A Comprehensive Review of Damping of Low Frequency Oscillations in Power Systems

Soumyadeep Maity, R.Ramya

Abstract— Abstract— The low frequency electromechanical oscillations, with frequency ranging from 0.1-3Hz, are inherent to electric power systems. The low frequency oscillations are related to the small signal stability of the power system and are detrimental to the goals of maximum power transfer and power system stability. Problems due to inadequate damping of such oscillations have been encountered through the history of power systems. This paper presents a comprehensive overview of damping of low frequency oscillations in power systems.

Keywords— Power system stabilizer, Robust, FACTS, optimization, ANN

I. INTRODUCTION

The low frequency oscillations are first detected during 1960-70's. It usually takes a waveform like sine, square etc. and it can incorporate with user defined signals. The oscillations are very low 0.1-3 Hz which are inter-area modes of oscillations which caused system collapse. The link between generators in the same area is very strong and oscillate against generators in the same area. The frequency is known as inter-area modes and the oscillation are inter-area oscillations. The frequency ranging from 0.2-2 Hz known as local modes of oscillations caused by one or more synchronous winging against large power system. In power system the small signal disturbance occurs due to changes in load and bulk transfer of power which causes generator rotor swings in presence of high gain AVR.

There are several blackouts caused by low frequency oscillations are:

- United Kingdom (1980), the frequency of oscillation of about 0.5 Hz.
- Taiwan (1984, 1989, 1990, 1991, 1992), frequency of oscillation around 0.78-1.05 Hz.
- West USA/Canada, System Separation (1996), frequency.
- Scandinavia (1997), frequency of oscillation about 0.5 Hz.
- China Blackout on 6th March (2003), frequency of oscillation around 0.4 Hz.
- US blackout on 14th August (2003), frequency of oscillation about 0.17 Hz.
- Italian Blackout on 28th September (2003), frequency about 0.55 Hz.

The control methods to damp the oscillations are discussed in fig. 1. The oscillations can be damped by PSS and FACTS devices. [1]

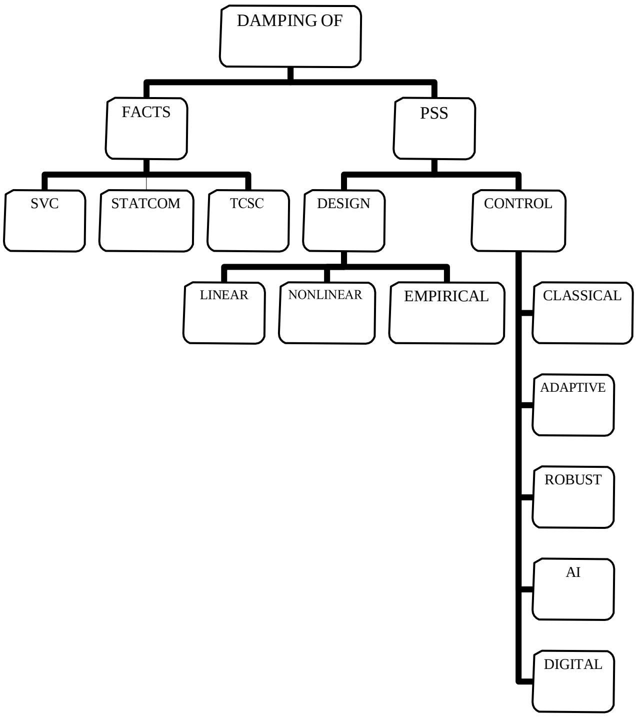

Figure 1: Methods to damp low frequency oscillations

II. FACTS DEVICES

The stable operation of the system done by maintaining the stability of the system. The use of FACTS devices in the system to provide reactive power, current control and voltage control. The effect of FACTS devices on rotor angle stability is analyzed in [2]. Among SVC, TCSC, SSSC the shunt compensator SVC provides a better result among the other devices.

The authors of [3] discusses the damping of inter-area and local modes of oscillations using controllable series capacitor and static var compensators. These are in the closed loop structure matrix in the system.

