e. the ability of the algorithm to search several possible solutions simultaneously. The optimization process through GA is initiated with random criterion of initial population which represents possible solution of the problem. This population is in the form of string and known as chromosome. Chromosome is consisting of a set of elements, called genes that hold a set of values for the optimization variables.

Fitness of each solution is evaluated by the value of objective function, which is called fitness function. Fitness of objective function is improved through evolution. Genetic operators are employed to select more fit individuals and create new population. These operators are namely: selection, crossover and mutation. The stopping criterion is defined through either maximum iteration count or tolerance of the function. Four main parameters affect the performance of algorithm: population size, number of generations, crossover and mutation rate.

Emad Elbeltagi *et al.* [161] presented comparison of evolutionary algorithms namely GA, PSO, Shuffled frog leaping and Memetic algorithm. In this work authors presented a comparison of application of algorithms for solving discrete and continuous optimization problem. The problem associated with local minima trap was discussed [82]. Valve point effect was observed in economic load dispatch problem with slight modified GA in [116]. Ying-Yi Hong *et al.* [134] proposed a scheme for minimize load shedding and maximize the lowest swing frequency. In this approach penalty functions and variable length chromosomes were utilized to determine the optimal shed loads at all stages. Do bofmin *et al.* [135] employed GA operators for simultaneous optimization of both phase compensation and gain setting of the stabilizers; proposed approach was tested over south eastern Brazilian System. Gerbex *et al.* [136] presented a genetic algorithm based approach to seek the location of FACTS devices, their types and their values. Four kind of FACTS controller were used in this study. GA consists of several operations namely initialization, reproduction and termination. According to Goldberg [112] the power of GA lies in it being able to find good building blocks. Some basic terms related with GA operations are exhibited here.

5.2.1 Key terms in GA optimization

a) **Fitness function:** A fitness function must be devised for each problem to be solved. Each iterative process ends up with a single numeric value called as fitness.

b) **Reproduction:** During the reproductive phase of the GA individuals are selected and recombine. Two parents are recombined by the employment of two basic forms of operators namely crossover and mutation.

   Crossover: It takes two individuals and cut their chromosome strings at some randomly chosen position, to produce two head and tail segments. The two offspring each inherit some genes from each parent. It is known as single point crossover.

   Mutation: It applied to each child individually after crossover. It randomly alters each gene with a small probability

c) **Convergence**: It is the progression towards increasing uniformity. If GA is implemented successfully fitness of each generation increases towards the global optimum. Fig. 5.3 shows the process of crossover and mutation.

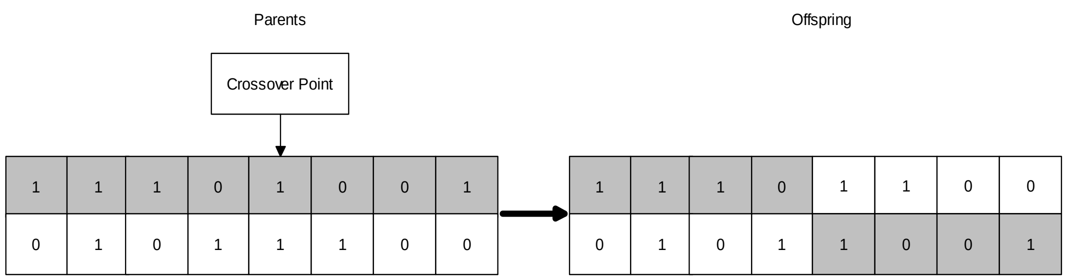

Fig.5.3: Crossover of single agent GA

5.3 OVERVIEW OF PARTICLE SWARM OPTIMIZATION

PSO is a kind of heuristic optimization algorithms. It is motivated from simulating certain simplified animal social behaviors such as bird flocking, and is first proposed by Kennedy and Eberhart in 1995 [115], It is an iterative, population-based process. Each particle represents a candidate solution to the problem. The particle undergoes two processes in PSO, position and velocity of the particle is changed with respect to time. The process of position change or exploration of the search space continues till the relatively unchanged position encountered. Process terminates also when computational limitations are exceeded [121]. PSO possess some beautiful attributes which makes it better than traditional optimization approaches. Following are the note worthy features of PSO.

1. PSO is a population based algorithm, it possess implicit parallelism. The probability to be trapped in local minima is very less for PSO.

2. PSO uses guide index for exploring search space in an efficient way. PSO is applicable on non differentiable functions also and this property makes it free from initial assumptions.

3. PSO uses probabilistic transition rules than deterministic rules. This makes PSO more flexible and robust. PSO can explore search space in a more efficient way than traditional optimization techniques.

4. Unlike GA, PSO has the flexibility to control the balance between global and local exploration of the search space. This unique feature helps PSO to overcome premature convergence.

5. Solution quality of PSO is free from initial guess.

The signature terms used in optimization process are described below:

a) **Particle:** It represents a candidate solution represented by an 'm' dimensional real valued vector. Here m represented the size of the problem.

$$X(t) = [X_1(t), X_2(t)....X_m(t)]$$

b) **Population:** it is set of particles, if it is equal to 'n' that means n particles at a time will explore the search space for optima.

$Pop(t) = [X_1(t), X_2(t).....X_m(t)]$

c) **Velocity:** It is the m dimensional real vector and it represents the speed of particle for exploring the search space.

d) **Inertia weight:** It is a control parameter of PSO. Inertia weight is used to control effect of previous velocities. It establishes tradeoff between local and global search exploration abilities.

e) **Individual best and global best:** In optimization process particle acquire several positions. The best position with respect to all positions (best fitness) acquired by it, is individual best .These are the terms used with reference to local and global minima in optimization process.

The particles are described by their two instinct properties: position and velocity. The position of each particle represents a point in the parameter space, which a possible solution of the optimization problem and the velocity is used to change the arrangement. Equation (5.1) and (5.2) describes the position and velocity updation of the particle.

$$v_{ij}^{(k+1)} = v_{ij}^{k} + c_1 r_1 \left(P_{ij} - x_{ij}^{k}\right) + c_2 r_2 \left(P_{gj} - x_{ij}^{k}\right) \tag{5.1}$$

$$x_{ij}^{(k+1)} = x_{ij}^{k} + v_{ij}^{(k+1)} \tag{5.2}$$

$i = 1, 2, 3, ..., N_P \qquad j = 1, 2, 3, ..., N_D$

Where N_p is the number of particles in the population; N_d is the number of variables of the problem (i.e. dimension of a particle); v_{ij}^{k} is the j^{th} coordinate component of the velocity of the i^{th} particle at iteration k; P_{ij} is the j^{th} coordinate component of the best position recorded by the $i^{th} n$ particle during the previous iterations; P_{gj} is the j^{th} coordinate component of the best position of the global best particle in the swarm, which is marked by g; x_{ij}^{k} is the j^{th} coordinate component of the current position of particle i^{th} at the k^{th} iteration; ω is the inertia weight, $c1, c2$ are the acceleration coefficients and $r1, r2$ are the uniformly distributed random values between 0 and 1. Fig. 5.4 shows the anatomy of the particle depicting the global, individual best and velocity of the particle.

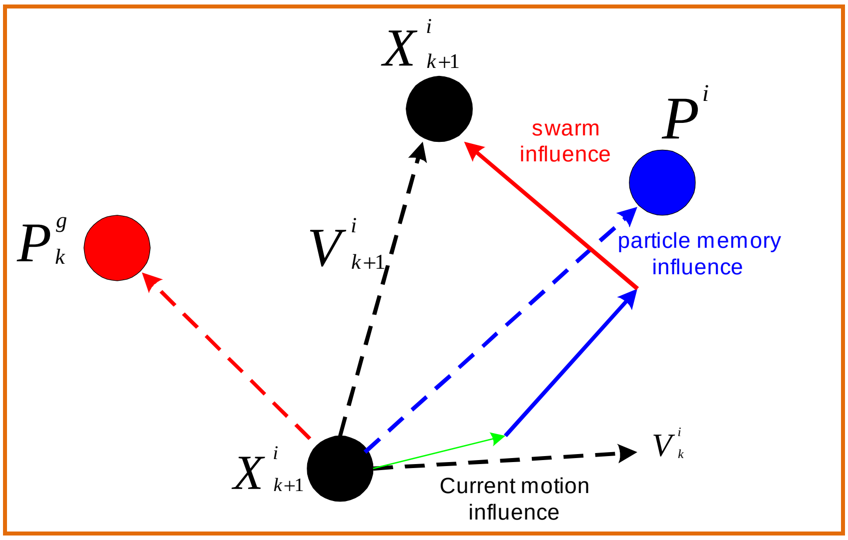

Fig.5.4: Anatomy of particle

PSO is applied in many optimization problems like NR problem, Economic load dispatch, PSS design, Optimal power flow and many others[74], [120]-[123] & [139]-[142]. Some approaches used multi agent PSO for exploring the search space in a more efficient way [141]. Distribution system planning with Distributed Generation (DG) reactive capability and system uncertainties were discussed in [142]

5.4 OVERVIEW OF GRAVITATIONAL SEARCH ALGORITHM

Over the last decades, there has been a growing interest in algorithms inspired by the behaviours of natural phenomena [115] & [141]-[146]. It is publicized by several researchers that these algorithms are well suited to solve complex computational problems such as optimization of objective functions [76], [77], [82] & [136], pattern recognition [146] & [147], control objectives [148]-[150], image processing [151] & [152] etc. Various heuristic approaches have been adopted by researches so far, GA[136], Simulated Annealing (SA) [80], Ant Colony Search Algorithm [148], Rashedi *et al.* [132] anticipated a new meta-heuristic algorithm called GSA in year 2009 [17]-[19]. A beautiful analogy between Newton's gravitational laws with the optimization prototype of the era is presented in the algorithm. The postulates of the algorithm say that every particle attracts towards each other and force exerted between two objects (agents) is proportional to the mass of the objects and inversely proportional to square of the distance between them. Force causes a global movement of all objects towards the objects with heavier mass. Heavier mass is analogous to the agent which has higher fitness values. GSA proposes four prepositions of a gravitational mass: its position, inertial mass, gravitational mass (active and passive).

The position of mass is representation of a solution and masses are specified by fitness of a function. It is assumed that given a system with N agents in search space represents solution to a problem. Equation (5.3) represents space dimension and the position of the agent x_i^d in d^{th} dimension.

$$x_i = \left(x_i, \dots x_i^d, \dots x_i^n\right), \quad for\ i = 1, 2, \dots, N \tag{5.3}$$

According to the Newton's law of attraction the force exerted by i^{th} mass due to j^{th} mass at time *t* represented by equation (5.4).

$$F_{ij}^{d}(t) = G(t)\frac{M_{pi}(t) \times M_{qj}(t)}{R_{ij}(t) + \varepsilon}\left(x_j^d(t) - x_i^d(t)\right) \tag{5.4}$$

Where $M_{pi}(t), M_{qj}(t)$ are active and passive gravitational mass, $G(t)$ is gravitational constant at time *t* and R_{ij} is euclidian distance between *i* and *j* agents defined by equation (5.5).

$$R_{ij}(t) = \left\| X_i(t), X_j(t) \right\|_2 \tag{5.5}$$

Force exerted on an agent *i* is randomly weighted sum of the forces exerted from other agents.

$$F_i^{d}(t) = \sum_{j=i\ j \neq i}^{m} rand_j\ F_{ij}^{d}(t) \tag{5.6}$$

Acceleration of the agent at time *t* in the d^{th} dimension on law of motion is used directly to calculate the force. In accordance with this law, acceleration is proportional to the force exerted and inversely proportional to mass of the agent.

$$a_i^d(t) = \frac{F_i^d(t)}{M_{ii}(t)} \tag{5.7}$$

Searching strategy of the algorithm is defined by updating velocity and position at time t and in d dimension.

$$v_i^d(t+1) = rand_i \times v_i^d(t) + a_i^d(t) \tag{5.8}$$

$$x_i^d(t+1) = x_i^d(t) + v_i^d(t+1) \tag{5.9}$$

The gravitational constant *G*, randomly at the starting and according time to control the search accuracy *G* is exponentially decayed.

$$G(t) = G(G_0, t) \tag{5.10}$$

$$G(t) = G_0\, e^{-\frac{\alpha t}{T}} \tag{5.11}$$

There α is a user specified constant, t is the current iteration and T is the total number of iterations.

5.5 OVERVIEW OF CUCKOO SEARCH ALGORITHM (CSA)

The CSA is introduced by yang and Deb in 2009 [127]-[130]. The CSA was inspired by compel brood parasitism of cuckoo species by laying their eggs in the nests of host birds. Some cuckoos have evolved in such a way that female scrounging cuckoos can reproduce or rather imitate the colors and patterns of the eggs of a few chosen host species. This reduces the probability of the eggs being abandoned. Yang and dev also suggested in their research that levy flights is useful for improve solution quality besides on random walk method. A Lévy flight is a random walk in which the step-lengths are distributed according to a heavy-tailed probability distribution. Each egg in a nest represents a solution .the objective it to employ good quality solution in the nest and replace those which are not so good solution. The algorithm based on three idealized rule:

- Each Cuckoo laid one egg only, and dumps the egg in a randomly chosen nest.
- The best nest (with quality solutions) will carry over the next generation.
- The number of available nest is fixed and a host can identify an alien egg with probability P_a [0, 1].

Based on the foresaid rules while generating new solutions:

$$x_i^{t+1} = x_i^t + \alpha \oplus Lev'y(\lambda) \tag{5.12}$$

Where $\alpha > 0$ is the step size, in this work it is taken 1. Random walk is a markov chain whose next location is depends on the current location (the first term in equation (5.12)) and the probability of the transition.

Primary observations about algorithm develop a sense of resemblance with hill climbing in combination with some large scale randomization [157]. However the algorithm is a population based algorithm similar to GA [112] and PSO [115] but randomization of the patterns is done in a more efficient way as the step length is heavy tailed. Thirdly the parameters to be tuned is less than GA and PSO, For these reasons the Cuckoo search found to be very generic and used for wide no of optimization problems. Parameters of algorithms are given in Appendix-F.

5.6 OBJECTIVE FUNCTION

To solve optimization process for PSS parameter estimation problem, objective function carries an archetype importance. The problem with eigenvalue based objective function was reported in prominently [82]. A brief section is kept in literature review to discuss problems mentioned in [82]. Combinatorial optimization is a combination of multiple objectives. In literature, there are lot of examples available for PSS parameter estimation problem. Point of consideration for taking speed deviation based objective function lies in that: objective function used in [77] & [78] did not possess any conflicting objectives. Solution of these problems resulted in enhanced damping and bigger negative real part of the eigenvalue. The fact is, if the real part of eigenvalue is maximized in negative half than damping is also enhanced. It is also observed in [83] that eigenvalue based objective functions gave lower frequency and higher frequency modes, which are bad for the health of the equipment. Equation (5.13) shows the speed deviation based objective function with constraints in equation (5.14). This objective function is used for optimization process.

$$\textbf{min}\ J = \sum_{t=0}^{t_{sim}} \Delta\omega_i^2 \tag{5.13}$$

$$\left\{\begin{matrix} K_i^{\textbf{min}} \le K_i \le K_i^{\textbf{max}} \\ T1_i^{\textbf{min}} \le T1_i \le T1_i^{\textbf{max}} \\ T3_i^{\textbf{min}} \le T3_i \le T3_i^{\textbf{max}} \end{matrix}\right\} \tag{5.14}$$

Where i stands for the generator no., K_s stands for PSS gain, and T_1, T_3 are the time constants of PSS.

