International Journal on Emerging Technologies **5**(1): 110-116(2014)

ISSN No. (Online) : 2249-3255

Taxonomy of Power System Optimizations Issues With Power Systm Stabilizers: An Overview

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(Received 05 February, 2014 Accepted 15March, 2014)

***ABSTRACT*: This paper presents a survey of literature on the various optimization methods applied to solve the power system problem. A review and a methodology-based classification of most of the publications on the topic are presented. A Power System Stabilizer (PSS) is the most cost effective approach of increase the system positive damping, improve the steady-state stability margin, and suppress the low-frequency oscillation of the power system. A PSS has to perform well under operating point variations. Power System Stabilizers is to enhance the damping of low frequency oscillations in power systems. Low frequency oscillation problems are very difficult to solve because power systems are very large, complex and distributed geographically. Therefore, it is necessary to utilize most efficient optimization methods to take full advantages in simplifying the problem and its implementation. Many successful and powerful optimization methods and algorithms have been employed to solve this problem. These optimization methodologies and techniques are widely diverse and have been the subject of ongoing enhancements over the years. However, Optimization techniques proved to be able to overcome these limits.**

Keywords: Power system Stabilizer, low frequency oscillation, optimization and small-signal stability.

I. INTRODUCTION

Power system dynamic performance is improved by the damping of system oscillations. PSS is widely used in the electric power industry for improve the performance and functions of power systems during normal and abnormal operations. It can increase the system positive damping, improve the steady-state stability margin, and suppress the low-frequency oscillation of the power system [1-6]. Design and application of PSS has been the subject of continuing development for many years. All part of the PSS topic are numerous and various. These are classified as: (a) mathematical modeling and proper signal selection, (b) finding the optimal placement of PSS, (c) coordination between the PSS and the FACTS, (d) the optimal parameters of the controller, and effect of PSS on system stability [7-15].

Electrical power systems are often operated in critical situations that may lead to stability problems in the power grid, and in worst-case blackouts. Large interruptions have historically occurred in many of power systems around the world and this may lead to panic and state of emergency in the society [16]. To reach this goal, an increasing amount of renewable energy sources such as wind farms and smaller hydro plants are implemented in the power grids. The results of this may increase the network stability problems and the grid cannot be loaded close to the limit of maximum transfer capacity. This can in some cases reduce the needs of new power lines and thereby valuable space in the community [17]."Power system stability is the ability of an electrical power system, for given operating conditions, to regain its state of operating equilibrium after being subjected to a physical disturbance, with the system variables bounded, so that the entire system remains intact and the service remains uninterrupted" [18]

For proper operation, this large integrated system requires a stable operating condition. The power system is a dynamic system. It is constantly being subjected to small disturbances, which cause the generators relative angles to change. For the interconnected system to be able to supply the load power demand when the transients caused by disturbance die out, a new acceptable steady state operating condition is reached. That is, the power system must be stable. It is important that these disturbances do not drive the system to an unstable condition. Stability in power systems is commonly referenced as the ability of generating units to maintain synchronous operation [19]. It is useful to classify the modes of instability of power systems. It is common to divide stability into the following types:

Rotor angle stability describes the ability for the synchronous machines to stay synchronized after a disturbance has occurred. This criterion can be uncovered by study of the oscillation in the power system. The rotor angle category can be further divided into small disturbance stability and transient stability.

Transient stability which is the ability to maintain synchronism when the system is subjected to a large disturbance. In the resulting system response, the changes in the dynamic variables are large and the nonlinear behavior of the system is important.

Small Signal Stability which is the ability of the system to maintain stability under small disturbance. Such disturbances occur continuously in the normal operation of a power system due to small variations in load and generation.

The stability of these oscillations is of vital concern, and is a prerequisite for secure system operation. These oscillations can be classified into two classes.