The design of PSS using TCSC is discussed in [4]. To find the optimal placement of PSS the participation factor technique is used. The optical placement of PSS is determined to the minimum damping ratio. Participation factors decides the optimal location of PSS. three cases are studied separately such individual design of PSS, individual design of TCSC and coordinated design of PSS

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with TCSC. The coordinated design is tuned by genetic algorithm. The modelling of different FACTS devices in multimachine is presented in [5]. In this paper two main FACTS devices SVC and TCSC are modelled in multimachine Differential Algebraic Equation model. This approach is simple and is applicable for larger systems. With this method any type of series, shunt and their combination can be added with the system. After incorporating FACTS controller individually with the combination of DAE model the voltage stability is checked with different loading conditions. The proper location of SVC is identified at bus 5 and TCSC is connected between bus 7 and 5 for a three machine nine bus system.

The authors in [6] defines the damping of oscillations by single FACTS device. The (MUFC) multi terminal unified power flow controller is connected with the Heffron-Phillips model and non-linear dynamic model. By modal analysis the weakly damped nodes are determined. This method is used for multi-mode oscillations connected with FACTS devices with multi control channels.

The control strategies, dynamics, operation of PSS connected with FACTS devices discussed in [7]. The results help to determine the optical placement of the PSS. It is used in power sectors to increase the damping ratios of electromechanical modes and increase the power transfer capability.

The generator swing dynamics for small signal stability is obtained by decoupling of voltage stability from angle stability. The test system of 10 machine and 39 bus is taken to check the accuracy of voltage instability. The effect of addition of Static Var Compensator is also identified. system stability at low gain exciter instability found in one swing modes whereas in swing dynamics more than one swing modes causes instability undergoes H_{opf} bifurcation. [8].

III. POWER SYSTEM STABILIZERS

The PSS came into being during 1950-1960's when the number of generators added to the utility due to large increment in loads. The inter-area mode and torsional mode of oscillations increases further without proper damping is provided. PSS is a cost-effective technology which provides sufficient damping torque to the system. The PSS always produces positive damping while AVR provides negative damping and synchronizing torque to the system

The modern stabilizers used in the market are of combinations of multi-band stabilizers. The multiband stabilizers are used to handle different oscillation frequencies and it has three separate signal bands. The digital stabilizers are produced with excitation systems with complete digital circuitry. The performance of PSS reduces with the number of machines in a system increases.

The PSS design categories divided into three categories:

a) Linear Control Methods
b) Non-Linear Control Methods
c) Empirical control Methods

The conventional PSS performance is limited to wide area operating conditions. The robust PSS came into being for wider area operations and improve in performances. The robust PSS can maintain the stability of the system under large uncertainties. The settling time of the robust PSS is much less than conventional PSS.

PSS control methodologies are:

a) Classical Methods
b) Adaptive and Variable Structure Methods
c) Robust Control Techniques
d) Artificial Intelligence Techniques
e) Digital Control Schemes

IV. CLASSICAL METHODS & RESULTS

The Conventional PSS is a single band PSS which may be analog or digital. It helps to maintain the small signal and transient stability. The conventional PSS has gain, washout filter and lead lag compensator.

The gain decides the amount of damping to the rotor oscillations whereas the washout circuit is used as high pass filter and removes DC offset from input signal. The lead-lag compensator improves an undesirable frequency response in the feedback of the system. [9]

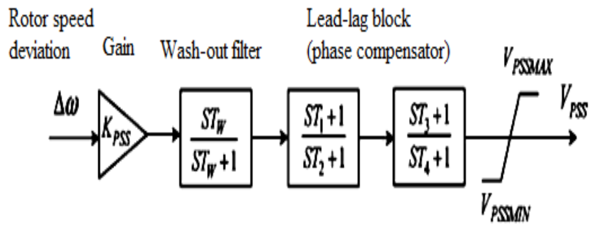

Figure 2: PSS structure

V. ADAPTIVE AND VARIABLE STRUCTURE METHODS

The authors of [10] discusses the design of adaptive fuzzy controller in modelling the generators in deregulated market.