For New England system it is assumed that all generators are containing PSS, so in this case total 30 parameters by keeping T_w, T_2 and T_4 constant [77] & [78]. For 16 generator 68 buses system while each generator is equipped with PSS, total 48 parameters are optimized [82]. Speed deviation based objective function tunes PSS for hard conditions as the objective function has two sub objectives:

1. Tune PSS for minimize overshoot of speed deviation curves.

2. For achieving minimum settling time

5.7 Simulation Results:

In this section results of application of different evolutionary designs are presented. The PSSs parameter evaluation problem is investigated on standard IEEE-39 and IEEE-68 bus systems[153] &[160]. Standard objective function which is based on the speed deviation of the generator is considered, as discussed in previous section. In stability studies ample amount of importance is given to the initial operating condition. In this study nonconforming loads (10% constant current 10% constant power and 60% constant impedance for active power) are assigned on New England System. According [82] System is observed in such a stressed condition that a small perturbation make it unstable. To perform this simulation study 2.5 GB ram 2.5 GHz icore-7 processing unit is used. Power System Toolbox (PST) [158] of MATLAB [154] is used for simulation studies.

5.7.1 IEEE 39 Bus System

For New England System all the generator machines are of two axis model of the synchronous machines, specifications are shown in Appendix-B. This system has 39 buses and 10 generators, 19 loads, 36 transmission lines. This system is organized into three areas.

Following conditions are taken to validate the effectiveness of proposed approach on New England System.

a) 3 φ 6 cycle disturbance at line 2-25
b) 3 φ 6 cycle disturbance at line 2-25 with line outage 16-21
c) 3 φ 6 cycle disturbance at line 10-13
d) 3 φ 6 cycle disturbance at line 10-13 with line outage 22-23
e) 3 φ 6 cycle disturbance on line 14-15
f) 3 φ 6 cycle disturbance on line 12-13

Although the damping controller designed through evolutionary algorithms is quite robust and proved effective in all operating contingencies yet to show the efficacy of the proposed controller extreme conditions are chosen [82]. The performance of the controller is exhibited in terms of hard conditions. For this reason here three phase faults are considered and speed responses of those generators are shown which are near by the fault locations.

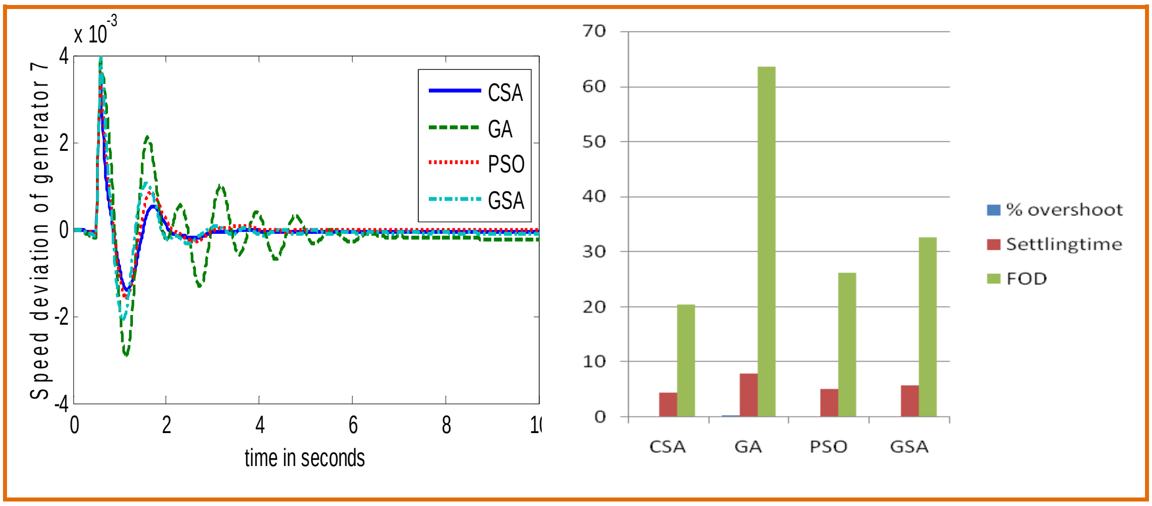

Fig.5.5: Speed deviation curve of generator 7 and its particulars

Fig. 5.5 shows the speed deviation curve of generator 7 with different PSSs settings obtained from algorithms, sub part of the Fig.5.6 shows that the GA has maximum in terms of FOD .FOD is nothing but a linear combination of settling time and overshoot of the swing curve which is a close replica of swing curve response. It is also worth mention here that as per Table 5.1 it can be concluded that overshoot, settling time and FOD is quite low as far as CSA is concerned. The poor response in terms of settling time, overshoot and FOD is of GA.

$$FOD = Os^2 + Ts^2 \tag{5.15}$$

Where Os is overshoot of curve and Ts is settling time of the curve.

Table 5.1: Comparative analysis of Speed deviation curve of generator 7

	Fault on Line 2-25		
	% overshoot	Settling time	FOD
CSA	0.3366	3.9	15.32
GA	0.3948	9.9	98.17
PSO	0.3564	6.08	37.09
GSA	0.3963	5.15	26.68

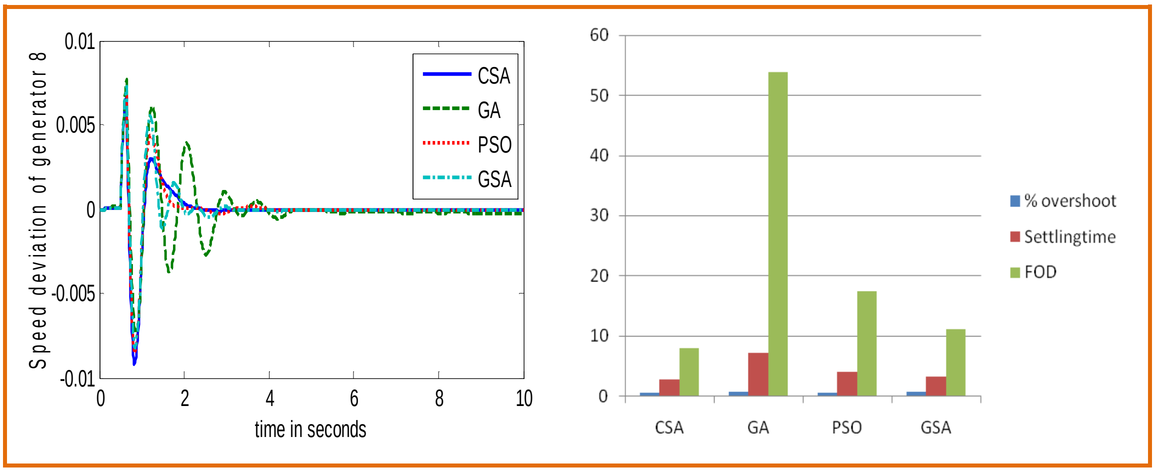

Fig.5.6: Speed deviation curve of generator 8 and its particulars

It is can also be concluded that as per Table 5.2 overshoot, settling time and FOD is quite low as far as CSA is concerned. GA shows poor response as FOD is 53.88 in this case. However PSO and GSA possess 17.42 and 11.22.

Table 5.2: Comparative analysis of Speed deviation curve of generator 8

Fault on Line 2-25			
	% overshoot	Settling time	FOD
CSA	0.6623	2.76	8.056241
GA	0.7696	7.3	53.88228
PSO	0.673	4.12	17.42733
GSA	0.7263	3.27	11.22041

Fig. 5.7 shows the speed deviation curve of generator 3 and statistics associated with this swing curve is shown in Table 5.3.

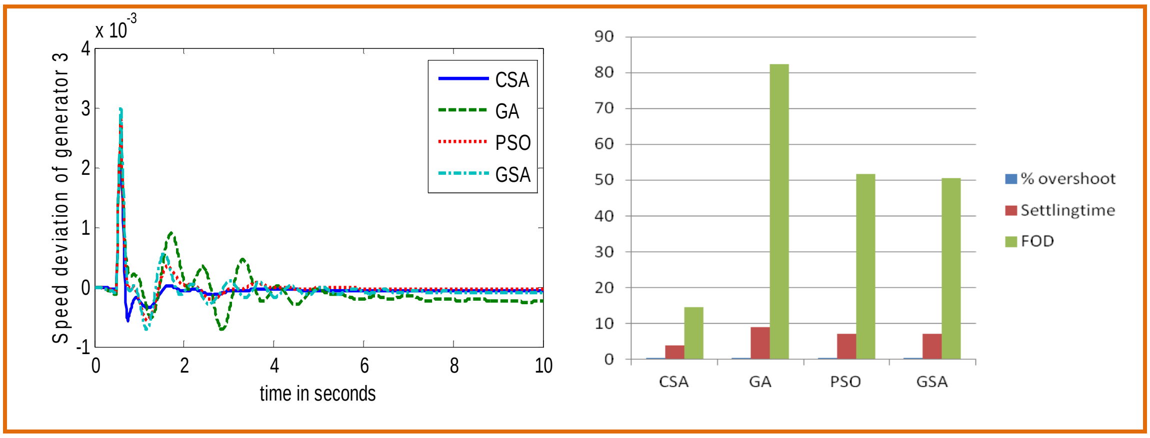

Fig.5.7: Speed deviation curve of generator 3 and its particulars

Table 5.3 gives Comparative analysis of Speed deviation curve of generator 3. It shows the same analogy with additional line outage of 16-21.

Table 5.3: Comparative analysis of Speed deviation curve of generator 3

Fault on Line 2-25 with line 16-21 out			
	% overshoot	Settling time	FOD
CSA	0.2726	3.8	14.51
GA	0.2736	9.07	82.34
PSO	0.2856	7.19	51.78
GSA	0.3014	7.11	50.64

Fig. 5.8 is a speed deviation curve of generator 4 with its statistics in sub part of this fig. Table 5.4 shows the statistics related with the speed deviation curve.

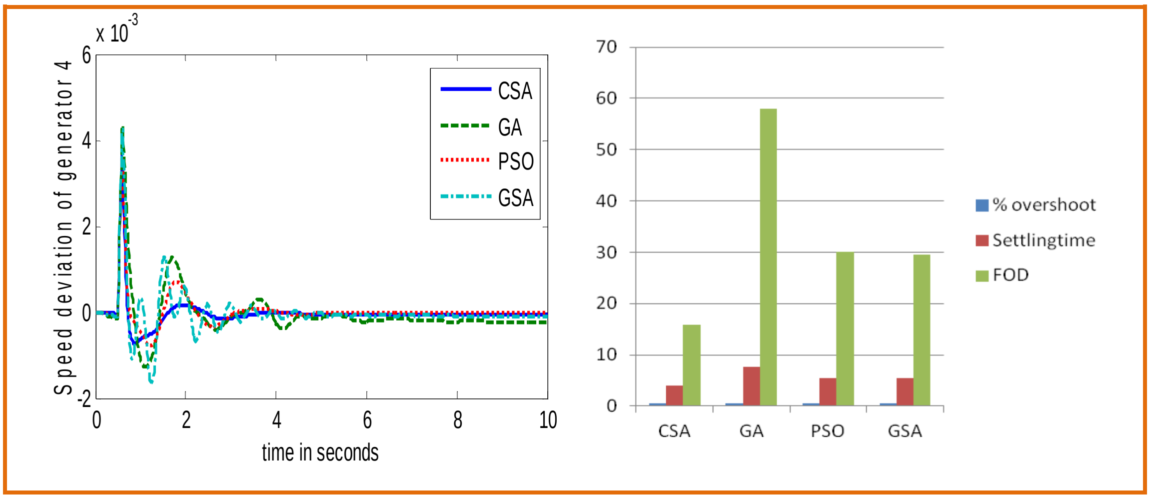

Fig.5.8: Speed deviation curve of generator 4 and its particulars

As per Table 5.4 it can be concluded that overshoot, settling time and FOD is quite low as far as CSA is concerned. However, overshoot(s) of the curves fall in a very short range but settling time varies in a wide range for the responses hence, FOD values are obtained in a wide range.

Table 5.4: Comparative analysis of Speed deviation curve of generator 4

	Fault on Line 2-25 with line 16-21 out		
	% overshoot	Settling time	FOD
CSA	0.5889	3.95	15.95
GA	0.6	7.59	57.97
PSO	0.58	5.46	30.15
GSA	0.5778	5.41	29.6

Fig.5.9 shows the speed deviation of generator 9 with fault condition while fault on line 2-25 with line 16-21 out. Fig. 5.10 shows the speed deviation of generator 6 while fault on line 10-13. Fig. 5.11 shows that GA is not able to mitigate the contingency condition.

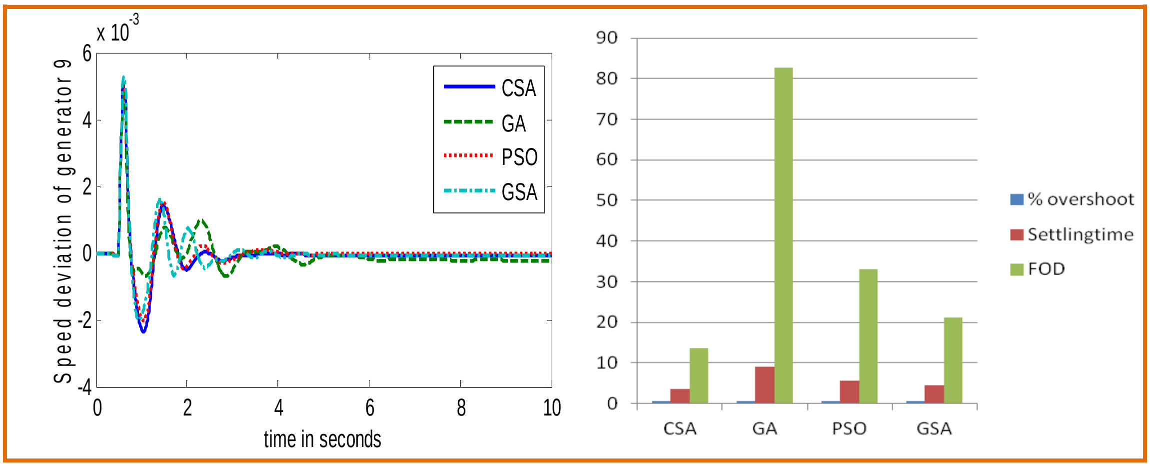

Fig.5.9: Speed deviation curve of generator 9 (fault on line 2-25 with outage on 16-21)

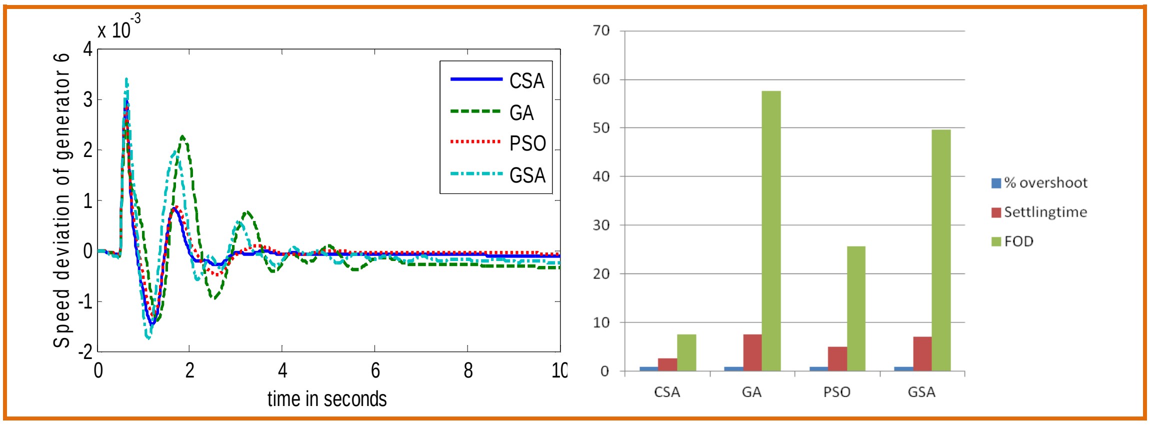

Fig.5.10: Speed deviation curve of generator 6 (fault on line 10-13)