The first is the oscillations associated with a single generator or a single plant that is called “local modes” or “plant modes”. Local modes normally have frequencies in the range of 0.7 to 2 Hz. The characteristics of these oscillations are well understood. They may be studied adequately, and satisfactory solutions to stability problems are developed from a system, which has detailed representation only in the vicinity of the plant. The second is the oscillations associated with groups of generators, or groups of plants. They are called “inter-area modes”. Inter area modes have frequencies in the range of 0.1 to 0.8 Hz. The characteristics of these modes of oscillation, and the factors affecting them, are not fully understood. They are more complex to study, and to control. A detailed representation of the entire interconnected system requires studying inter-area modes [19]. For stability point of view, subsequent analysis has shown that these swings are due to poor damping characteristics caused by modern voltage regulators with comparatively high gain [19, 20].

According to the previous analysis there is a really important need for damping these oscillations. To compensate the unwanted effect of these voltage regulators, additional signals are introduced in the feedback loop of voltage regulators. The additional signals are mostly speed deviation, AC bus frequency or accelerating power [23]. Essentially, they use the power amplification capability of the generators to generate a damping torque in phase with the speed change. This is achieved by injecting a stabilizing signal into the excitation system voltage reference-summing junction. The devices set up to provide these signals through properly chosen transfer function have been called “power system stabilizers” [19, 20, 22].

(A) Structure of PSS

The conventional lead–lag structure is chosen in this study as a Conventional PSS (CPSS). The structure of the CPSS controller model is shown in Fig.1

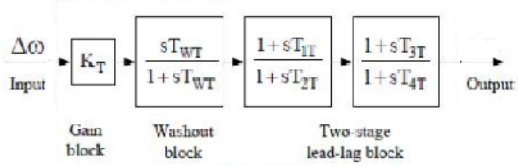

Fig.1. Structure of Power System Stabilizer.

It consists of a gain block, signal wash out block and a two stage lead-lag phase compensation blocks. It consists of a gain block with gain K_T, a signal washout block and two-stage phase compensation block as shown in figure.

The phase compensation block provides the appropriate phase-lead characteristics to compensate for the phase lag between input and the output signals. The signal washout block serves as a high-pass filter, with the time constant T_W high enough to allow signals associated with oscillations in input signal to pass unchanged. The transfer functions of the PSS

$$u_{PSS} = K_T\left(\frac{sT_W}{1+sT_W}\right)\left(\frac{1+sT_1}{1+sT_2}\right)\left(\frac{1+sT_3}{1+sT_4}\right)$$

II. POWER SYSTEM MODELS FOR LOW FREQUENCY OSCILLATION

The power system model for low frequency oscillation studies consists of the machine model, the exciter model and the stabilizer model.

(A) The machine model

Mathematical models of synchronous machines vary from the classical model to the detailed model depending on the degree of detail used. Moreover the synchronous machine can be expressed by the fourth order model .

(B)The exciter model

The basic function of an excitation system is to provide direct current to the Synchronous machine field winding which will contribute in regulating the terminal voltage (V_t). The excitation system model can be represented by a single time constant system ($E_{q'2}$and $E_{d'2}$).

III. POWER SYSTEM OPTIMIZATION

The Power System Optimization (PSO) is advanced security constrained optimal power flow (SCOPF) software that is also a tool for optimal sizing and placement of reactive power resources (reactors, capacitors, and SVCs). The control settings such as generators active power, transformer taps, scheduled voltages of generators are optimized not only for the base case system configuration but also for up to fifty different system configurations. PSO in the SCOPF mode finds an operating point that optimizes a given objective function and satisfies a set of physical and operating constraints for the base network configuration and contingency situations. In the reactive power planning mode of operation, PSO determines a minimum cost reactive power expansion plan in VAR equipment which ensures feasible system operation simultaneously for the normal state (basecase) and under contingency situations.

The PSO utilizes the state-of-the art in optimization techniques to assist engineers to minimize system losses, perform economic dispatch, minimize load shedding, plan reactive power resources, and optimize system voltage profile with minimum control setting movements. The present release of PSO supports the following power system optimization functions:

1. Minimization of Total System Losses: PSO finds the optimum control settings for the generators scheduled voltages, active power generations, transformer taps, SVCs scheduled voltages such that a total system active power loss is minimized. PSO at the same time makes sure that all system voltages are within user defined range, power flows through lines and transformers are within limits, active power generations are within minimum and maximum generators limits, and transformer taps are within their upper and lower bounds.