PSS based on heuristic dynamic programming in [11]. It is the combination of dynamic programming and reinforcement learning of non-linear optimal PSS.

VI. ROBUST CONTROL TECHNIQUES

The robust stabilization is made for different operating conditions which comprises the actual design of phase compensation and gain. The time domain simulations provide the durations oscillations lasted [12]. The eigen values of the whole system is calculated to know the state space and to provide the damping to oscillatory nodes [13]. The authors of [14] discusses the robust co-ordination AVR and PSS. The terminal voltage is rectified and the error is fed to the exciter as input. By solving the multimachine case we can determine the peak time, settling time and steady

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state error. The technique of designing of fixed parameter decentralized for interconnections of systems is proposed in [15]

During small signal stability the eigen value analysis is done to gather the information about stability nodes. QR algorithm is used to define eigen values of non-symmetrical matrices. The comparison of QR and BR is compared in [16].

The models of SMIB and multimachine are compared in terms of terminal voltage, rotor angle and rotor speed with comparisons of conventional and robust PSS. The robust control design focus on stability, noise rejection, disturbance rejection and avoiding of actuator separations.

The robust performance is defined by the performance of maintaining the stability by using the uncertainties in the design. The tuning of the controller is developed with different system variations and input signals along with the reduced number of iterations calculated. [17]

The frequency-based stabilizer is dependent on terminal frequency which is derived from terminal current and voltage. Its main advantage is sudden phase shift in transient condition. The improvement of stability under high communication delays is discussed in [18]. The authors of [19], discusses the eigen values of three different power system and the accuracy, convergence and consistency of eigen value calculations and alternative methods are discussed. H∞ loop shaping techniques are introduced to design robust PSS for SMIB designing. The selection of weighting functions is shown for the controller. Various operating parameters are compared with the conventional model in [20].

The WSCC system is used in [21] to focus on rotor angle stability and fault clearing time. After removing the fault, the time taken by the system to regain synchronism is reduced. In [22] the performance of the system is analyzed by creating fault in different locations of the WSCC model. The settling time of rotor angle and speed is reduced with the use of PSS. The pre-fault conditions are studied by load flow methods using Newton-Raphson method. Different types of faults are applied in load flow to check the highest fault. The L-L-L-G fault is created at three generators to identify the settling time which provides the generator 1 has taken more than other generators to regain synchronism. John F. Hauer [23] discusses the threats of controller robust when the number of systems increases.

In [24] the location of PSS is considered as one of the important factors of PSS performance. The location of the PSS has an impact on performance for local mode oscillations. The inter-area modes of oscillations mostly depend on voltage of the load bus. When the frequency of two oscillations are close the oscillation in one part of the excites the another. This happens due to resonance which may lead to a wrong conclusion. The Kharitonov theorem in [25] is used to highlight wide loading conditions where the analytical coefficients of transfer function are obtained. The non-linear differential equations describe the leading and lagging power factors which describe system dynamics.

A robust coordinated optimization technique is used for the evaluation of ranges to damp critical systems and stability limit to overcome the uncertainties. A set of differential algebraic equation is linearized for a given operating point by H∞ optimal controller in [26] For a MIMO system the H∞ mixed sensitivity is more suitable but to problems in choosing the weighting functions the loop shaping is chosen for the frequency domain. The constraints of the loop might create a problem for large systems. The main advantage of selecting the loop shaping procedure is the normalized co prime factorization (NCF) approach. In this PSS design the root-locus, frequency response, damping ratio, state space and participation matrix should be calculated properly before the design. [28]

The authors of [29] discusses wide range of load characteristics of robust PSS the controller selection is an important part for the system. To find the best controller among the selected controllers the Bode magnitude plot of the general controller K should be taken. The controller whose Bode magnitude is closer to the general controller is selected as the best controller. The stability index of the system is the fast method for accessing system stability. It decreases the computational time of the system.

