Review of Conventional Power System Stabilizer Design Methods

Ahmed A. Ba-muqabel*, and Dr.Mohammad A. Abido**

King Fahd University of Petroleum and Minerals, Dhahran, Eastern Region, 183/31261, Saudi Arabia (* bamugabel96@yahoo.com,** mabido@kfupm.edu.sa)

***Abstract* — In the past two decades, the utilization of supplementary excitation control signals for improving the dynamic stability of power systems has received much attention. In recent years, several approaches based on modern control theory and intelligent control and optimization techniques have been applied to PSS design problem. This paper introduces a review on the techniques applied on the conventional PSS design only. The techniques could be mainly classified into linear and nonlinear. Each classification includes several design methods which make the PSS more effective and robust in damping out the low frequency oscillations.**

***Index Terms* — Power system stabilizer (PSS), Low frequency oscillations, Damping, Dynamic, Stability .**

I. INTRODUCTION

Beginning in the late 1950's and early 1960's, most of the new generating units added to electric utility systems were equipped with continuously-acting voltage regulators. As these units became a larger percentage of the generating capacity, it became apparent that the voltage regulator action had a detrimental impact upon the dynamic stability or the steady-state stability of the power system. This is due to the oscillations of small magnitude and low frequency which are typically in the range of 0.7 to 2 Hz for local mode and 0.1 to 0.8 Hz for inter-plant or inter-area mode. Without timely and properly handling and control, these oscillations can sustain, continue to grow, spread through out the system and eventually cause the system disconnection and collapse. [1] & [2]

Supplementary excitation control of the low frequency oscillations is well known as a power system stabilizer (PSS). It was developed to aid in damping the electromechanical oscillations via modulation of the generator excitation. Although modern control methods have been used by several researchers to minimize the prescribed objective function, power system utilities still prefer the conventional lead-lag power system stabilizer structure. The reason behind that might be the ease of online tuning and the lack of assurance of the stability related to some adaptive or variable structure techniques. [3] Since the PSS has attracted the attention of researchers, extensive research has been conducted in the following fields:

- Effect of PSS on system stability. [4]-[8]
- Optimum PSS location & number. [9, 10]
- PSS tuning methods. [11]-[13]
- PSS input signals. [14]-[16]
- Practical experience in design, installation & operation of PSS. [17, 18]

II. POWER SYSTEM STABILIZER BASICS

The block diagram of a single-input PSS is shown in fig.1. Various structures of PSS can be implemented. The common structures are:

(a) Lead-lag structure or conventional PSS (CPSS)

$$u_{PSS} = K\,\frac{sT_w}{1+sT_w}.\left(\frac{1+sT_1}{1+sT_2}\right)^P y$$

or,

$$u_{PSS} = K\,\frac{sT_w}{1+sT_w}.\left(\frac{1+sT_1}{1+sT_2}\right)\left(\frac{1+sT_3}{1+sT_4}\right)y$$

Where, y is the input signal.

(b) Proportional-integral-derivative structure.

$$u_{PSS} = \frac{sT_w}{1+sT_w}.\left(K_P + \frac{K_I}{s} + K_D s\right)y$$

(c) Other structures based on optimal, adaptive, variable structure, intelligent… etc.

The common input signals used are the speed, frequency, electric and accelerating power deviations. However, PSS can be either conventional PSS (one-band PSS) which is (analog or digital) or multi-band PSS as in Fig. 2. In this paper, a literature survey on the design methods of the conventional PSS only will be presented.