2. Minimization of Total Generation Cost: (also known as economic dispatch) PSO will allocate active power generations to different generators in the system such that total generation cost is minimized. Again PSO will make sure that all system constraints are met (i.e. system voltages are within user defined range, power flows through lines and transformers are within limits, etc.).

3. Minimization of Controls Movements: PSO finds minimum controls movements (generators scheduled voltages, active power generations, transformer taps, SVCs scheduled voltages) such that all system voltages are within user defined range, power flows through lines and transformers are within limits, active power generations are within minimum and maximum generators limits, and transformer taps are within their upper and lower bounds.

4. Minimization of Load Shedding: PSO will determine the minimum amount of load shedding (including locations) required such that all system constraints are met (i.e. system voltages are within user defined range, power flows through lines and transformers are within limits, etc.)

5. Minimization of Reactive Power Resource Allocation Cost: PSO minimizes the cost of addition of new reactive resources (i.e., capacitors/inductors) such that all system constraints are met. The user can select the locations of reactive power resources or PSO program will identify the most effective sites.

The following optimization functions will be supported in the next release of the PSO (these functions are already implemented and at the present time they are in the V&V stage):

1. Maximization of Active Power Flow Across an Interface: PSO maximizes active power flow across an interface (set of circuits) while at the same time maintaining feasibility in the contingency configurations and basecase (i.e., all system constraints are met). This function is of paramount importance in determination of "Available Transfer Capability" (ATC).

2. Maximization of Loads at a Group of Buses: PSO maximizes the load at a group of buses while maintaining the same load power factor and feasibility in the basecase and contingency configurations. PSO can also determine the optimal direction of load increase. Candidate sites for load increase can be specified individually, by area, or by zone. This objective function can be used in the computation of voltage stability margins (voltage collapse) capability in a given area.

3.Maximization of Active Power Transfer between two Groups of Buses: PSO maximizes the active power transfer between any pair of network buses while insuring system feasibility in the basecase and contingency configurations. This function can also be used to determine the "Available Transfer Capability" (ATC).

4. Minimization of Swing Bus Generation: PSO will re-allocate the power generation at the swing bus(es) to all other generators in the system such that all system constraints are met.

PSO is capable of handling power systems comprising thousands of buses and has been successfully used to optimize the planning and operation of large number of complex power systems.

A variety of optimization methods and techniques have been proposed to solve the problems of power systems optimal operations and planning since the beginning of the last century [24]. Among the earliest optimization techniques applied to the problem were the so-called the base load procedure, the best point loading and the incremental method. A historical survey, which highlights the earliest works in the field, is offered in [24]. At present, several methods and algorithms have been in use to solve power system optimization problems [25,26]. These include mathematical methods, iterative approaches, artificial intelligence tools, and hybrid techniques.

Over the years, different methodologies have been applied. With the development of the mathematical and computational techniques, additional details of the problem have been addressed. In the beginning, only the thermal plants were considered and before long, the hydraulic operational and topological constraints were tackled.

These techniques are principally based on the criterion of local search through the feasible region of solution [25]. Applied optimization methods can be mathematical programming algorithms such as linear and non-linear programming, dynamic programming and interior-point methods .

Among the other methods are the artificial intelligence techniques including neural networks, fuzzy systems and the evolutionary methods such as genetic algorithms and the simulated annealing.

The methods considered in this survey can be classified as follows:

- Lagrangian relaxation and Benders decomposition-based methods
- Mixed-integer programming
- Dynamic programming
- Evolutionary computing methods
- Artificial intelligence methods
- Interior-point methods

These optimization methods can be generally classified into two main groups: deterministic methods and heuristic methods. Deterministic methods include Lagrangian relaxation and Benders decomposition methods, mixed-integer programming, dynamic programming and interior-point methods. Genetic algorithms, particle swarm optimization and other evolutionary methods are heuristic.