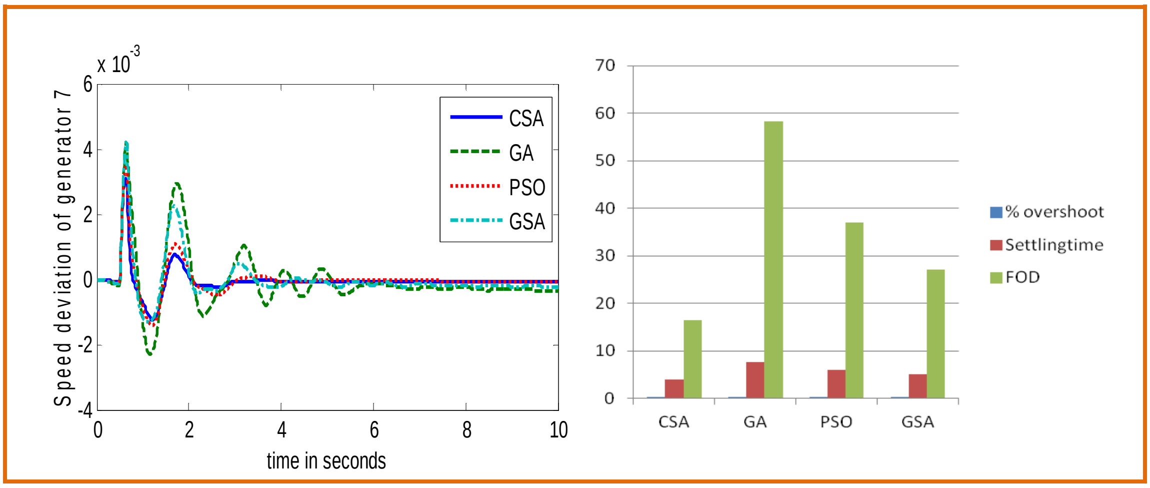

Fig.5.11: Speed deviation curve of generator 7 (fault on line 10-13)

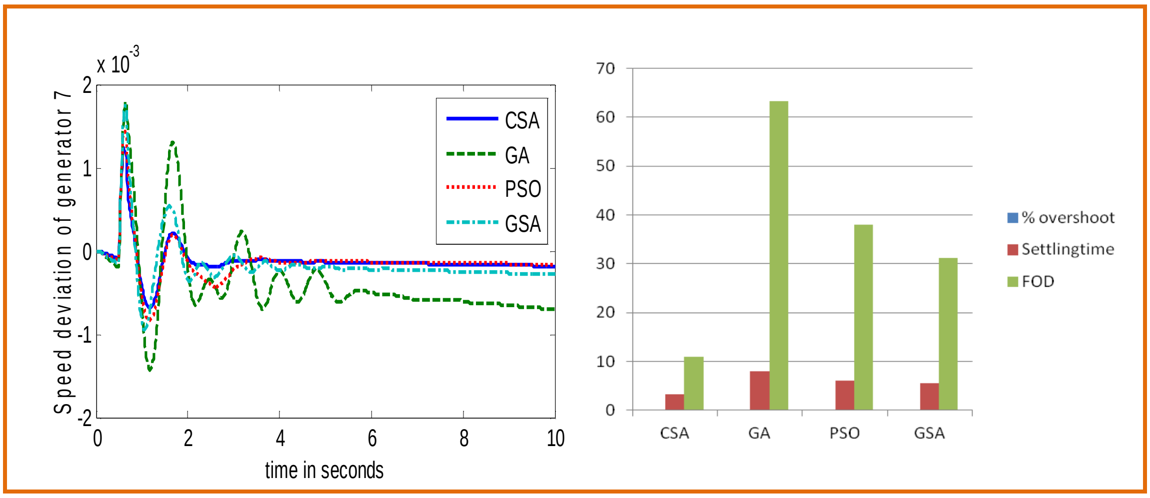

Fig.5.12: Speed deviation curve of generator 7 (fault line10-13 and line 22-23 out)

Fig. 5.12 shows the speed deviation curve of generator 7 with different PSSs settings which are obtained from algorithms sub part of this figure shows that the GA has maximum in terms of FOD. GA is not able to mitigate the contingency condition and system is thrown to an unstable zone with GA tuned PSS. However, CSA is able to mitigate all the frequency deviations caused by 3 phase 6 cycle disturbance.

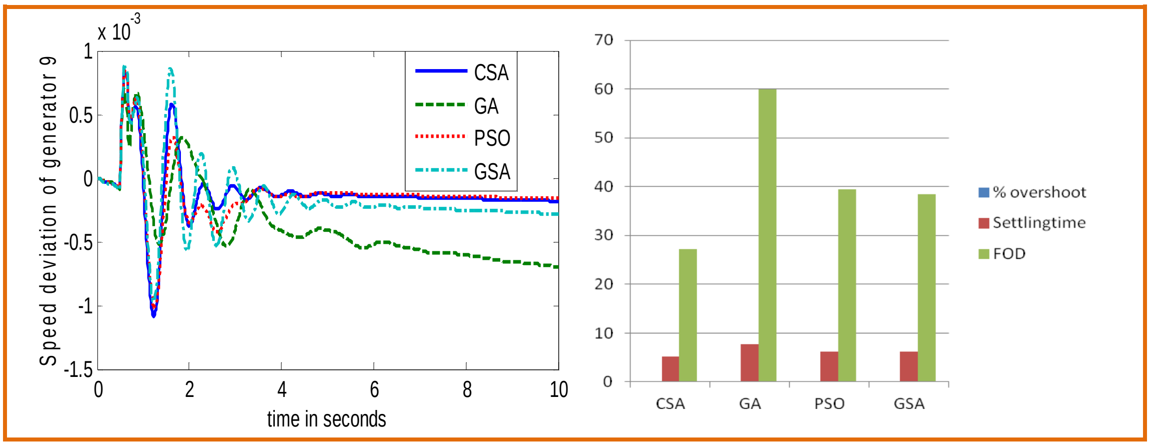

Fig.5.13: Speed deviation curve of generator 9 and its particulars

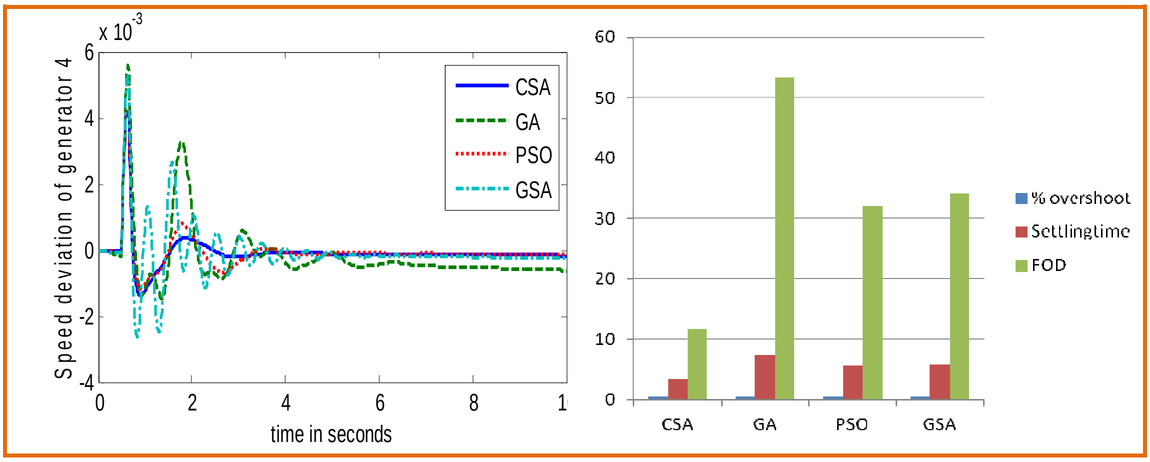

Fig.5.14: Speed deviation curve of generator 4 (fault on line14-15)

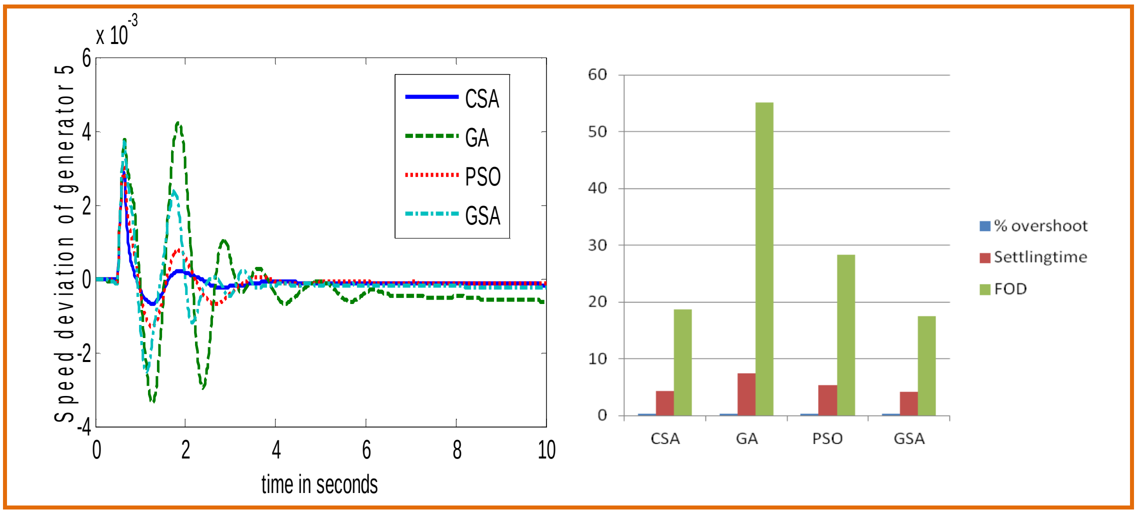

Fig.5.15: Speed deviation curve of generator 5 (fault on line14-15)

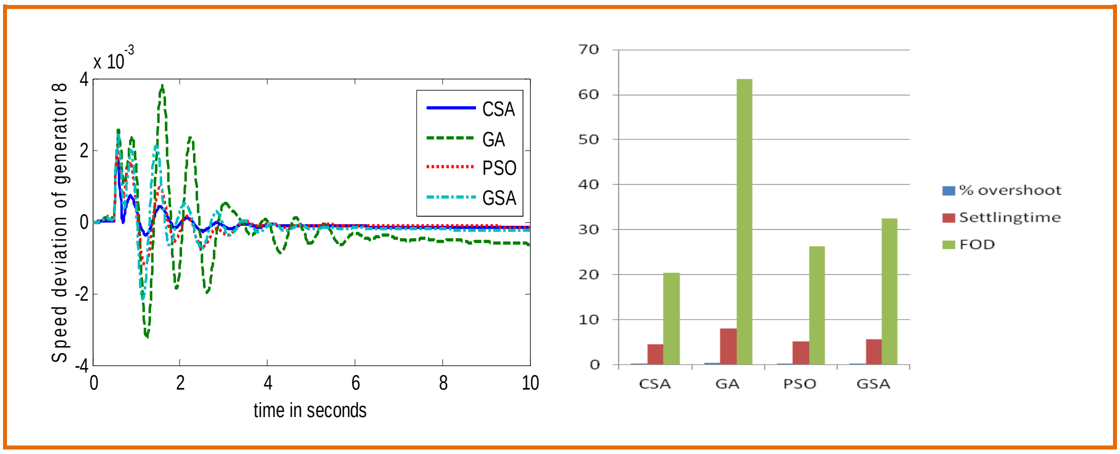

Fig.5.16: Speed deviation curve of generator 8 (fault on line12-13)

Table 5.5 Comparative analysis of Speed deviation curve of generator(s)

Fault location*	Algorithm	% overshoot	Settling time	FOD
Fault on Line 2-25 with line 16-21 out (9)	CSA	0.5042	3.67	13.72
	GA	0.4818	9.08	82.68
	PSO	0.5	5.72	32.97
	GSA	0.64	4.55	21.11
Fault on Line 10-13 (6)	CSA	0.8	2.63	7.557
	GA	0.853	7.54	57.58
	PSO	0.8572	5	25.73
	GSA	0.86	7	49.74
Fault on Line 10-13 (7)	CSA	0.29	4.05	16.49
	GA	0.41	7.62	58.23
	PSO	0.3564	6.08	37.09
	GSA	0.37	5.19	27.07
Fault on Line 10-13 with line 22-23 out (7)	CSA	0.12	3.31	10.97
	GA	0.17	7.95	63.23
	PSO	0.14	6.16	37.97
	GSA	0.17	5.59	31.28
Fault on Line 10-13 with line 22-23 out (9)	CSA	0.08	5.22	27.25
	GA	0.06	7.74	59.91
	PSO	0.08	6.28	39.44
	GSA	0.08	6.2	38.45
Fault on Line 14-15 (4)	CSA	0.42	3.38	11.6
	GA	0.55	7.28	53.3
	PSO	0.42	5.64	31.99
	GSA	0.49	5.82	34.11
Fault on Line 14-15 (5)	CSA	0.27	4.32	18.74
	GA	0.41	7.41	55.08
	PSO	0.3	5.32	28.39
	GSA	0.3	4.18	17.56
Fault on Line 12-13 (8)	CSA	0.16	4.52	20.46
	GA	0.37	7.96	63.5
	PSO	0.21	5.12	26.26
	GSA	0.24	5.7	32.55

*(Values shown in parentheses are the generator no.)

Following point can be concluded from Table 5.5.

1. GA provides a poor damping response as the overshoot and settling time of the speed deviation curves under different contingencies are much higher than expected values. However, in some cases the GA provide a very poor design that values of speed deviation(s) are keep on increasing or decreasing as per figs. 5.13 to 5.16.

2. Values of FOD in some case observe decrement of more than 70% especially line outage(s) are considered with the faults. Fig. 5.13 is the case where simulation time is considered as the settling time in FOD calculations.

3. FOD values are fall in a very short range. FOD values would not be able to present a fruitful comparison, when the problem is solved with PSO and GSA. It is required that comparison should be established on the basis of processing time and convergence characteristics of the algorithms.

4. Values of FOD, Settling time and overshoot have minimum values when the optimization process is solved by CSA. It gives the direct conclusion that CSA is more efficient and out played on almost all algorithms.

5.7.2 IEEE 68 Bus System

In this study nonconforming loads (10% constant current, 10% constant power, 60% constant impedance for active power and 60% constant impedance for reactive power) are assigned on 16 Generator 68 Buses. IEEE 68 bus system is a large system with 52 load buses and 16 generator all having two axis model configurations [158]-[160]. System is in stressed condition due to this loading pattern. This detail has taken from [82]. Following contingencies are developed to test the efficacy of the proposed controller(s). Details are shown in Appendix-C.

a) 3 φ 6 cycle Fault on line 1-2
b) 3 φ 6cycle Fault on line 8-9
c) 3 φ 6 cycle Fault on line 2-25
d) 3 φ 6 cycle Fault on line 21-22
e) 3 φ 6 cycle Fault on line 15-16
f) 3 φ 6 cycle Fault on line 43-44.