For both small signal and transient stability we have to calculate some steps such as:

a) Selecting the test system
b) Power flow calculations
c) Linear analysis and modal analysis
d) Time domain simulation

The authors of [30][31] gives a brief discussion of about steps associated to proceed upto designing of robust controllers. It includes the IEEE 11 bus test system to determining the mode shapes of the system. The A value of the participation matrix, mode shape is used to determine whether the system will provide oscillations in the exited state or not.

According to K.A. Folly [32] the design of a robust power system stabilizer combines H∞ control with bilinear transformation. The bilinear transformation is used to inherent the prevention of pole-zero cancellation to the H∞ mixed sensitive design. The suitable parameters should be assigned for preventing the pole-zero cancellations. It assigns the dominant poles in the single plane and applied to SMIB system. The simulations show the best performance for both structured and unstructured uncertainties. The main advantages are that we can reassign the dominant poles at our desired locations and the simulations are in frequency and time domain.

For a non-linear PSS in [33] we have to co-ordinate between terminal voltage, rotor speed and output power. To design this PSS a nonlinear feedback controller is designed using linear quadratic regulator. It can stabilize the decentralized linear time varying system. The main advantage of this type of controller is the feedback does not depend operating conditions. The iterative process is done to get the output. The authors of [34] discusses the

H∞ model reduction of the SIMO and MIMO systems. The models are reduced with Linear Matrix Inequality constraints. These constraints provide a state space model or frequency sampled equations. Zhaojun Bai in [35] discusses the numerical solution of the non-symmetric eigen value problem.

In a large-scale power system, the problems in synthesis of an optimal robust distributed controller are discussed in [36]. This synthesis done on a multi-area power system and applicable in a multiple interconnected LTI systems.

Another problem arises in case of wind parks. The renewable energy source always has some operating variables which is not easy to solve. The inputs and outputs always vary in such cases. The stability analysis in such case is solved by H_2/H_∞ robust stabilizers.

The WSCC model is connected to the DFIG wind turbine in [37]. The system stability of the wind turbine is improved by the robust PSS by identifying the worst damping ability of each swing nodes.

H∞ based non-linear sliding mode controller is a type of robust control. It is applied for interconnected systems with constant time varying delays. The stochastic variation of time delays results open communication network in the system but it requires more control energy. [38]

VII. ARTIFICIAL INTELLIGENCE TECHNIQUES

The PSS parameter optimization technique considering multi-operating conditions discussed in [39]. In this process stability of eigen values identified by distribution limit and distribution of eigen values by probabilistic method is discussed. The nonlinear programming approach is done by using the attributes of eigen values i.e. expectations and variances. The probabilistic approach requires independent number of systems operating samples and containing multiple stabilizers for a multimachine system.

In [40] Ant Colony Optimization is used for multi-objective design of multimachine PSS. the Ant Colony Optimization metaheuristic technique is used to solve the optimization problem. The optimization problem is formed from the fine tuning of PSS parameters. The results of Ant Colony Optimization PSS are compared to conventional PSS, Particle Swarm based optimization PSS, Genetic local Search based PSS, Chaotic Optimization based PSS. the results show that the Ant Colony PSS has maximum overshoot and less settling time than other methods.

The bio-inspired algorithm in [41] includes Cuckoo Search Algorithm, Particle Swarm Optimization algorithm and Genetic Algorithm. The eigen value based multi objective function shift unstable nodes to left side of the s- plane. The Cuckoo Search Algorithm PSS provides wide range of performance than others.

The authors of [42] discusses the coordinated nonlinear programming model of FACTS device STATCOM with PSS. the modified simplex-simulated annealing (MSSA) to solve the programming model. The MSSA shifts all the eigen values into specified regions of s-plane. MSSA approach combines simulated annealing and conventional methods to improve robustness of initial parameter setting.

M. A. Abido [43] discusses the robust PSS design using the Tabu search optimization technique. This shifts the damping nodes at several loading conditions and the results shows the effectiveness. Tabu Search algorithm is used for the optimal setting of conventional PSS parameter.