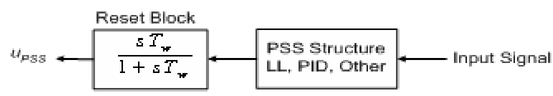

Fig. 1: PSS Structure

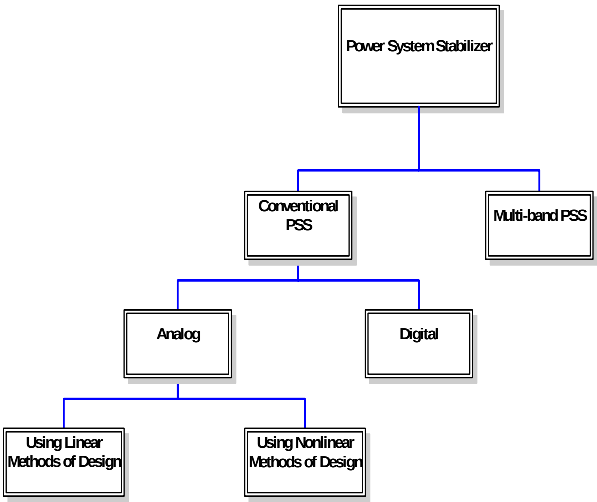

Fig. 2: Types of PSS

III. Analog Conventional PSS

In general, analog conventional power system stabilizer design methods could be categorized into linear and nonlinear methods of design.

A. Linear Methods of Design

Several linear methods were proposed to design the power system stabilizers which are:

1. *Pole-Placement*

Controllers obtained from simultaneous stabilization techniques have fixed gains constant to adaptive controllers. These reasons induced Othman and his co-workers in [19] 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 in [20]. In this method, participation factors were used to select the sites and number of stabilizers in a multi-machine system.

2. *Pole-Shifting*

Previous works on self-tuning PID stabilizers deal with a single machine infinite bus system. Wu and Hsu in [21] extended the previous results to a multi-machine power system. A pole-shifting technique, which is different from the pole-assignment method and the minimum variance algorithm adopted were developed for the tuning of the stabilizer's parameters. By continuously estimating system input-output relationship from the measured inputs and outputs, the gain settings of the self-tuning PID stabilizer were adjusted in real-time. In addition, shifting the real parts of complex open-loop poles to any desired positions was the work presented in [22].

3. *Linear Quadratic Regulator Formulation*

Power utility operators are eager to obtain all generators and turbine control input signals within their own power station to get better accuracy in the identified signals. The authors in [23] presented a power system stabilizer using the differential geometric linearization approach. This stabilizer used information at the secondary bus of the step-up transformer as input signals to the internal generator bus by defining the secondary bus as the reference bus instead of an infinite bus. However, PSS designed using Linear Quadratic Regulator (LQR) formulations required complete measurements which were neither practical nor economical for most cases. Thus, a power system stabilizer based Linear Quadratic Gaussian Regulator with loop transfer recovery was presented in [24].

4. *Linear Matrix Inequalities*

Scavoni & et al. [25] applied to power systems a design method for robust controllers based on the solution of LMI. Boukarim & et al., however, proposed in [26] two low-order centralized and decentralized PSSs using the LMI. The centralized controllers require much low gain to achieve the same amount of damping enhancement, have less disturbance rejection capabilities and require fast communication links to implement.

5. *Linear Optimal Control*

Linear optimal control theory was applied in [27] to design an output feedback controller. It has been extensively tested under wide-range of operating conditions and found to result in consistently good control.

6. *Quantitive Feedback Theory*

Shrikant and his colleague in [28] thought to extend the conventional stabilizer performance to cover a wide range of operating and system conditions by simply retuning the existing PSS. They have handled the parametric uncertainty in the small signal linearized model of the plant using the quantitive feedback theory (QFT). In addition, a robust power system stabilizer using quantitive feedback theory was designed by Sedigh and et al. in [29]&[30] to overcome the problem of parameters variations.

7. *Eigenvalue Sensitivity Analysis*

In [31], the power system stabilizer and the FACTS device stabilizer coordination was carried out by an objective function based on second-order eigen-sensitivities. The objective function was solved by two means: the Levenberg-Marquardt method and a genetic algorithm in face of various operating conditions. Considering multi-operating conditions, however, the probabilistic approach was applied to robust PSS design in [32]. Two types of probabilistic sensitivity indices were developed for PSS site selection and parameter adjustment. The authors in [33] used both the righteigenvector and the left-eigenvector to define the sensitivity of PSS effect to select the best PSS locations for damping local and inter-area oscillations.