IV. TAXONOMY OF PSO WITH PSS

The review efforts geared towards PSS developed based on Optimization techniques, which effectively enhance both small signal stability and transient stability and equally provide superior performances. Various techniques are such as Tabu search (TS), simulated annealing (SA), Ant Colony Optimization (ACO), Harmony search (HS), evolutionary programming (EP), bacteria foraging optimization (BFO), genetic algorithm (GA), particle swarm optimization (PSO) Bee colony, Artificial Bee Colony (ABC), SFLA algorithm, etc have been used. Research showed controllers designed based on a conventional control theory, modern and adaptive control theories, suffer from some limitations. However, Optimization techniques proved to be able to overcome these limits. Hence, more researchers preferred to utilize these approaches for the power systems. There are some classification of optimization method applied for power system stabilizers is as follows:

(A) Robust Design of Multimachine Power System Stabilizers Using Simulated Annealing:

Robust design of multimachine Power System Stabilizers (PSS's) using Simulated Annealing (SA) optimization technique is presented. The proposed approach employs SA to search for optimal parameter settings of a widely used conventional fixed-structure lead-lag PSS (CPSS). The parameters of the proposed simulated annealing based power system stabilizer (SAPSS) are optimized in order to shift the system electromechanical modes at different loading conditions and system configurations simultaneously to the left in the -plane. Incorporation of SA as a derivative-free optimization technique in PSS design significantly reduces the computational burden. One of the main advantages of the proposed approach is its robustness to the initial parameter settings. In addition, the quality of the optimal solution does not rely on the initial guess. The performance of the proposed SAPSS under different disturbances and loading conditions is investigated for two multimachine power systems. The eigenvalue analysis and the nonlinear simulation results show the effectiveness of the proposed SAPSS's to damp out the local as well as the interarea modes and enhance greatly the system stability over a wide range of loading conditions and system configurations.

SA algorithm [27,28] is a derivative-free promising algorithm for handling the combinatorial optimization problems. It has been theoretically proved that SA algorithm converges to the optimal solution [27]. In addition, the SA algorithm is robust *i.e.* the final solution quality does not strongly depend on the choice of the initial solution. Another strong feature of SA algorithm is that a complicated mathematical model is not required and the problem constraints can be easily incorporated [27].

(B) Voltage Profile Improvement Using Unified Power Flow Controller with Artificial Immune System: Voltage profile is one of the concerned issues in power system studies. This is due to the fact that voltage profile decay can be experienced by the system when system is subjected to load increment or disturbances. Unscheduled increment of load variation in a power transmission system has driven the system to be stressful, leading to potential cascading trip on the entire system. Thus, close monitoring of load variation in a power network can help to avoid the system operating close to its maximum capacity. In addressing this phenomenon, special scheme can be implemented such as reactive power compensation; installation of flexible AC transmission system (FACTs) devices and capacitor placement.

Identification of the optimal value of compensating capacitors required proper optimization technique; able to search the optimal solution with less computation time. This presents the voltage profile improvement using unified power flow controller (UPFC) approach based on artificial immune system (AIS). In this study, AIS optimization engine is developed for voltage profile improvement which utilized UPFCs as the control variables embedded into the system's data. Implementation on the IEEE Reliability Test System (RTS); considering several variations in the AIS properties indicated AIS potential in solving voltage control problems. Verification through comparison of results using evolutionary programming utilizing the similar system data indicated that AIS is feasible to solve voltage depreciation problems.

Artificial Immune System (AIS) is a biological immune system which is highly parallel, distributed and adaptive system. In other words, AIS is an adaptive system inspired by theoretical immunology and observed immune functions, principles and models, which are applied to complex problem domains. Some of the scopes of AIS are; fault and anomaly detection, data mining, agent based systems, scheduling, autonomous control, optimization, robotics and security of information systems. In this study, it focuses on cloned selection concept and the affinity maturation (or mutation) process.

AIS involves several operators such as initialization, fitness computation, cloning, mutation, cloned selection and new generation definition. The AIS algorithm is given in the following procedural steps:-

i. Initial population process.

ii. Cloning process. The AIS will produce the same number of clones for each individual.

iii. The affinity maturation procedure which will result a population of matured clones.

iv. Determine the affinity of the matured clones in conjunction with the objective function whether to maximize or minimize.

v. Compare the affinity of the memory population, if converge the optimization is achieved, if diverge the algorithm go back to ii.