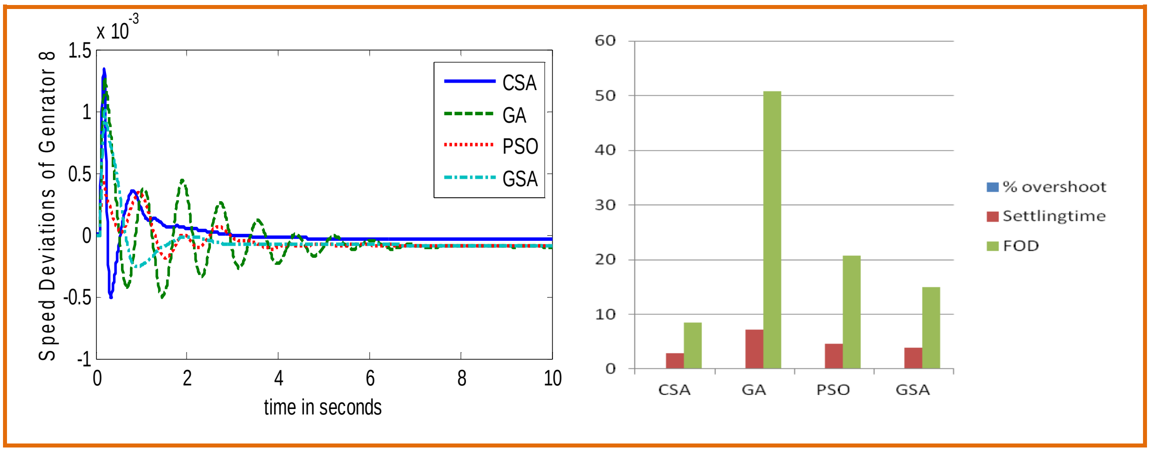

Fig.5.17: Speed deviation curve of generator 8 (fault on line1-2)

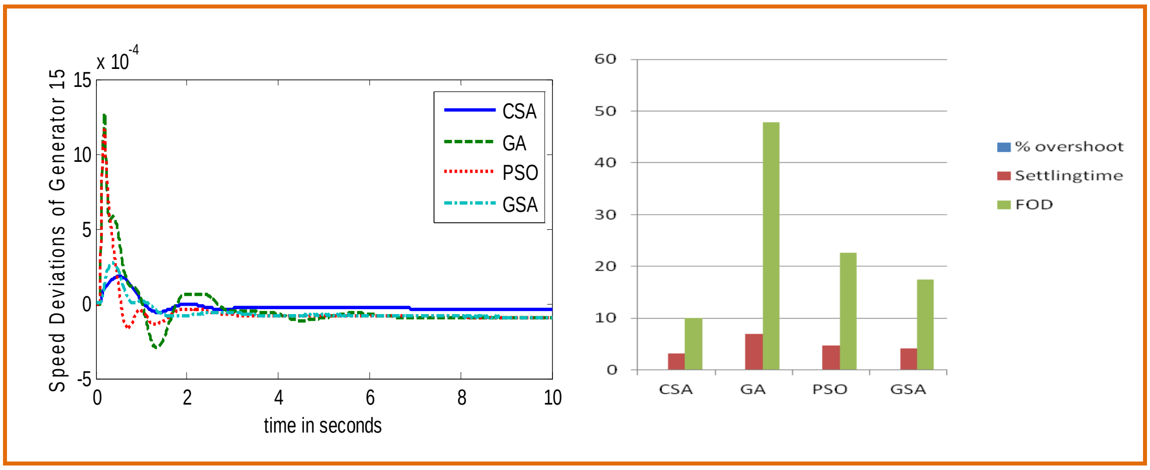

Fig.5.18: Speed deviation curve of generator 15 (fault on line1-2)

Figs. 5.17 and 5.18 shows the speed deviations of generator 8 and 15, when a 3 φ fault is considered for 6 cycle at time t=0 to 0.1 sec. Further Table 5.6 shows the statistics related with the speed deviation curves of generator 8 and 15. It shows that with CSA, response is better and observed very low values of FOD as compared with GA. Almost 50% reduction in the values are observed with CSA. However, the performance of PSO and GSA is also comparable, however GSA outperformed PSO.

Table 5.6 Comparative analysis of speed deviation curves for fault at line (1-2)

Fault location	Algorithm	% overshoot	Settling time	FOD
Fault on Line 1-2 (8)	CSA	0.13	2.92	8.543
	GA	0.12	7.13	50.85
	PSO	0.04	4.55	20.7
	GSA	0.1	3.86	14.91
Fault on Line 10-13 (15)	CSA	0.018	3.16	9.986
	GA	0.12	6.92	47.9
	PSO	0.1	4.76	22.67
	GSA	0.02	4.18	17.47

Fig. 5.19 shows speed deviation curve for generator 6 for fault on line 8-9. Statistics related with the curve is exhibited in Table 5.7.

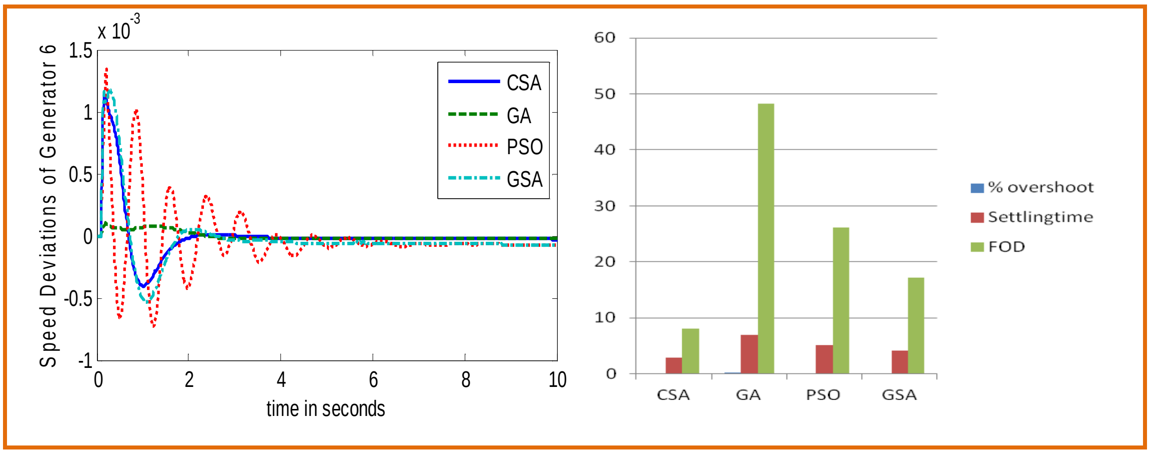

Fig.5.19: Speed deviation curve of generator 6 (fault on line 8-9)

Table 5.7 Comparative analysis of speed deviation curves for fault at line (8-9)

	Fault on Line 8-9		
	% overshoot	Settling time	FOD
CSA	0.1	2.85	8.133
GA	0.3	6.94	48.25
PSO	0.04	5.11	26.11
GSA	0.11	4.15	17.23

Fig. 5.20 shows the speed deviation curve for generator 15 for fault on line 2-25. It can be observed from Table 5.8 that values of FOD are much higher for GA.

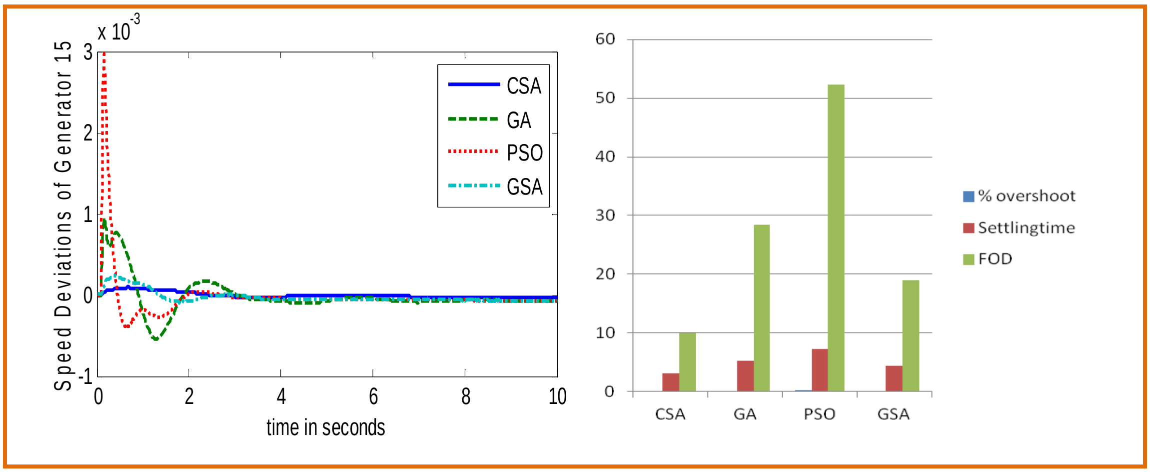

Fig.5.20: Speed deviation curve of generator 15 (fault on line 2-25)

It is also concluded that value of overshoot is much higher when PSSs is tuned with PSO settings.

Table 5.8: Speed deviation curve of generator 15 (fault on line 2-25)

	Fault on Line 2-25		
	% overshoot	Settling time	FOD
CSA	0.08	3.16	9.992
GA	0.09	5.33	28.42
PSO	0.29	7.23	52.36
GSA	0.02	4.36	19.01

Figs. 5.21 & 5.22 show the speed deviations of generator8 and 10 under fault line 21-22.

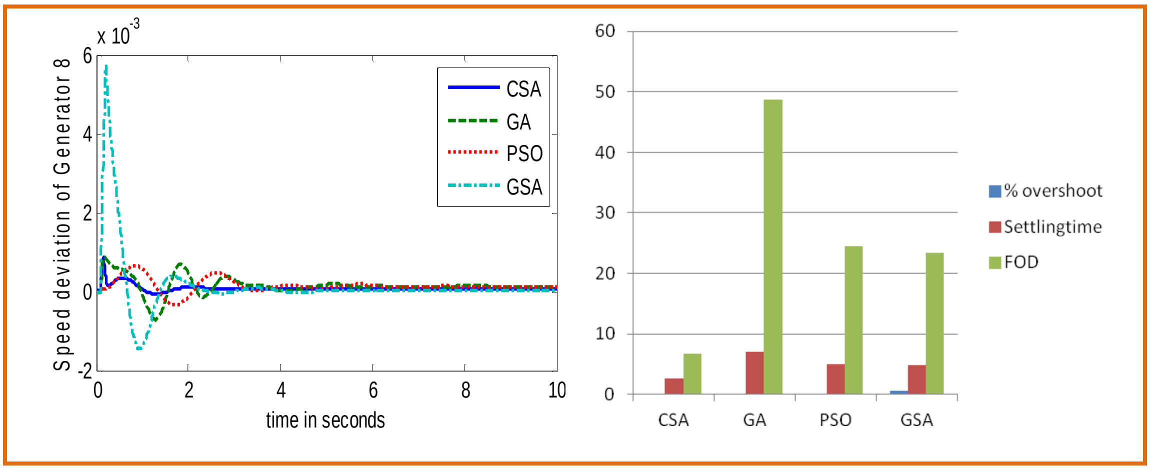

Fig.5.21: Speed deviation curve of generator 8 (fault on line 21-22)

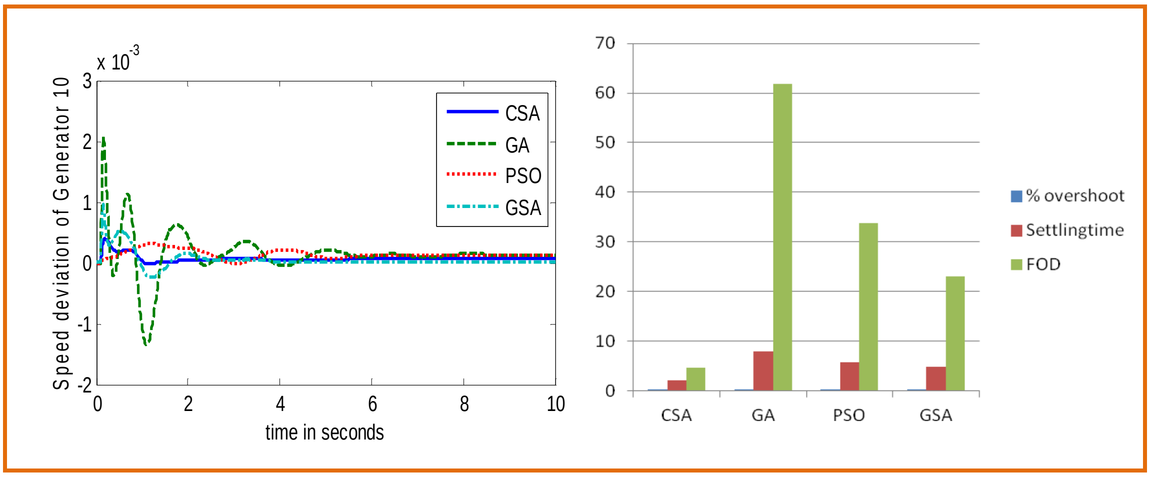

Fig.5.22: Speed deviation curve of generator 10 (fault on line 21-22)

Table 5.9 shows the statistics of fault condition line 21-22. It is observed that a significant amount of reduction in FOD values is observed in case of CSA. However, in this case PSO and GSA observed almost similar values. In case of GA the response is very poor as settling time is much more in case of GA.

Table 5.9 Speed deviation curve statistics fault on line 21-22

Fault location	Algorithm	% overshoot	Settling time	FOD
Fault on Line 21-22 (8)	CSA	0.07	2.6	6.765
	GA	0.1	6.98	48.73
	PSO	0.06	4.95	24.51
	GSA	0.57	4.81	23.46
Fault on Line 21-22 (10)	CSA	0.03	2.16	4.667
	GA	0.2	7.86	61.82
	PSO	0.03	5.81	33.76
	GSA	0.09	4.8	23.05

Figs. 5.23 & 5.24 show the speed deviation curve for generator 7 and generator 9.

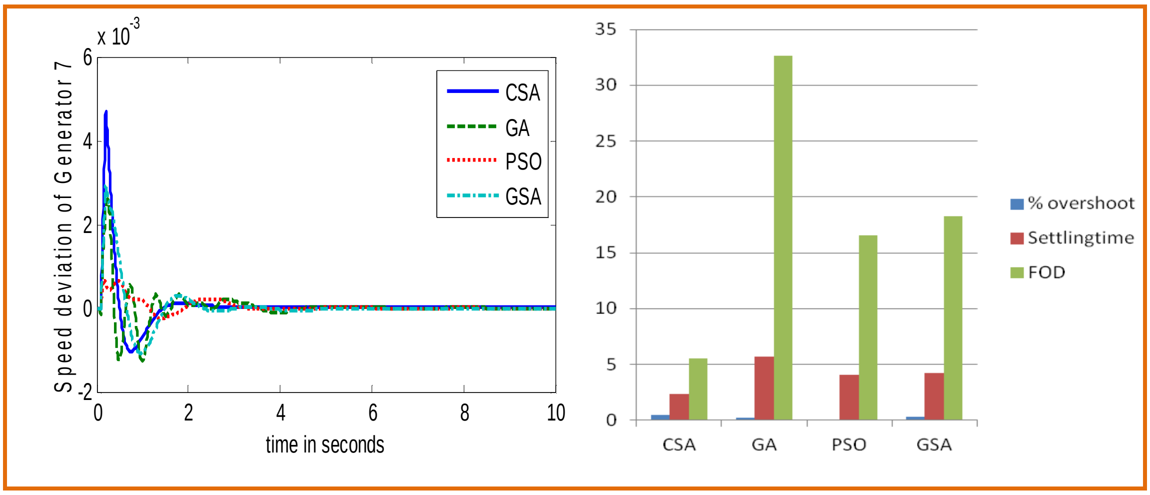

Fig.5.23: Speed deviation curve of generator 7 (fault on line 15-16)

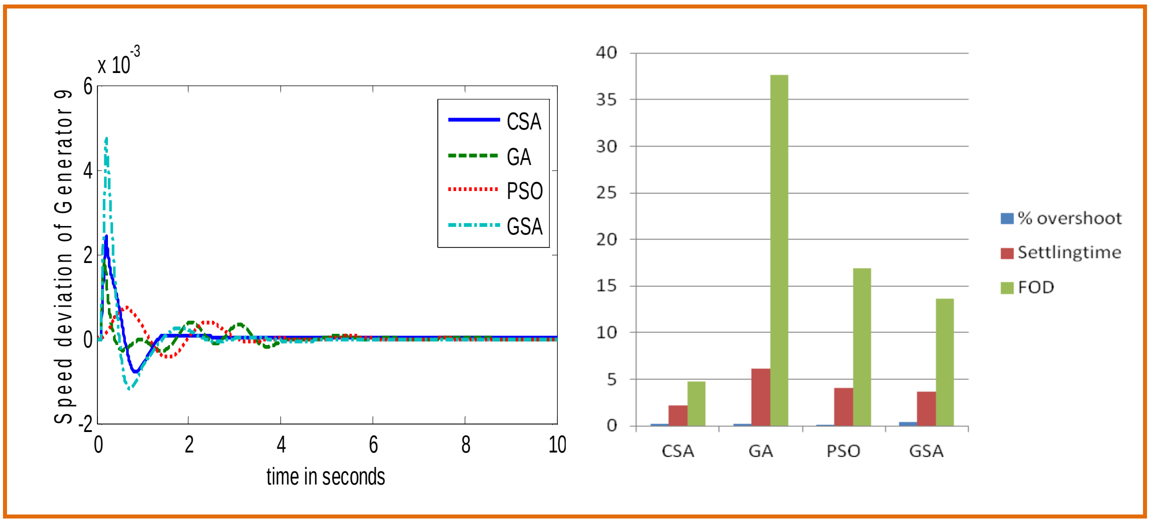

Fig.5.24: Speed deviation curve of generator 9 (fault on line 15-16)

Following points are worth mentioning here:

1. FOD values for CSA is lowest in the cases. However, the values for GA are very high in both cases. It can be concluded that PSS tuned by GA doesn't show a good dynamic response.