8. Sliding Mode Control

A nonlinear PSS with a new sliding mode control (SMC) technique has been proposed in [34]&[35]. The latter had good performance for most perturbations but often required more control energy.

9. Conventional P-Vr Method

Gibbard & Vowles aimed to ensure that intra-station, local & exciter modes are well damped. They have outlined in [36] a procedure based on P-Vr method to design a robust PSS over a wide range of operating conditions.

10. Reduced Order Model

In [37], reduced order models were used to design feasible control schemes with little performance degradation.

11. H_2 Control

Application of H_2 optimal adaptive control algorithm in a power system stabilizer was described in [38]. The algorithm deals with disturbance attenuation in the sense of H_2 norm for nonlinear systems. The controller was free from repetitive parameter tuning.

B. Nonlinear Methods of Design

To improve the damping torque applied by the PSS, researchers have used different nonlinear techniques including the following:

1. Adaptive Control

Adaptive control techniques could be classified into two categories:

- *Adaptive Automatic Methods*

Because of fixed structures and parameters of traditional PSS, adaptive techniques [39, 40] have been applied on the design of PSS in recent years in order to reduce lacking of adaptivity to system operating condition changes. Examples involved the generalized Multivariable Minimum Variance (GMMV) control technique in [2] and the Model Reference Adaptive Control-Almost Strictly Positive Real (MRAC-ASPR) theory as in [41].

- *Self-Tuning & Self-Scaling Methods*

References [42]-[50] all proposed several self-tuning and self-scaling PSS s with various characteristics.

- Heuristic Dynamic Programming

Liu and Venayagamoorthy proposed a PSS based on heuristic dynamic programming in [51]. HDP combined the concepts of dynamic programming and reinforcement learning in the design of nonlinear optimal PSS. It was a class of adaptive critic designs.

2. Intelligent Control & Optimization Methods

There were eight main intelligent techniques used to design the power system stabilizer which are:

- *Genetic Algorithm*

Genetic algorithm is independent of the complexity of the performance index. It suffices to specify the objective function and to place finite bounds on the optimized parameters too. Because of that, researchers have used it either to simultaneously tune multiple controllers in different operating conditions [52]-[54] or to enhance the power system stability as in [55, 56] via PSS & SVC based stabilizer when applied independently & also through coordinated application. On the other hand, others did not use GA because of several reasons mentioned in [57].

- *Tabu Search*

To avoid computations of sensitivity factors and eigenvectors, Abido & Abdel-Magid [57] have used the TS to design a PSS for a multi-machine system.

- *Particle Swarm Optimization*

Unlike the other heuristic techniques, PSO is characterized as simple in concept, easy to implement, computationally efficient, and has a flexible and well-balanced mechanism to enhance the global and local exploration abilities. Thus, PSO has been proposed in the design of PSS in [58]-[60].

- *Simulated Annealing*

Simulated annealing is a derivative-free optimization algorithm and no sensitivity analysis is required to evaluate the objective function. All these reasons induced the researchers [61]-[64] to design a simulated annealing based power system stabilizer.

- *Neural Networks*

Two reasons are put forward for using ANN in power system stabilizer design which are the extremely fast processing facility and the ability of ANN to realize complicated nonlinear mapping from the input space to the output space. The work on the application of neural networks to the PSS design includes online tuning of conventional PSS parameters, the implementation of inverse mode control, direct control, and indirect adaptive control. [51, 65] Nearest to this work was the design of an indirect adaptive neural network based PSS by Liu and his co-workers in [66] and by Shamsollahi and Malik in [67]. However, the latter considered the effect of the trapped delay lines in the controller structure. In [67, 68], the authors have proposed a neuro-identifier to identify the plant in real-time and a neuro-controller to damp the power system oscillations. Different kinds of NN have been used by researchers in PSS design. This includes the layered and multi-layer feed-forward NN as in [69] & [70, 71] respectively. On the other hand, Yilmaz & et al. [72] have used back-propagation NN to seek for strong correlation among the state variables. In addition, while one radial basis function (RBF) network has been used in PSS design in [73]-[75], two recurrent ones were employed in [76].