(C) Design of AVR and PSS for Power System Stability based on Iteration Particle swarm Optimization

The coordination between the Automatic Voltage Regulator (AVR) and Power System Stabilizers (PSSs) to enhance damping of oscillations over a wide range of system uncertainties so that the power system stability and transfer capability performance can be improved. The coordinated design problem is formulated as an optimization problem which is tackled using Iteration particle Swarm Optimization (IPSO). The parameters of AVR and PSS are optimized using the application of the proposed IPSO techniques to minimize the oscillations in power system during disturbances in a single machine infinite bus system (SMIB). The performance of the proposed IPSO technique in terms of parameter accuracy and computational time is compared with the traditional PSO techniques to validate the results obtained. The results of the time domain simulations and eigenvalue analysis show that the proposed IPSO method provides a better optimization technique as compared to the traditional PSO technique.

Both AVR and PSS controllers are Designed and optimized by minimizing the objective function (J) in order to improve the system response in terms of oscillation and settling time. Despite there are several methods to come up with the improvement of the performance of the control system, such as integral of squared error (ISE), integral of time weighted squared error (ITSE), integral of absolute error (IAE) and integral of time weighted absolute value of error (ITAE), but in this work, the ITAE of the speed deviation ($\Delta\omega$) is used as the fitness function (J). The proposed Iteration Particle Swarm Optimization is applied to solve for the coordinated design problem and to search for the optimal set of AVR and PSS parameters. IPSO method is considered for tuning lead lag type PSS.

The IPSO method is an improvement of PSO technique to enhance the solution quality and computing time of the algorithm. In the algorithm, three best values are used to update the velocity and position of the particles which are *Gbest*, *Pbest* and *Ibest*. The definition and the method to find the *Pbest* and *Gbest* values in the IPSO are similar as traditional PSO where *Pbest* is defined as the best solution that has been achieved by individual particle until the current iteration while the *Gbest* is the best value among all particles in the population. In other word, each particle will have their own *Pbest* value but the *Gbest* is only a single value at any iteration. Meanwhile, the new parameter *Ibest* is defined as the best point of fitness function that has been attained by any particle in the present iteration and causes the improvement in searching process of IPSO.

Most of the steps for the IPSO are similar to the traditional PSO; the slight difference appears during finding the new velocity for updating the new position. With the *Ibest* parameter, the improvement on searching capability and increases on efficiency of the IPSO algorithm in achieving the desired results in power system stabilizers design is attained.

(D) Robust Tuning of Modern Power System Stabilizers Using Bacterial Foraging Algorithm

Excitation system subcommittee introduced a new type of power system stabilizer model, the multiband power system stabilizers (IEEE PSS4B). Although it requires two input signals, like the widely used IEEE PSS2B, the underlying principle of the new IEEE PSS4B makes it sharply different. This method based on Bacterial Foraging Algorithm (BFA) to simultaneously tune these modern power system stabilizers (PSSs) in multimachine power system. Simulation results of multi-machine power system validate the efficiency of this approach. This method is effective for the tuning of multi-controllers in large power systems.

This modern PSS can easily be tuned just like conventional delta-omega PSS, while mitigating two major operational problems which had restricted the application of the old PSS technology utilizing electrical power or terminal frequency, namely the excess VAR modulation during mechanical power reference changes for the first and adverse torsional interactions for the second. The stabilizers designed to damp one particular mode of oscillation can produce adverse effects in the other modes. Thus, the multimodal nature of oscillations and the mutual interaction among generating units should be considered in PSS designs.

Local optimization techniques like gradient descent method [29] failed to provide the optimum PSS parameters. Heuristic techniques such as Genetic Algorithms (GAs) [30], tabu search algorithm [31] and simulated annealing [14] have been applied earlier to PSS design. Studies have revealed that GA has a degraded performance if the function to be optimized is epistatic.