2. Although the values of FOD are in a close range for PSO and GSA. GSA gives overall better dynamic response as compared with GA and PSO.

3. Surprisingly in case of speed deviations of generator 7, it is observed that PSO has smallest overshoot as compared with other algorithms. CSA gives highest overshoot in this case.

4. Settling time is very low in both cases for CSA tuned PSS. The highest values of settling time are observed in case of GA.

Table 5.10 Speed deviation curve statistics fault on line 15-16

Fault location	Algorithm	% overshoot	Settling time	FOD
Fault on Line 15-16 (7)	CSA	0.46	2.31	5.548
	GA	0.26	5.71	32.67
	PSO	0.06	4.07	16.57
	GSA	0.29	4.26	18.23
Fault on Line 15-16 (9)	CSA	0.24	2.17	4.767
	GA	0.18	6.13	37.61
	PSO	0.07	4.11	16.9
	GSA	0.47	3.66	13.62

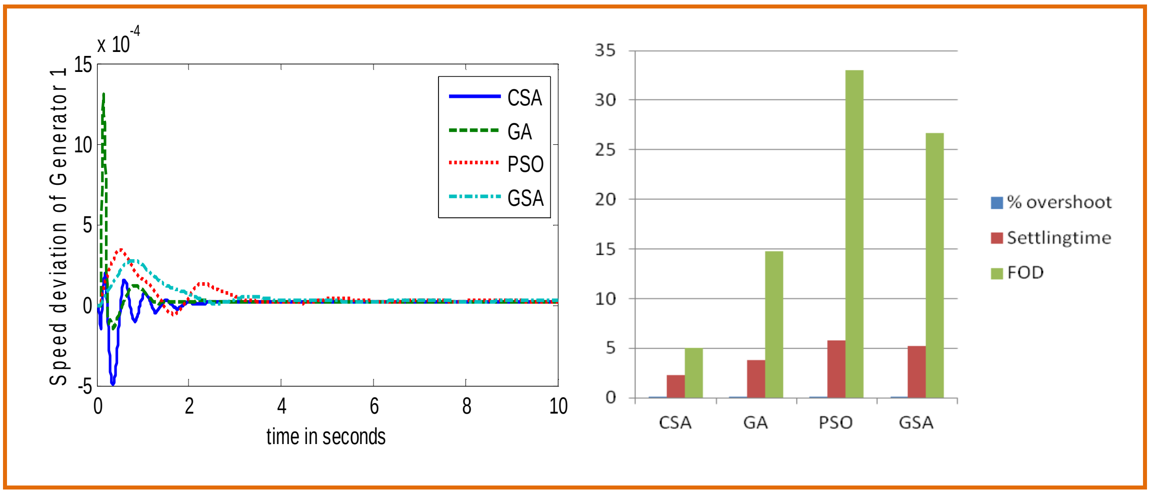

Fig.5.25: Speed deviation curve of generator 1 (fault on line 43-44)

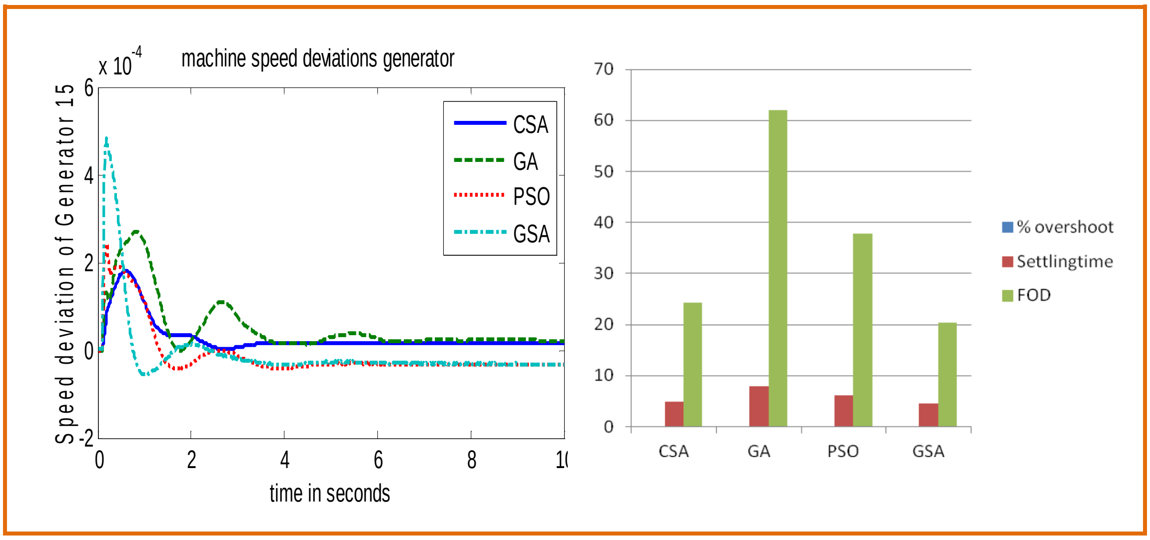

Fig.5.26: Speed deviation curve of generator 15 (fault on line 43-44)

To present a meaningful comparison optimization process is run for 100 trials and standard deviations of the value of objective function is shown in Table 5.11

Table 5.11 Comparative analysis of Algorithm(s)

Comparison Criterion	Algorithm	Number of Variables	
		30	48
Standard Deviation in value of objective function After 100 successive run	GA	0.05467	0.2447
	PSO	0.01739	0.0856
	GSA	0.0298	0.0795
	Cuckoo Search	1.75E-14	3.22E-14
% Success Rate	GA	60	50
	PSO	77	76
	GSA	78	85
	Cuckoo Search	100	100
% Overshoot (Average)	GA	0.300	0.19
	PSO	0.297	0.08
	GSA	0.2963	0.012
	Cuckoo Search	0.300	3.80E-01
Settling Time (sec.) (Average)	GA	8.495	6.87
	PSO	5.97	6.06
	GSA	5.482	4.32
	Cuckoo Search	4.2346	2.22
Figure of Demerit (FOD) (Average)	GA	29.435625	77.44036
	PSO	16.415425	36.7237
	GSA	15.1425312	17.2089
	Cuckoo Search	12.2258176	4.929844

Success rate is defined as the percentage of the number of objective function values less than or equal to minimum value obtained in optimization process divided by the number of total runs. Following points can be observed.

1. A critical Analysis of algorithms based on 5 criterions is presented in Table 5.11. It is observed that the solution quality obtained from GA is poorest as the standard deviations in 100 successive runs are maximum when tested for both the systems.

2. Success rate of the algorithm is defined as the ability of the algorithm to provide potential solutions in each run, it is observed from here that GA lags in this case also for 30 parameters the success rate is just 60% and it is reduced with the increase in no. of parameters in next case. However for this criterion PSO outperformed over the GA and GSA.

3. The overshoot and settling time and FOD are the derivatives of rotor swing curves for both test cases. Different cases are exhibited to show the better understanding of the results. A decisive evolution is concluded while observing the % overshoot and settling for the different cases and each case depicts that these criterion is minimum for CSA.

Tables 5.12-5.15 show the parameters optimized by all four algorithms for New England and 16 Generator 68 Bus systems.

Table 5.12 PSS parameters calculated by GA & PSO (New England)

Gen. No.	GA			PSO		
	T1	T3	Kstab	T1	T3	Kstab
1	0.091975826	0.077530934	7.698208262	0.0204457	0.0200001	7.8615205
2	0.781606472	0.779498237	14.71733479	0.9290901	1.1464788	10.415079
3	1.807653684	0.301201774	7.048318609	1.2076554	1.038699	8.5027975
4	1.247418752	1.961125095	14.93575586	1.1933833	1.9999894	5.0110313
5	1.034091443	0.925408678	14.296286	1.144322	1.099436	13.74749
6	1.924550378	0.512862713	13.99524447	1.8365203	0.4902554	7.8381868
7	1.31504651	0.7904365	6.5	1.126319	0.7679441	5.9898128
8	1.244829248	1.065748866	13.99958847	1.2443777	1.0620832	7.79468
9	1.053273965	0.226923141	12.0114335	0.8918224	0.0211454	12.329652
10	0.233139595	0.385510174	14.46058036	0.0210033	0.3768268	8.0103207

Table 5.13 PSS parameters calculated by GSA & CSA (New England)

Gen. No.	GSA			CSA		
	T1	T3	Kstab	T1	T3	Kstab
1	1.0339548	0.3367701	9.0065945	0.0200001	0.02	14.191026
2	0.8426066	0.780066	9.5913447	0.477801	0.7304389	14.131649
3	1.6023151	0.4233835	8.2551014	1.8938761	0.0200004	15
4	1.0983189	1.9975143	9.9022499	1.0531732	2	5.0000003
5	0.8300998	1.1107345	7.6236189	1.1741949	1.1286531	14.23879
6	1.2758715	0.5155985	12.627158	1.8690004	0.4838934	14.176164
7	1.1814902	0.760658	9.809671	1.1343124	0.7843223	13.884469
8	1.3019967	0.9694291	9.3419996	1.2202922	0.9631269	14.155749
9	1.0175367	0.3588955	9.7413422	0.9261673	0.0200003	5.0000308
10	0.5196331	0.3995118	9.6750936	0.02	0.02	14.192062

Table 5.14 PSS parameters calculated by GA & PSO for 16 Generator 68 Bus System

Gen. No.	GA			PSO		
	T1	T3	Kstab	T1	T3	Kstab
1	0.657555907	0.396990575	7.900081203	0.0202138	0.0207645	8.1588827
2	0.747063449	0.614925634	7.47865455	0.7147192	1.0798388	6.4243441
3	1.892231648	0.602113367	8.183116995	1.7497314	0.3080448	7.3567431
4	1.172235406	1.990799541	5.106932714	1.513601	1.9997043	10.834574
5	1.238828171	1.070112991	14.21427592	1.2287134	1.1643143	7.9004653
6	1.912318781	0.475926088	13.16648647	1.5315668	0.4788047	7.7116331
7	1.267690477	0.809720412	13.83587609	1.3072435	0.8627624	12.570019
8	1.237158182	1.634812542	14.04459647	0.7219181	1.3727827	10.745454
9	0.947720499	0.276204038	12.25248642	1.0200399	1.3979964	7.2467549
10	1.952179609	0.536207965	12.42926266	1.6852046	0.955324	9.9278552
11	0.778347915	0.88588865	13.28056814	1.7122473	1.2129449	11.576263
12	1.554770328	1.567119646	8.579581833	1.1048755	1.9361948	11.458888
13	0.547648597	0.765576923	7.181107461	1.6062268	1.7681798	10.807105
14	0.056333548	1.165018307	12.492914	1.170335	0.501922	9.8239076
15	0.917624931	0.662974301	5.997030891	0.6699902	1.5160082	10.27428
16	0.816325378	1.965683477	10.63303662	1.5582112	1.9940662	11.612648

Table 5.15 PSS parameters calculated by GSA & CSA for 16 Generator 68 Bus System

Gen. No.	GSA			CSA		
	T1	T3	Kstab	T1	T3	Kstab
1	0.5761144	0.6868397	8.8893444	0.02	0.02	14.162005
2	1.0040147	1.0922598	8.8564325	0.4833417	0.7336872	13.854139
3	1.553172	0.705796	8.4198544	1.8731639	0.044242	14.98248
4	0.7178155	1.9988135	11.933378	1.0629392	1.9999806	5.0000014
5	1.1357927	1.1034039	7.4015874	1.17005	1.1305937	7.8003839
6	1.3410825	0.5449176	8.3093361	1.8808844	0.4867386	14.148613
7	1.2153667	0.8037862	9.4726447	1.1413483	0.779601	8.0017798
8	1.2789071	1.0166037	7.1682723	1.2116089	0.9526336	14.097851
9	1.008402	0.524603	9.2709313	0.9265913	0.0228458	15
10	0.7923703	0.3827618	9.649176	0.0200342	0.0200518	7.8449226
11	0.7599955	1.0494624	9.2139103	0.4927065	0.7269397	7.8367889
12	1.5425287	0.5764812	8.5029167	1.8938903	0.0235917	15
13	0.6800556	1.978894	10.989167	1.0506565	1.9999901	10.998535
14	1.205347	1.0362071	9.1166969	1.1748076	1.1350684	7.8550376
15	1.2962942	0.4547598	8.6934068	1.873185	0.4851215	14.190936
16	0.9447213	0.7436265	10.837007	1.1282808	0.7833022	7.947788

Convergence Characteristics

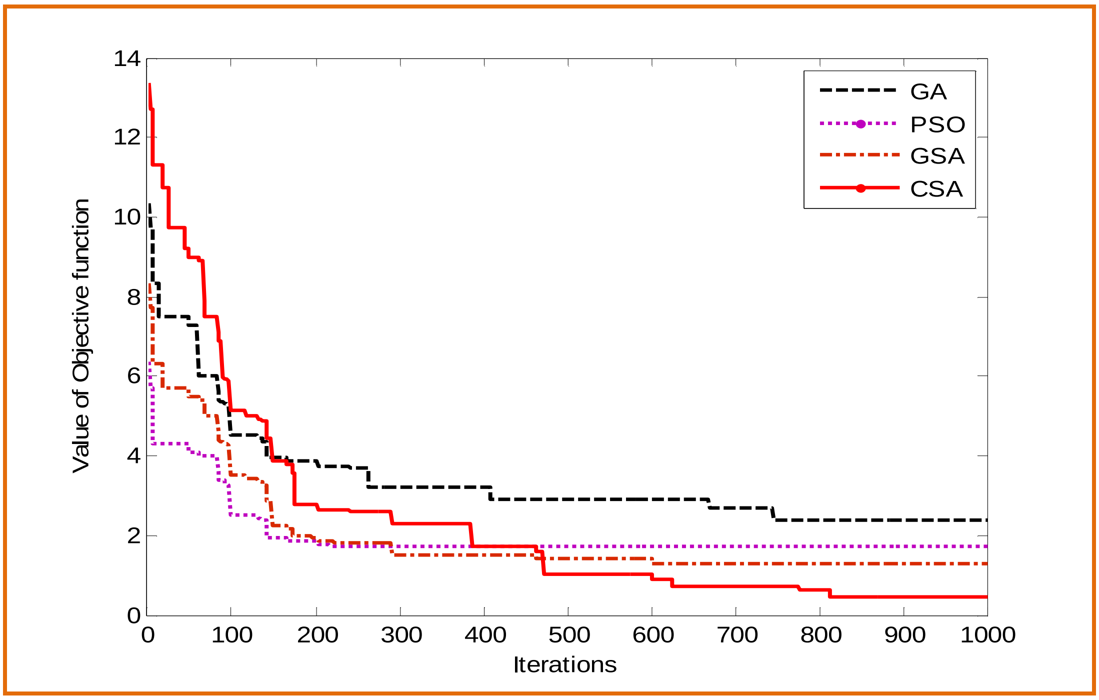

Fig.5.27: Convergence characteristics of all four algorithms for 16 generators 68 bus system.