- *Support Vector Machine*

The SVM is a novel type of learning machines based on the statistical learning theory. Boonprasert &

his companions in [77] were compared the support vector regression based PSS to NN based PSS and RBF based PSS and it gave most robust results.

- *Fuzzy Logic*

Fuzzy logic controllers are model-free controllers. They do not require an exact mathematical model of the controlled system. Paper [78] summarized the development of a fuzzy logic PSS during last several years whereas paper [79]-[81], proposed a systematic procedure for FLPSS design. To enhance the stability of power systems, FLC based PSS, a PID FLPSS, self-learning FLC based PSS and augmented FLPSS were introduced in [81,82], [83] [46]& [5] respectively. In [84], a FLPSS was designed with no chattering and steady state offset problems. However, references [35], [48]-[50] [85, 86] all proposed design methodologies of different FL based adaptive PSS. The last but not the least, is the fuzzy polar PSS proposed in [87] using frequency domain methods.

- *Rule-Based Method*

Expert system rule based power system stabilizers were proposed in [86] [88, 89]. Although they showed promising results, they were subjective and somewhat heuristic.

3. *Lyapunov Method*

The lyapunov direct method showed that the system was exponentially stable with the properly chosen control gains. In [90], Robak & et al. compared two control structures for lyapunov based PSS.

4. *Frequency Response Methods*

Frequency response is not markedly affected by change of operating conditions. A multi-machine expression in [91] was derived using operational matrix techniques for the analysis of the frequency responses. However, a two single machine infinite bus model was derived from a multi-machine system by coherency based equivalent reduction technique for the same purpose. These frequency responses were necessary for the design of PSS since the component of the frequency response depending on the generator only has a fixed shape regardless of the generator operating condition. Prony analysis has been used to determine the modes of power system oscillation from network generator swing curves [92] and to obtain the transfer function models in large systems for PSS design [93]. Papers [30] & [94] used the frequency domain based quantitive feedback theory, and the periodic output feedback technique respectively in the PSS design.

5. *Dissipativity Method*

A framework for the analysis of performance and synthesis of power system stabilizers was introduced in [95]. This framework was based on a dissipativity concept. The concept was to view the role of PSS as one of dissipating rotor energy and to quantify energy dissipation using the system theory notation of passivity.

6. *Agent Technology*

Ni and his co-workers proposed in [96] a supervisory level PSS (SPSS) using wide area measurement. The SPSS operated as a software agent that contained a fuzzy logic controller switch to select the appropriate robust controller for the corresponding system operating condition.

7. *Gain Scheduling Method*

A design of an optimum gain scheduling PSS was proposed in [97] since it was difficult to obtain a fixed set of feedback gains which gave satisfactory performance over a wide operating range. However, time delay can make a control system have less damping and, consequently, losing its synchronism. Thus, a centralized wide area control design using system wide data has been investigated by Hongxia and Heydt in [98] to enhance large interconnected power systems dynamic performance. A gain scheduling (GS) method was proposed to accommodate the time delay.

8. *Phasor Measurements*

An architecture for multi-site power system control using wide area information provided by GPS based phasor measurement units was proposed in [99]. This architecture provided a step-wise development path for the global control of power systems.

9. *Optimization Methods*

In [100], the minimax optimization technique was used to tune of power system stabilizers. Fathizadeh and his co-workers in [101] formulated the power system stabilizer design problem as a parameter constrained nonlinear optimization problem to maximize the stability margin. In addition, paper [102] presented a reduced order feedback controller designed with a weighting matrix optimization technique while paper [3] introduced an optimal design of PSSs using evolutionary programming optimization technique.

IV. Digital Conventional PSS

The digital stabilizers designed have low orders, require considerably slow sampling rates for implementation, and outperform the conventional (analog) power system stabilizer on a series of dynamic performance tests. These advantages induced researchers to improve the digital power system stabilizer. In [103], three robust digital PSS designs were studied and compared using H_∞ and optimization. The H_∞ based optimization could considerably improve performance and robustness of power systems.