The authors in [44] describes the design of multiple optimal PSS using small population-based particle swarm optimization (SPPSO) and bacterial foraging algorithm (BFA). The SPPSO uses the regeneration concept to achieve the PSO for larger population. The two algorithms can be suitable of robust performance for both small and large disturbances. This can provide robust performance for various operating conditions. The SPPSO is better in performance in terms of computational complexity.

The Cuckoo Search algorithm is implemented in New England system for the optimal tuning of PSS. The results are compared with GA and particle swarm analysis. The Cuckoo Search algorithm used to shift poorly damped nodes to a D shaped region of the left half of s-plane. [45]

M. A. Abido [46] uses Simulated Annealing to design the PSS for multimachine system. It is optimized to shift the electromechanical nodes to the left of s-plane. The main advantage is the robustness to initial parameter setting and eigen vector calculation is inessential for objective function.

The H∞ robust power system stabilizers are designed using the Fuzzy and ANN controllers in [47]. This is designed using enhanced artificial bee colony (EABC) algorithm. The results using fuzzy and ANN is compared to conventional ABC and EABC concluding that EABC can be a better option for future use.

The design of robust PSS using genetic algorithm in multimachine is discussed in [48]. The effectiveness of genetic algorithm depends on the choice of search space which is a set of potential solutions. The potential solutions contain global optimum and local optimum. The choice of search engine should be done properly which allows the GA to diversify its population. The GA performance can be improved by convergence rate and solution quality. The non-dominated sorting GA is used to design robust multimachine PSS in [49]. It can provide higher performance under various faults.

The authors in [50] discussed the simultaneous damping of controllers using genetic algorithm. The tuning method provided system stabilization over a prespecified set of operating conditions. GA operators are used to in simultaneous optimization for both gain settings and phase compensations. For larger power systems parallel processing i.e., high-performance computing is used.

The design of robust PSS design using Taguchi principle is done in [51]. The optimization of objective function and PSS parameters are done by GA. Taguchi principle is applied to the SMIB system in which signal to noise ratio used to represent optimization objective. The optimization problem is to optimize the sound noise ratio.

The authors in [52] discussed the robust tuning of Proportional Integral derivative Power system Stabilizer (PID-PSS) with Static Var Compensator (SVC) using GA in multimachine power systems. Residue method is applied to determine the location of SVC. The change of speed as input to stabilizer along with other results are compared to conventional stabilizers to know the effectiveness of the robust stabilizer.

The use of Fuzzy logic Controller in multimachine system enhance the stability of speed deviation and acceleration of PID controller compared by conventional model. [53]

The design of robust PSS using less control energy is a challenge. The use of GA is to solve the optimization problem. It is applied on the first order lead-lag compensator and system uncertainties are modeled by an inverse additive uncertainty. The objective function of the system is the less control energy of the system. [54]

VIII. DIGITAL CONTROL SCHEMES

The authors in [55] uses D space simulator to identify the characteristics of the multimachine system. The transient model of WSCC is taken as a test system to check upon robustness towards uncertainties. The performance is measured depending on changes in load variation and mechanical torque.

Based nonlinear optimization a robust control theory is applied to linearize the uncertainties. This is applied to a three machine nine bus model is considered for the loop shaping procedure. The loop shaping is done by Glover-McFarlane H∞ loop shaping procedure. The efficiency of the real time robust controller is tested by DS1005 and DS1104 stations. The design of the controller can be done with H∞ optimal controller, H_2/H_∞ mixed sensitivity controller and H∞ loop shaping controller. [56]

IX. CONCLUSION

The control method investigated in this study focused on the use of PSS in conjunction with AVRs of the generators to mitigate the low frequency oscillations. The damping of the LFOs contributes to the enhancement of the stability limits of the system, signifying power transfer through the system. In this paper an effective methodology and the techniques used by the researchers to effectively perform the control actions to meet the growing stability problems is presented.

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