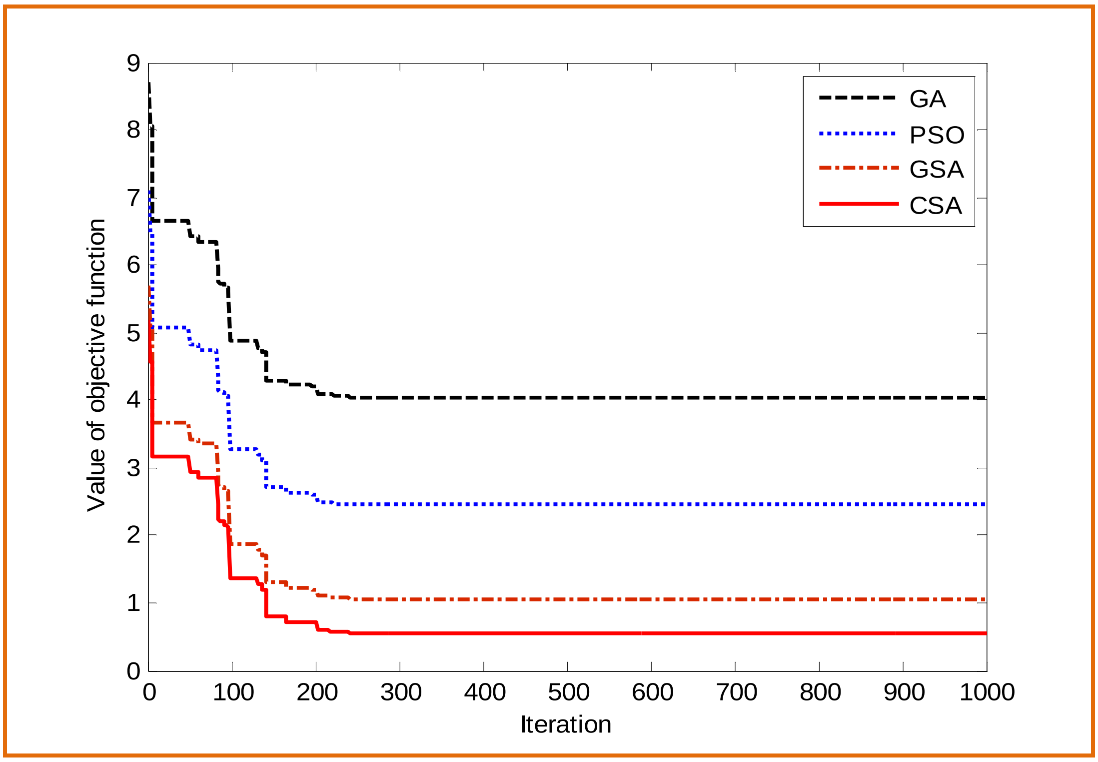

Fig.5.28: Convergence characteristics of all four algorithms for 10 generators 39 bus system.

Fig. 5.27 shows the convergence characteristics of GA, PSO, GSA and CSA for 16 generator 68 bus systems. It is observed that GA presented a poor design, it is also validates from the convergence characteristics that GA is not only very slow but also converge prematurely. For present a meaningful analysis, population size and maximum iteration is kept constant for all optimization processes. Initial population size is kept 100 and maximum iteration count is kept 1000. Relative performance of PSO and GSA can also be judged value of objective function. Value of objective function obtained in case of GSA is less than PSO. CSA converges in least time and the value of objective function is lowest as compared with other algorithms. Fig. 5.28 shows the convergence characteristics of all four algorithms for New England system. Value of objective function for GA is 4.4096, for PSO 2.4497, for GSA 1.0496 and for CSA it is minimum 0.5496. The same can be observed from the convergence characteristics for New England system.

Table 5.16 Comparison of algorithms on the basis of time elapsed

Algorithm	Time elapsed in optimization process (s)	
	New England	16 Generator 68 Bus System
GA	156.43	213.76
PSO	143.78	195.68
GSA	134.67	171.24
CSA	112.09	154.45

It is observed from Table 5.16 that optimization process required longer time when it is addressed with GA, however the faster and effective convergence is obtained with the CSA. Noteworthy observation can be derived from the Table 5.16 that, when the no. of variables are increased in optimization process with the time elapsed is also increased. CSA algorithm shows efficacy to deal with complex optimization process in less time.

5.8 SUMMARY

PSS tuning is an important aspect for achieving small signal stability. A very well tuned PSS can mitigate the small signal oscillation. This chapter is an effort to present application of evolutionary algorithms for designing PSS for two multimachine networks. Multimachine networks are prone to inter area oscillations. The geographical constraints and complexity of these networks are major parameters for carrying out studies of small signals. In chapter 4, it is observed that, there is a high probability to be trapped in local minima while, solving PSS parameter estimation by gradient search based schemes. This fact advocates the acute need of solving above said problem with multi point search based algorithms.

It is also observed from Chapter 3 that only proper tuned PSS will serve adequate damping in the network. PSS tuning problem is carried out in two standard IEEE test networks. Speed deviation based objective function is employed for solving the PSS parameter estimation problem. The convergence related issues of eigenvalue based objective function were described in detail by S.K.Wang [82].

Evolutionary based algorithms are metaphoric mimicry of nature in the form of mathematical frame work. These algorithms are not only fast and efficient but also provide quality solutions. This chapter presents a momentous comparison of all four evolutionary based algorithms. Following conclusions are drawn from this chapter:

1. CSA is found most efficient and fast for PSS parameter estimation process for both multimachine networks. On the basis of standard deviations obtained, by running 100 trials of optimization processes, it can be concluded that CSA provides better solution quality than GA, PSO and GSA.

2. GA is very slow i.e. time elapsed for optimization process is very high. GA shows premature convergence in 10 generators 39 bus system as the value of objective function obtained by GA is much higher than others.

3. Success rate of GSA and PSO lies in a close range for these optimization processes. Not much difference is observed in terms of time elapsed in optimization process and standard deviations of the objective function.

4. Significant amount of reduction in standard deviation is observed when the optimization processes are run by CSA. It ensures the best solution quality through optimization process.

5. Non linear simulations under different operating conditions, topological changes and different perturbations validate the efficacy of the evolutionary design application in PSS parameter estimation.

6. In damping studies, designer has two aims 1. Robust design 2. Fast response. A meaningful analysis of curves is attached with the speed deviation curve which indicates not only the overshoot but also the settling time. Different hard operating conditions validate robustness of the design.

Chapter 6
Conclusion

The objective of this chapter is to abridge main contributions and findings on the work carried out in this thesis and also suggest some scope for future research work in this area. The focus of this thesis is to carry out small signal stability studies on multi machine networks.

Chapter I introduces the problem and acted as prelude to explore new dimensions in stability studies.

Chapter II is an effort to exhibit a state of art literature review on the methods, procedures and protocols of outfitting Power System stabilizer (PSS) on multi machine system. The chronological development in PSS design problem is presented in this section. To find different dimensions, the literature review is not only scant to few optimization processes but also it covers various classical algorithms of optimal control and methodology based on adaptive control. Trajectory sensitivity approaches, evolutionary algorithms based designs and location finding methods are major fulcrum of this review. Literature review is aggregated and presented in a chronological manner so that each and every aspect of the small signal stability can be touched in an efficient manner. Based on the extensive literature review the research objectives are formed and the direction of the research work is aggregated towards achieving these research objectives.

Chapter III is a proposal of a set of new location identification indexes based on statistical attributes. Eigenvalue and overshoot sensitivity indices are calculated and the comparison of the same was done with the conventional indice Sensitivity of PSS Effect (SPE) [32] and Participation factors (PF) [16]. The statistical attribute in form of standard deviations and mean is given to the real part of the eigenvalue and overshoot of the damping modes to inculcate different operating conditions. The probabilistic distributions of these parameters are a replica of different contingencies and give a more realistic approach to the analysis.

Shortcomings of the existing indices namely PF & SPE are revealed and exhibited through eigenvalue analysis.

Following are the major contribution of this work.

1. A probabilistic opposite approach for identifying effective locations of PSS in multi machine power system is introduced in this chapter. Under different operating conditions of power system, variations of the eigenvalues are described by the normal distribution. Normal distributions of the eigenvalues are defined by the expectations and variance. Sensitivity analysis of the real part of the eigenvalues & overshoots of swing modes with respect to the PSSs gain is presented. Modal analysis is performed to identify the poorly damped modes and effect on the mode's behavior is judged by outfitting PSSs at different locations as suggested by proposed index. The results are compared with the residue and participation factor methods.

2. It is based on the probabilistic distribution of eigenvalues & overshoots. This distribution is expressed by its expectation and variance under the assumption of normal distribution. PSSs improve both expectations and variances for all concerned eigenvalues.

3. The proposed method is more realistic as it takes load variations and nodal voltage injections as important parameters for probabilistic distribution. Conventional methods are more deterministic.

4. Results obtained from proposed indexes are compared with conventional indexes SPE [32] and PF [16] to ensure the effectiveness of the proposed method.

5. Variation in the real part of the eigen value is observed with different stabilizer gain, from this analysis it is concluded that the indexes are able to locate the perfect candidate locations in multimachine power system however, if PSS is placed on the location suggested by the index and it is not tuned properly, than it is as equal as the absence of the same, from this analysis importance of parameter estimation is emerged very strongly.

These indexes are calculated for New England and 16 generator 68 bus large power networks which are prone towards interarea oscillations.

Comparative analysis with AVR gain modulation is presented in effective manner, to show and validate the efficacy of the proposed indexes.

Chapter IV investigates and addresses the problem of parameter estimation through trajectory sensitivity approach. In many problems, which are related with the real operations, the behavior of objective function is unknown. In PSS parameter estimation problem, objective function and PSS parameters are not explicitly interlinked. In such cases prediction of shape and behavior of function is an intimidating task to perform. This chapter unfolds the importance of trajectory sensitivity analysis for exploring the dynamic nature of PSS parameter estimation problem. Usually, it is a complement of non linear simulation. The chapter introduces three schemes to depict the problem related with multimodal objective function. Firstly, the optimization is done by using golden section method and, than sequential and simultaneous approach is applied for estimation of the parameters. Modification of the existing schemes is proposed while altering the optimization sequence in sequential scheme and starting search with different initial search points. A comparative analysis is presented to exhibit complexity of the parameter estimation problem over New England system.

Following are the noteworthy contribution from this work:

1. Trajectory sensitivity approach is a replica of non linear simulation where the parametric influence is observed over the flow of objective function, the importance of this analysis is to determine the shape and behavior of objective function under different parametric influences.

2. PSS parameter estimation is addressed with three schemes initially [83] & [156]-[157].These schemes are based on gradient conjugate descent method, initially the comparison is shown with the classical golden section search method.

3. The jacobian calculated by both schemes gives ample information about the system. The value of jacobian element depicts the sensitivity of the objective function with respect to different parameters of PSS, such as if value of jacobian is higher than it shows that particular variable is more sensitive than others which possess low value .

4. It is concluded that scheme I which is a sequential design paradigm is able to present a substantially good design however other scheme based on simultaneous approach and golden section [156] search don't offer a good design and also badly trapped in local minima, which is the major disadvantage of the line search methods [157].

5. Further both schemes are modified with proper initialization it is concluded that Scheme II with proper initialization shows an overall good response under different contingencies, perturbations, different fault locations and topological changes in the network.

6. An unabated dilemma persist in the sequential optimization that how to decide the sequence of the optimization, surprisingly this problem is not addressed in literature [83]. For modification of the schemes the locations or candidates which has larger value of the jacobian elements are tuned first and sequential tuning scheme is modified.

7. The responses observed in different perturbations suggest the superiority of the scheme II over scheme I and scheme I old [83]. The superiority of the scheme is validating through the calculation of overshoot and settling time of swing curves. A weighted combination of overshoot and settling time is formed to create a figure of demerit which is low in the case of scheme I.

Surprisingly in literature less work is reported to predict and model the eigenvalue objective functions over PSS parameters.

Chapter 5 presents application of four evolutionary based search methods for PSS parameter estimation problem. These algorithms are namely Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Gravitational Search Algorithm (GSA) and Cuckoo Search Algorithm (CSA). A brief description of each method is presented along with the pseudo code to facilitate their implementation. The comparative analysis is done over two test cases which are namely New England power system and 16 generator 68 bus systems. The major parameters of comparative analysis are overshoot, settling time, Figure of Demerit (FOD) and standard deviations and means of objective function. Less work is reported in literature for establishing a meaningful comparison of evolutionary algorithms. This chapter presents a comparison of evolutionary algorithms based on their convergence characteristics.

To examine the health of algorithms, a decisive evaluation is carried out by running the optimization process for 100 trials. Following are the major conclusions drawn from this chapter:

1. Application of algorithms in PSS design is presented in this work. The proposed design tested over two standard IEEE test systems under various operating system conditions.

2. Standard deviations in objective function after 100 trials is calculated for both test systems by all the algorithms, it can be concluded that the values of standard deviations are low when the system is addressed with CSA. High values of standard deviations depict bad health and lack of search efficiency of the algorithms.

3. Best values are those values which are appearing as a result in the process, multiple times. Success rate of the algorithm is defined as how many times the value of objective function is going equal to or less than the best value.

MAJOR CONTRIBUTIONS

1. The accuracy and consistency of existing PSS location indices have been evaluated on standard IEEE test systems.

2. Simple and computationally efficient PSS location identification indices based on probabilistic distribution have been proposed to find effective locations in standard IEEE test systems.

3. Two trajectory sensitivity based schemes with a new modified scheme is presented. Modification is proposed for existing sequential design scheme. Modification is based upon the sequence selection through the gravity of jacobian indice. The proposed schemes are tested on standard IEEE test system under various operating/system conditions.

4. Comparative analysis of application of four Evolutionary based algorithms are presented to obtain a robust design of PSS. The proposed designs are tested over different operating/system conditions.

SCOPE FOR FUTURE SCOPE

The research work reported in this thesis can be an important basis for future research activities related to small signal stability. Based on research carried out in thesis, the future research directions that appear from this thesis are summarized below:

1. The capacity of the device can be explored for its possible applications under smart grid technology. The possibility of use of a PSS device for online adaptive tuning against wide range of operating conditions in power system can be investigated.

2. Chapter 3 proposed two indices based on probabilistic distribution of overshoot and real part of eigenvalue. Sensitivity of these parameters is calculated with respect to PSS gain. This analysis may be extended to derive the relationship between overshoot and real part of the eigenvalues with the time constants of PSS.

3. There is sufficient possibility to overcome shortcoming of impairing synchronizing torque by embedding transient stability excitation control (discontinuous excitation control) in schemes presented in chapter 4, thus the overall stability can be achieved by single PSSs parameter settings.

4. Setting paradigm for the gain of PSS ought to utilize digital computer or information processing system, primarily based on instrumentation has the potential to form the authorization of PSS installation as an awfully easy process within the future.

5. In chapter 4 and 5 Objective function based on speed deviations and eigenvalues real part are used. More objectives can be added with the existing objective function like noise management. Noise in the power system has an adverse effect on stabilizer performance; some stabilizers are vulnerable

towards the noise signals and problems. The work can be extended by including multiple objectives in the PSS parameter estimation problem.

6. The problem of parameter estimation and verdict of the PSS performance under arc furnace, intermittent loads lays in the future scope.

7. Development of new torsional filtering schemes, which ensure sufficient margin of safety while dealing with torsional interactions in multi machine power system.