V. Conclusion

In this paper, a review of the techniques used by researchers in designing the conventional (analog and digital) PSS only was presented. These techniques could be classified as linear and nonlinear. Each classification includes several design methods which make the PSS more effective and robust in damping out the low frequency oscillations. However, a review of the multi-band PSS design methods could be considered in the future.

ACKNOWLEDGEMENT

The authors wish to acknowledge the support of KFUPM.

REFERENCES

[1] E. V. Larsen, and D. A. Swann, "Applying power system stabilizers, parts I, II & III," *IEEE Trans. Power App. & Sys.*, vol. PAS-100, no. 6, pp. 3025-3046, June 1981.

[2] J. J. Dai, and A. A. Ghandakly, "A Decentralized adaptive control algorithm and the application in power system stabilizer (PSS) design," IEEE, pp.1641-1648, 1995.

[3] M. A. Abido, and Y. L. Abdel-Magid, "Optimal design of power system stabilizers using evolutionary programming," IEEE Trans. Energy Con, vol. 17, no. 4, pp. 429-436, December 2002.

[4] K. E. Bollinger, and S. Z. Ao, "PSS performance as affected by its output limiter," IEEE Trans. Energy Con., vol. 11, no. 1, pp. 118-124, March 1996.

[5] H. A. Toliyat, and et al., "Design of augmented fuzzy logic power system stabilizers to enhance power systems stability," IEEE Trans. Energy Con., vol. 11, no. 1, pp. 97-103, March 1996.

[6] K. C. Lee, "Analysis of power system stabilizers application for controlling poorly damped oscillations in the ALCAN/B.C. Hydro power systems," IEEE Trans. Power Sys., vol. 8, no. 1, pp. 255-263, February 1993.

[7] M. A. Reza, and M. A. Choudhry, "Design of a robust power system stabilizer over a wide range of load charactristics," IEEE, pp.8-13, 1990.

[8] C. M. Lim and et al., "Design of stabilizers in multimachine power systems," IEEE Proc., vol. 132, Pt. C, no. 3, pp. 146-153, May 1985.

[9] A. Feliach and X. Yang, "Identification of power system stabilizers locations," IEEE Proc of 28th conf on Dec. & control, pp. 1831-1835, December 1989.

[10] J. Lu and et al., "Identification of optimum sites for power system stabilizer applications," IEEE Trans. Power Sys., vol. 5, no. 4, pp. 1302-1308, Nov. 1990.

[11] R. J. Fleming and et al., "Selection of parameters of stabilizers in multimachine power systems," IEEE Trans. Power App. & sys., vol. PAS-100, no. 5, pp. 2329-2333, May 1981.

[12] L. Kiss, and J. Zerenyi, "A new conception for constructing and tuning power system stabilizers," 2003 IEEE Bologna power Tech Conf, June 23-26, Bologna.

[13] P. Kundur & et al., "Application of power system stabilizers for enhancement of overall system stability," IEEE Trans. Pr Sys.,vol. 4, no. 2, pp. 614-626,May 1990.

[14] K. E. Bollinger, and et al., "Accelerating power versus electrical power as input signals to power system stabilizers," IEEE Trans. Energy Con., vol. 6, no. 4, pp. 620-626, December 1991.

[15] G. J. Rogers, "The application of power system stabilizers to a multigenerator plant," IEEE Trans. Power Sys., vol. 15, no. 1, pp. 350-355, February 2000.

[16] J. J. Sanchez-Gasca, and et al., "Multivariable control for damping interarea oscillations in power systems," 1989 IEEE Control Sys. magazine, pp. 28-32, January 1989.

[17] A. Fretwell, and et al., "Design, installation and operation of power system stabilizers on the Hongkong electric power system," IEEE Int. Conf. on Adv. in pr. sys control, operation. & management, pp. 534-541, Nov.1991.

[18] A. Murdoch, and et al., "Practical application considerations for power system stabilizer controls," 1999 IEEE PES SM, pp. 83-87, 1999.

[19] H. Othman, and et al., "On the design of robust power system stabilizers," IEEE Proc of 28th conf on Dec. & control, pp. 1853-1857, December 1989.