A new evolutionary computation technique, called Bacterial Foraging Algorithm (BFA) [32] has been proposed as a solution to the above mentioned problems and drawbacks. In this scheme, the foraging (methods for locating, handling, and ingesting food) behavior of *E. coli* bacteria present in our intestines is mimicked. They undergo different stages such as chemotaxis, swarming, reproduction, and elimination and dispersal. In the chemotaxis stage, it can have tumble followed by a tumble or a tumble followed by a run. On the other hand, in swarming, each *E. coli* bacterium will signal other via attractants to swarm together. Furthermore, in reproduction the least healthy bacteria die and the other healthiest bacteria each split into two bacteria, which are placed in the same location. Besides, in elimination and dispersal, any one bacterium is eliminated from the total set just by dispersing it to a random location on the optimization domain. A bacterial foraging optimization scheme is used for simultaneously tuning the modern power system stabilizers, PSS2B and PSS4B.

(E) Optimal Design of Fuzzy Based Power System Stabilizer Self Tuned by Robust Search Algorithm

In the interconnected power system network, instability problems are caused mainly by the low frequency oscillations of 0.2 to 2.5 Hz .The supplementary control signal in addition with AVR and high gain excitation systems are provided by means of Power System Stabilizer (PSS). Conventional power system stabilizers provide effective damping only on a particular operating point. But fuzzy based PSS provides good damping for a wide range of operating points. The bottlenecks faced in designing a fuzzy logic controller can be minimized by using appropriate optimization techniques like Genetic Algorithm, Particle Swam Optimization, Ant Colony Optimization etc. The membership functions of FLC are optimized by the new breed optimization technique called Genetic Algorithm. This design methodology is implemented on a Single Machine Infinite Bus (SMIB) system. Simulation results on SMIB show the effectiveness and robustness of the proposed PSS over a wide range of operating conditions and system configurations.

Conventional power system stabilizers are designed based on eigen value analysis which utilizes two basic tuning techniques phase compensation and root locus. Phase compensation is widely used and compensates for the phase lags by providing a damping torque component. Root locus involves shifting of eigen values related to the power system modes of oscillation by shifting the poles and zeros of the stabilizer [33]. CPSS are designed based on linearized theory. But as we know power systems are non-linear and are very complex .So the parameter of the CPSS is ineffective for various operating points. Also there is no interaction between the CPSS stabilizer parameters as time varies. This result in degradation of the performance of the stabilizer. Later a novel approach called Fuzzy Logic has been proposed to design the PSS.

FLPSS is designed in the time domain whereas CPSS is designed in frequency domain. A fuzzy logic power system stabilizer performs well and produces positive results for a wide range of operating conditions. Though fuzzy logic approach enhances the dynamic stability it also has some bottlenecks like generation of membership functions, creation of rules and choice of scaling factors which is done by trial and error method [35]. This made the design procedure a laborious one and thus became a time consuming task. Incorporation of GA in fuzzy logic power system stabilizer design will significantly reduce the time consumed in the design procedure.

On the other hand GA is a search algorithm rooted in the mechanics of natural selection and natural genetics and is used in various power system problems [36]. The main theme of GA is robustness, the balance between efficiency and efficacy necessary for survival in many different environments. GA provides an alternative to traditional optimization techniques by using directed random searches to locate optimal solutions in complex power system problems. Thus the performance of fuzzy logic based power system stabilizer can be significantly enhanced by operating genetic based learning mechanism. This deals with the improved and novel design approach for single machine infinite bus system where the parameters are tuned using this balanced optimization technique. This is also based on the optimization criteria integral of SMSE (Sum of Mean Squared Error).

A GA is an exploratory procedure that is able to locate near optimal solutions to complex problems. It maintains a set of trial solutions often called as individuals and forces them to evolve towards an acceptable solution. Generally GA's are based on two assumptions [34].

(i) An individual's fitness is an accurate measure of its relative ability to solve the problems

(ii) That combining individuals will enable the formation of improved off spring.

V. CONCLUSION

This paper presents a survey of literature on the various optimization methods applied to solve the PSS problems. The PSO algorithm has been proposed to optimally tune the PSS parameters for the improvement of the relative stability and secure operation of power systems. However, Optimization techniques proved to be able to overcome these limits. Hence, more researchers preferred to utilize these approaches for the power systems. In this paper a serious attempt is made to present a comprehensive analysis of optimization techniques for designing PSSs, which were recently proposed by various researchers.

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