Appendix A

Matrix Analysis Fundamentals

A.1 EIGEN VALUES AND EIGENVECTORS

The Lyapunov stability 1st method is the fundamental analytical basis for power system small signal stability assessment. It is based on eigen value analysis. The properties of eigen values and eigen vectors for stability study are listed here. A power system or any other dynamic system can be represented by a state variable model after linearization as:

$$\dot{x} = Ax + Bu$$
$$y = Cx + Du$$

Where A is the state matrix, x is vector of state variables, u is vector of control variables, and y is vector of output variables. The process of finding the state matrix's eigen values corresponds to finding nontrivial solutions of,

$$AV = AV \Leftrightarrow Av_i = \lambda_i v_i$$

Where, if A is $n \times n$ matrix, V is a $n \times n$ matrix, whose columns are Av_j, $j = 1, \ldots, n,$ and $\Lambda = diag\{\lambda_i\}$ is a $n \times n$ diagonal matrix. Λ and V satisfying the equation are vector of eigen values and matrix of *right eigenvectors* of A respectively. It can be solved by,

$$\mathbf{det}(A - \Lambda I) = 0$$

Where Λ is the vector of eigen values of A. The *left eigenvectors* can be calculated by solving,

$$W\ A = \Lambda A \Leftrightarrow w_i^T A = \lambda_i w_i^T$$

Where w_i are the i^{th} *left eigenvectors* of A corresponding to the i^{th} eigen value λ_i. Note that W^T is a matrix with *left eigenvectors* as its rows, and V is the matrix with *right eigenvectors* as its columns.

The left and right eigenvectors are orthogonal and as used in the techniques, are normalized, i.e. they satisfy,

$$w_i^T v_j = \begin{cases} 0, \; if \quad i \neq j \\ 1, \; if \quad i = j \end{cases}$$

A.2 PARTICIPATION FACTOR

The participation factors are defined using the information provided by the right and left eigenvalues,

$$p_{ij} = w_{ji}^T v_{ij}$$

The participation factor p_{ij} represents the net participation of the i^{th} state in the j^{th} mode. As followed from the orthogonality property of the right and left eigenvectors, the sum of the participation factors for one state is one.

Appendix B

IEEE 39-bus Test System

Table B.1: Bus data

Bus No.	Bus Type*	Voltage	Angle	Generator		Load	
				Pg	Qg	Pd	Qd
1	3	1.048	-9.43	0	0	0	0
2	3	1.0505	-6.89	0	0	0	0
3	3	1.0341	-9.73	0	0	3.22	0.024
4	3	1.0116	-10.53	0	0	5	1.84
5	3	1.0165	-9.38	0	0	0	0
6	3	1.0172	-8.68	0	0	0	0
7	3	1.0067	-10.84	0	0	2.338	8.4
8	3	1.0057	-11.34	0	0	5.22	1.76
9	3	1.0322	-11.15	0	0	0	0
10	3	1.0235	-6.31	0	0	0	0
11	3	1.0201	-7.12	0	0	0	0
12	3	1.0072	-7.14	0	0	0.085	0.88
13	3	1.0207	-7.02	0	0	0	0
14	3	1.0181	-8.66	0	0	0	0
15	3	1.0194	-9.06	0	0	3.2	1.53
16	3	1.0346	-7.66	0	0	3.294	3.23
17	3	1.0365	-8.65	0	0	0	0
18	3	1.0343	-9.49	0	0	1.58	0.3
19	3	1.0509	-3.04	0	0	0	0
20	3	0.9914	-4.45	0	0	6.8	1.03
21	3	1.0337	-5.26	0	0	2.74	1.15
22	3	1.0509	-0.82	0	0	0	0
23	3	1.0459	-1.02	0	0	2.475	0.846
24	3	1.0399	-7.54	0	0	3.086	-0.922
25	3	1.0587	-5.51	0	0	2.24	0.472
26	3	1.0536	-6.77	0	0	1.39	0.17
27	3	1.0399	-8.78	0	0	2.81	0.755
28	3	1.0509	-3.27	0	0	2.06	0.276
29	2	1.0505	-0.51	0	1	2.835	1.269
30	2	1.0475	-4.47	2.5	1.3621	0	0
31	2	1.04	0	5.7293	1.7036	0.092	0.046
32	2	0.9831	1.63	6.5	1.759	0	0
33	2	0.9972	2.18	6.32	1.0335	0	0
34	2	1.0123	0.74	5.08	1.64	0	0
35	2	1.0493	4.14	6.5	2.0884	0	0
36	2	1.0635	6.83	5.6	0.9688	0	0
37	2	1.0278	1.26	5.4	-0.0444	0	0
38	2	1.0265	6.55	8.3	0.1939	0	0
39	1	1.03	-10.96	10	0.6846	11.04	2.5

*Bus type: (1) Slack Bus, (2) Generator bus, (3) Load bus

All Values shown are in per unit (pu) at 60 Hz on a 100 MVA base.

Table B.2: Line data (in pu)

From bus	To Bus	Line Impedance		line charging (p.u.)	Tap Ratio
		Resistance (p.u.)	Reactance (p.u.)		
1	2	0.0035	0.0411	0.6987	0
1	39	0.001	0.025	0.75	0
2	3	0.0013	0.0151	0.2572	0
2	25	0.007	0.0086	0.146	0
2	30	0	0.0181	0	1.025
3	4	0.0013	0.0213	0.2214	0
3	18	0.0011	0.0133	0.2138	0
4	5	0.0008	0.0128	0.1342	0
4	14	0.0008	0.0129	0.1382	0
5	8	0.0008	0.0112	0.1476	0
6	5	0.0002	0.0026	0.0434	0
6	7	0.0006	0.0092	0.113	0
6	11	0.0007	0.0082	0.1389	0
7	8	0.0004	0.0046	0.078	0
8	9	0.0023	0.0363	0.3804	0
9	39	0.001	0.025	1.2	0
10	11	0.0004	0.0043	0.0729	0
10	13	0.0004	0.0043	0.0729	0
10	32	0	0.02	0	1.07
12	11	0.0016	0.0435	0	1.006
12	13	0.0016	0.0435	0	1.006
13	14	0.0009	0.0101	0.1723	0
14	15	0.0018	0.0217	0.366	0
15	16	0.0009	0.0094	0.171	0
16	17	0.0007	0.0089	0.1342	0
16	19	0.0016	0.0195	0.304	0
16	21	0.0008	0.0135	0.2548	0
16	24	0.0003	0.0059	0.068	0
17	18	0.0007	0.0082	0.1319	0
17	27	0.0013	0.0173	0.3216	0
19	33	0.0007	0.0142	0	1.07
19	20	0.0007	0.0138	0	1.06
20	34	0.0009	0.018	0	1.009
21	22	0.0008	0.014	0.2565	0
22	23	0.0006	0.0096	0.1846	0
22	35	0	0.0143	0	1.025
23	24	0.0022	0.035	0.361	0
23	36	0.0005	0.0272	0	1
25	26	0.0032	0.0323	0.513	0
25	37	0.0006	0.0232	0	1.025
26	27	0.0014	0.0147	0.2396	0
26	28	0.0043	0.0474	0.7802	0
26	29	0.0057	0.0625	1.029	0
28	29	0.0014	0.0151	0.249	0
29	38	0.0008	0.0156	0	1.025
31	6	0	0.025	0	1

Table B.3: Generator data (in pu)

Bus No.	Base MVA	Leakage reactance	Resistance	Xd	Xd'	Xd"	T'do	Xq	Xq'	Xq"	T'qo	H
30	1000	0.125	0.0014	1	0.31	0	10.2	0.69	0.31	0	1.5	4.2
31	1000	0.35	0.027	2.95	0.697	0	6.56	2.82	0.697	0	1.5	3.03
32	1000	0.304	0.00386	2.495	0.531	0	5.7	2.37	0.531	0	1.5	3.58
33	1000	0.295	0.00222	2.62	0.436	0	5.69	2.58	0.436	0	1.5	2.86
34	1000	0.54	0.0014	6.7	1.32	0	5.4	6.2	1.32	0	0.44	2.6
35	1000	0.224	0.0615	2.54	0.5	0	7.3	2.41	0.5	0	0.4	3.48
36	1000	0.322	0.00268	2.95	0.49	0	5.66	2.92	0.49	0	1.5	2.64
37	1000	0.28	0.00686	2.9	0.57	0	6.7	2.8	0.57	0	0.41	2.43
38	1000	0.298	0.003	2.106	0.57	0	4.79	2.05	0.57	0	1.96	3.45
39	1000	0.03	0.001	0.2	0.06	0	7	0.19	0.06	0	0.7	50

Appendix C

IEEE 68-bus Test System

Table C.1: Bus data

Bus No.	Bus Type	Voltage	Angle	Generator		Load	
				Pg	Qg	Pd	Qd
1	3	1	0	0	0	2.527	1.1856
2	3	1	0	0	0	0	0
3	3	1	0	0	0	3.22	0.02
4	3	1	0	0	0	5	1.84
5	3	1	0	0	0	0	0
6	3	1	0	0	0	0	0
7	3	1	0	0	0	2.34	0.84
8	3	1	0	0	0	5.22	1.77
9	3	1	0	0	0	1.04	1.25
10	3	1	0	0	0	0	0
11	3	1	0	0	0	0	0
12	3	1	0	0	0	0.09	0.88
13	3	1	0	0	0	0	0
14	3	1	0	0	0	0	0
15	3	1	0	0	0	3.2	1.53
16	3	1	0	0	0	3.29	0.32
17	3	1	0	0	0	0	0
18	3	1	0	0	0	1.58	0.3
19	3	1	0	0	0	0	0
20	3	1	0	0	0	6.8	1.03
21	3	1	0	0	0	2.74	1.15
22	3	1	0	0	0	0	0
23	3	1	0	0	0	2.48	0.85
24	3	1	0	0	0	3.09	-0.92
25	3	1	0	0	0	2.24	0.47
26	3	1	0	0	0	1.39	0.17
27	3	1	0	0	0	2.81	0.76
28	3	1	0	0	0	2.06	0.28
29	3	1	0	0	0	2.84	0.27
30	3	1	0	0	0	0	0
31	3	1	0	0	0	0	0
32	3	1	0	0	0	0	0
33	3	1	0	0	0	1.12	0
34	3	1	0	0	0	0	0
35	3	1	0	0	0	0	0
36	3	1	0	0	0	1.02	-0.1946
37	3	1	0	0	0	60	3
38	3	1	0	0	0	0	0
39	3	1	0	0	0	2.67	0.126
40	3	1	0	0	0	0.6563	0.2353
41	3	1	0	0	0	10	2.5
42	3	1	0	0	0	11.5	2.5
43	3	1	0	0	0	0	0
44	3	1	0	0	0	2.6755	0.0484

Bus data (Continued...)							
45	3	1	0	0	0	2.08	0.21
46	3	1	0	0	0	1.507	0.285
47	3	1	0	0	0	2.0312	0.3259
48	3	1	0	0	0	2.412	0.022
49	3	1	0	0	0	1.64	0.29
50	3	1	0	0	0	1	-1.47
51	3	1	0	0	0	3.37	-1.22
52	3	1	0	0	0	24.7	1.23
53	2	1	0	2.5	0	0	0
54	2	1	0	5.45	0	0	0
55	2	1	0	6.5	0	0	0
56	2	1	0	6.32	0	0	0
57	2	1	0	5.052	0	0	0
58	2	1	0	7	0	0	0
59	2	1	0	5.6	0	0	0
60	2	1	0	5.4	0	0	0
61	2	1	0	8	0	0	0
62	2	1	0	5	0	0	0
63	2	1	0	10	0	0	0
64	2	1	0	13.5	0	0	0
65	1	1	0	35.91	0	0	0
66	2	1	0	17.85	0	0	0
67	2	1	0	10	0	0	0

Table C.2: Line data

From bus	To Bus	Line Impedance		line charging (p.u.)	Tap Ratio
		Resistance (p.u.)	Reactance (p.u.)		
1	2	0.0035	0.0411	0.6987	0
1	30	0.0008	0.0074	0.48	0
2	3	0.0013	0.0151	0.2572	0
2	25	0.007	0.0086	0.146	0
2	53	0	0.0181	0	1.025
3	4	0.0013	0.0213	0.2214	0
3	18	0.0011	0.0133	0.2138	0
4	5	0.0008	0.0128	0.1342	0
4	14	0.0008	0.0129	0.1382	0
5	6	0.0002	0.0026	0.0434	0
5	8	0.0008	0.0112	0.1476	0
6	7	0.0006	0.0092	0.113	0
6	11	0.0007	0.0082	0.1389	0
6	54	0	0.025	0	1.07
7	8	0.0004	0.0046	0.078	0
8	9	0.0023	0.0363	0.3804	0
9	30	0.0019	0.0183	0.29	0
10	11	0.0004	0.0043	0.0729	0
10	13	0.0004	0.0043	0.0729	0
10	55	0	0.02	0	1.07
12	11	0.0016	0.0435	0	1.06
12	13	0.0016	0.0435	0	1.06
13	14	0.0009	0.0101	0.1723	0
14	15	0.0018	0.0217	0.366	0
15	16	0.0009	0.0094	0.171	0
16	17	0.0007	0.0089	0.1342	0
16	19	0.0016	0.0195	0.304	0
16	21	0.0008	0.0135	0.2548	0
16	24	0.0003	0.0059	0.068	0
17	18	0.0007	0.0082	0.1319	0
17	27	0.0013	0.0173	0.3216	0
19	20	0.0007	0.0138	0	1.06
19	56	0.0007	0.0142	0	1.07
20	57	0.0009	0.018	0	1.009
21	22	0.0008	0.014	0.2565	0
22	23	0.0006	0.0096	0.1846	0
22	58	0	0.0143	0	1.025
23	24	0.0022	0.035	0.361	0
23	59	0.0005	0.0272	0	0
25	26	0.0032	0.0323	0.531	0
25	60	0.0006	0.0232	0	1.025
26	27	0.0014	0.0147	0.2396	0
26	28	0.0043	0.0474	0.7802	0
26	29	0.0057	0.0625	1.029	0
28	29	0.0014	0.0151	0.249	0
29	61	0.0008	0.0156	0	1.025
9	30	0.0019	0.0183	0.29	0
9	36	0.0022	0.0196	0.34	0
9	36	0.0022	0.0196	0.34	0

Line data (Continued...)					
36	37	0.0005	0.0045	0.32	0
34	36	0.0033	0.0111	1.45	0
35	34	0.0001	0.0074	0	0.946
33	34	0.0011	0.0157	0.202	0
32	33	0.0008	0.0099	0.168	0
30	31	0.0013	0.0187	0.333	0
30	32	0.0024	0.0288	0.488	0
1	31	0.0016	0.0163	0.25	0
31	38	0.0011	0.0147	0.247	0
33	38	0.0036	0.0444	0.693	0
38	46	0.0022	0.0284	0.43	0
46	49	0.0018	0.0274	0.27	0
1	47	0.0013	0.0188	1.31	0
47	48	0.0025	0.0268	0.4	0
47	48	0.0025	0.0268	0.4	0
48	40	0.002	0.022	1.28	0
35	45	0.0007	0.0175	1.39	0
37	43	0.0005	0.0276	0	0
43	44	0.0001	0.0011	0	0
44	45	0.0025	0.073	0	0
39	44	0	0.0411	0	0
39	45	0	0.0839	0	0
45	51	0.0004	0.0105	0.72	0
50	52	0.0012	0.0288	2.06	0
50	51	0.0009	0.0221	1.62	0
49	52	0.0076	0.1141	1.16	0
52	42	0.004	0.06	2.25	0
42	41	0.004	0.06	2.25	0
41	40	0.006	0.084	3.15	0
31	62	0	0.026	0	1.04
32	63	0	0.013	0	1.04
36	64	0	0.0075	0	1.04
37	65	0	0.0033	0	1.04
41	66	0	0.0015	0	1
42	67	0	0.0015	0	1
52	68	0	0.003	0	1
1	27	0.032	0.32	0.41	1