[20] Y. Yu, and Q. Li, "Pole-placement power system stabilizers design of an unstable nine-machine system," IEEE Trans. Pr Sys., vol. 5, no. 2, pp.353-358, May 1990.

[21] C. Wu, and Y. Hsu, "Design of self-tuning PID PSS for multi-machine power systems," IEEE Trans. Power Sys., vol. 3, no. 3, pp. 1059-1064, August 1988.

[22] M. K. El-Sherbiny, and et al., "Optimal pole shifting for power system stabilization," EPSR 66 (2003) 253-258.

[23] M. Nambu, and Y. Ohsawa, "Development of an advanced power system stabilizer using a strict linearization approach," IEEE Trans. Power Sys., vol. 11, no. 2, pp. 813-818, May 1996.

[24] G. Radman, "Design of PSS based on LQG/LTR formulations," IEEE, pp. 1787-1792, 1992.

[25] F. E. Scavoni, & et al., "Design of robust power system controllers using linear matrix inequalities," 2001 IEEE Porto power Tech Conf. 10th-13th Sep, Porto, Portugal.

[26] G. E. Boukarim, & et al., "A comparison of classical, robust, & Decentralized control designs for multiple PSSs," IEEE Pr Sys,vol.15,no.4,pp.1287-1292,Nov 2000.

[27] V. M. Paina, and et al., "Optimal output feedback control of power systems with high-speed excitation systems," IEEE Power App. & Sys., vol. PAS-95, no. 2, pp. 677-686, March/April 1976.

[28] P. S. Rao, and I. Sen, "Robust tuning of power system stabilizers using QFT," IEEE Trans.Cont. Sys. Tech., vol. 7, no. 4, pp. 478-486, July 1999.

[29] A. K. Sedigh, & G. Alizadeh, "Design of robust PSS using quantitive feedback theory," IEE contl Conf., pub. no.389, pp. 416-421, March 1994.

[30] A. F. Okou, & et al., "Towards a systematic procedure to design robust PSSs," IEEE, pp. 2361-2366, 2000.

[31] J. M. Ramirez, & I. Castillo, "PSS & FDS simultaneous tuning," EPSR 68 (2004) 33-40.

[32] C. T. Tse, & et al., "Robust PSS design by probabilistic eigenvalue sensitivity analysis," EPSR 59 (2001) 47-54.

[33] E. Z. Zhout, and et al., "Theory and method for selection of power system stabilizer location," IEEE Trans. Energy Con., vol. 6, no. 1, pp. 170-176, March 1991.

[34] S. S. Sharif, "Nonlinear PSS design technique," IEEE, pp. 44-47, 1995.

[35] C. M. Falkner, and B. S. Heck, "Accelerating power versus electrical power as input signals to power system stabilizers," IEEE Proc. Amer. Contl. Conf. Washington, pp. 1550-1555, June 1995.

[36] M. Gibbard, & D. Vowles, "Design of PSSs for a multi-generator power station,"IEEE,pp.1167-1171, 2000.

[37] A. Feliachi, & et al., "PSSs design using optimal reduced order models part II: design," IEEE Trans. Power Sys., vol. 3, no. 4, pp. 1676-1684, November 1988.

[38] A. Soos, & O. P. Malik, "An H_2 optimal adaptive PSS," IEEE Trans. Energy Con., vol. 17, no. 1, pp. 143-194, March 2002.

[39] W. Gu, "System damping improvement using adaptive PSS," IEEE Proc of Canadian conf on Elec. & computer engineering, Edmonton, Canada,pp.1245-1247,May 1999