Table C.3: Generator data (in pu)

Bus No.	Base MVA	Leakage reactance	Resistance	Xd	Xd'	Xd"	T'do	T"do	Xq	Xq'	Xq"	T'qo	T"qo	H
53	300	0.003	0	0.969	0.248	0.147	12.6	0.045	0.6	0.25	0	0.035	0	3.4
54	800	0.035	0	1.8	0.42529	0.30508	6.56	0.05	1.7207	0.3661	0.30508	1.5	0.035	4.9494
55	800	0.0304	0	1.8	0.38309	0.32465	5.7	0.05	1.7098	0.36072	0.32465	1.5	0.035	4.9623
56	800	0.0295	0	1.8	0.29954	0.24046	5.69	0.05	1.7725	0.27481	0.24046	1.5	0.035	4.1629
57	700	0.027	0	1.8	0.36	0.27273	5.4	0.05	1.6909	0.32727	0.27273	0.44	0.035	4.7667
58	900	0.0224	0	1.8	0.35433	0.28346	7.3	0.05	1.7079	0.3189	0.28346	0.4	0.035	4.9107
59	800	0.0322	0	1.8	0.29898	0.24407	5.66	0.05	1.7817	0.27458	0.24407	1.5	0.035	4.3267
60	800	0.028	0	1.8	0.35379	0.27931	6.7	0.05	1.7379	0.31034	0.27931	0.41	0.035	3.915
61	1000	0.0298	0	1.8	0.48718	0.38462	4.79	0.05	1.7521	0.42735	0.38462	1.96	0.035	4.0365
62	1200	0.0199	0	1.8	0.48675	0.42604	9.37	0.05	1.2249	0.47929	0.42604	1.5	0.035	2.9106
63	1600	0.0103	0	1.8	0.25312	0.16875	4.1	0.05	1.7297	0.21094	0.16875	1.5	0.035	2.0053
64	1900	0.022	0	1.8	0.55248	0.44554	7.4	0.05	1.6931	0.49901	0.44554	1.5	0.035	5.1791
65	12000	0.003	0	1.8	0.33446	0.24324	5.9	0.05	1.7392	0.30405	0.24324	1.5	0.035	4.0782
66	10000	0.0017	0	1.8	0.285	0.23	4.1	0.05	1.73	0.25	0.23	1.5	0.035	3
67	10000	0.0017	0	1.8	0.285	0.23	4.1	0.05	1.73	0.25	0.23	1.5	0.035	3
68	11000	0.0041	0	1.8	0.35899	0.27809	7.8	0.05	1.6888	0.30337	0.27809	1.5	0.035	4.45

Appendix D

Excitation System

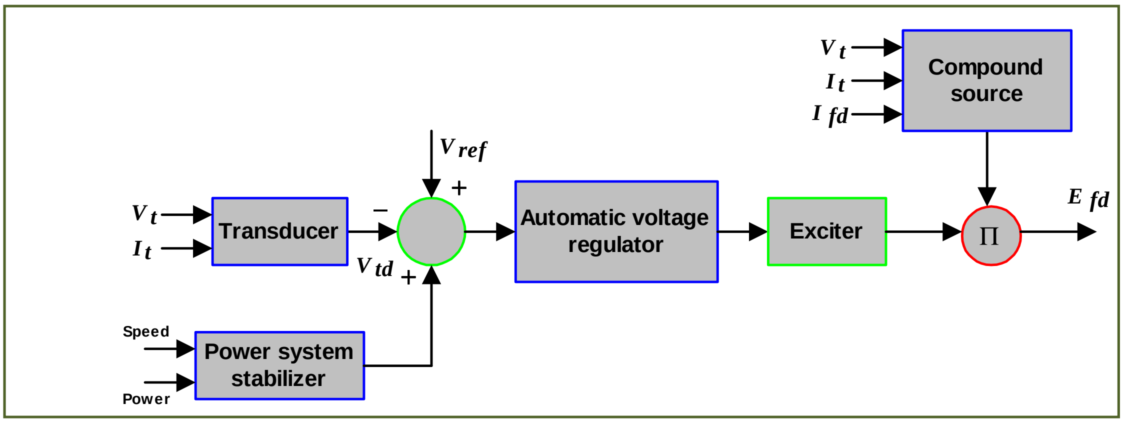

Fig. D.1:System block diagram

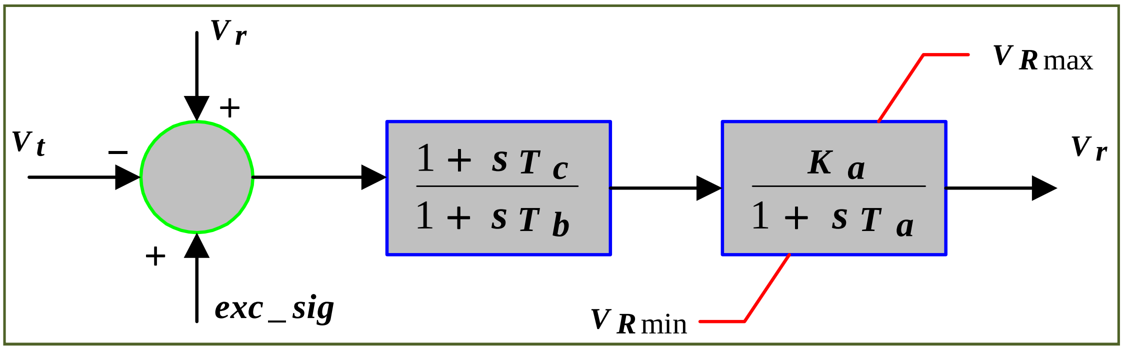

Fig. D.2: Exciter with AVR

Appendix E

Single Line diagram of IEEE bus test system

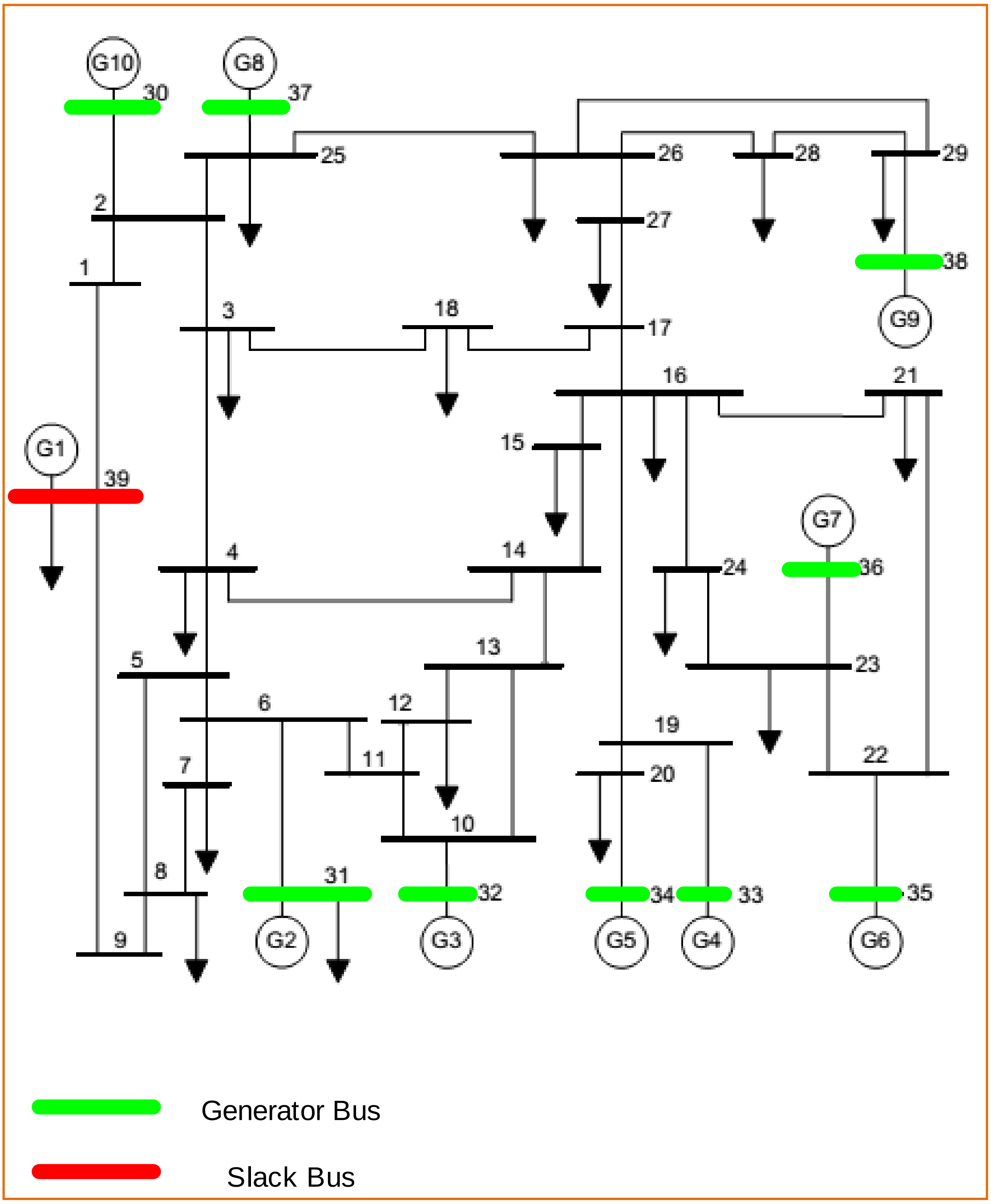

Fig. E.1: Single Line diagram of IEEE 39 bus test system

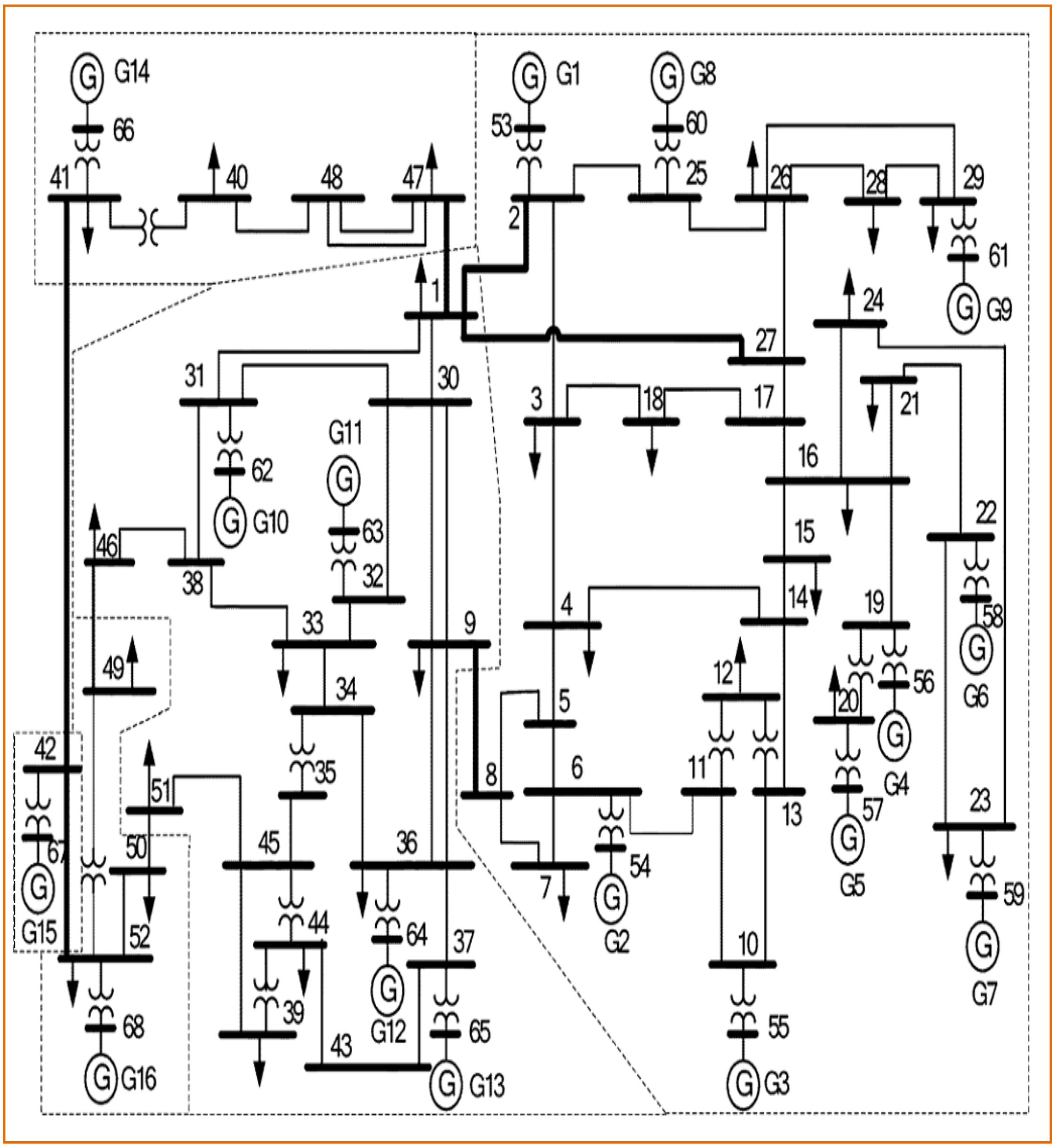

Fig. E.2: Single Line diagram of IEEE 68 bus test system

Appendix F

Parameters of Algorithm

- Maximum no. of Iterations =1000
- Population Size=100
- **Parameter for GA**
  - Crossover =8e-1
  - Mutation Probability =1e-3.
- **Parameter for PSO**
  - Inertia=0.4,
  - C_1 & C_2 =2.
- **Parameter for GSA**
  - α=20;
  - G_0=100;
  - N=50;
- **Parameter for CSA**
  - Discovery rate of alien eggs/solutions pa=0.25;

List of Publications

INTERNATIONAL JOURNAL

1. Akash Saxena and Vikas Gupta, "**A Hybrid Particle Swarm Optimization Approach for Design Power System Stabilizer**" *International Journal of Engineering and Technology* vol. 2, no. 6, pp. 524-528, 2010. Print ISBN-1793-8236, DOI- 10.7763/IJET.2010.V2.175.
2. Akash Saxena, B.P. Soni and Vikas Gupta "**A Comparative Analysis of Population Based Topologies in Power System Stabilizer Design for Multi machine Power System**" Research Journal of Applied Science & Engineering Technology (Accepted for Publication)

INTERNATIONAL CONFERENCES

1. Akash Saxena, Manish Gupta and Vikas Gupta, "**Automatic generation control of two area interconnected power system using Genetic algorithm**" IEEE International Conference on Computational Intelligence & Computing Research (ICCIC), 2012 ,Print ISBN- 978-1-4673-1342-1, DOI- 10.1109/ ICCIC.2012.6510170.
2. Akash Saxena, B.P. Soni and Vikas Gupta" **A new Minimax Synthesis approach for PSS design in Multi machine Power System**" IEEE International Conference on Advanced Communication, Control & Computing Technologies (ICACCCT-2014). ISBN-978-1-4799-3914-5.
3. Akash Saxena and Vikas Gupta "**Aspects of Smart Grid in India**" International Conference on Computer and Electrical Engineering, Singapore, 14-15 October 2011.

PAPER (COMMUNICATED)

1. Akash Saxena, B.P. Soni and Vikas Gupta, "**A Robust Design Methodology for Multi Machine Power System Stabilizer by Using Chebyshev Interpolation**" IEEE *transactions on Power System.*
2. Akash Saxena and Vikas Gupta, "**Trajectory Sensitivity approaches for tuning PSS in Multimachine power system**" International Journal of Computer & Electrical Engineering.

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