[40] H. F. Wang, & et al., "An adaptive PSS based on turbine governor control," IEE 2nd Int. Conf. on Advances in

power system control, operation & management, pp. 285-289, December 1993, Hong Kong.
[41] J. Ritonja, & et al., "Design of an adaptive PSS," IEEE, ISIE'99-Bled, Slovenia, pp. 1306-1311, 1999.
[42] A. Eichmann, & et al., "A prototype self-tuning adaptive PSS for damping of active power swings," IEEE, pp. 122-126, 2000.
[43] S. Deghdy, & et al., "Design of a PSS based on self-tuning regulator," IEEE, pp. 1046-1049, 1994.
[44] A. M. Sharaf, & et al., "A global deviation based PSS," IEEE Proc of Canadian conf on Elec. & computer engineering, Edmonton, Canada,pp.1289-1292,May 1999
[45] A. M. Sharaf, & et al., "A self adjusting PSS," IEEE Proc of Canadian conf on Elec. & computer engineering, Edmonton, Canada,pp.1298-1303,May 1999
[46] T. Abdelazim, & O. P. Malik, "An adaptive PSS using on-line self-learning fuzzy systems," IEEE, pp. 1715-1720, 2003.
[47] J. Lu, & et al., "A fuzzy logic-based adaptive PSS for multi-machine systems," EPSR 60 (2001) 115-121.
[48] J. Lu, & et al., "A fuzzy logic-based adaptive PSS for multi-machine systems," IEEE, pp. 111-115, 2000.
[49] A. Sharma, & M. L. Kothari, "Intelligent dual input PSSs for multi-machine system," IEEE, pp. 168-173, 2002.
[50] N. Hosseinzadeh, & A. Kalam, "A direct adaptive fuzzy PSS," IEEE Trans. Energy Con., vol. 14, no. 4, pp. 1564-1571, December 1999.
[51] W. Liu, & et al., "A heuristic dynamic programming based PSS for a turbogenerator in a single machine power system," IEEE, pp. 270-276, 2003.
[52] A. Andreoiu, & K. Bhattacharya, "Lyapunov's method based genetic algorithm for multi-machine PSS tuning," IEEE, pp. 1495-1500, 2002.
[53] A. Hasanovic, & A. Feliachi, "Genetic algorithm based inter-area oscillation damping controller design using matlab," IEEE, pp. 1136-1141, 2002.
[54] Y. L. Abdel-Magid, & et al., "Power system output feedback stabilizer design via genetic algorithms," IEEE conf. publication no. 446, pp. 56-62, September 1997.
[55] M. A. Abido, & Y. L. Abdel-Magid, "Coordinated design of a PSS and an SVC-based controller to enhance power system stability," EPSR 25 (2003) 695-704.
[56] Y. L. Abdel-Magid, & M. A. Abido, "Optimal multiobjective design of robust PSSs using genetic algorithms," IEEE Trans. Power Sys., vol. 18, no. 3, pp. 1125-1132, August 2003.
[57] M. A. Abido, & Y. L. Abdel-Magid, "Eigenvalue assignments in multimachine power systems using tabu search algorithm," Computer and Electrical engineering 28 (2002) 527-545.
[58] M. A. Abido, "Optimal design of PSSs using particle swarm optimization," IEEE Trans. Energy Con., vol. 17, no. 3, pp. 406-413, September 2002.
[59] M. A. Abido, "Particle swarm optimization for multi-machine PSS design," IEEE, pp. 1346-1351, 2001.
[60] M. A. Abido, "Optimal design of PSSs using particle swarm optimization," IEEE Trans. Energy Con., vol. 17, no. 3, pp. 406-413, September 2002.
[61] M. A. Abido, "An efficient heuristic optimization technique for robust PSS design," EPSR 58 (2001) 53-62.
[62] M. A. Abido, "Simulated annealing based approach to PSS and FACTS based stabilizer tuning," Electrical power and energy systems 22 (2000) 247-258.
[63] M. A. Abido, "Robust design of multimachine PSSs using simulated annealing," IEEE Trans. Energy Con., vol. 15, no. 3, pp. 297-304, September 2000.
[64] M. A. Abido, "Pole-placement technique for PSS and TCSC-based stabilizer design using simulated annealing," Electrical power and energy systems 22 (2000) 543-554.
[65] R. Segal, & et al., "A self-tuning PSS based on artificial neural network," Electrical power and energy systems 26 (2004) 423-430.
[66] W. Liu, and et al., "Adaptive neural network based PSS design," IEEE, pp. 2970-2975, 2003.
[67] P. Shamsollahi, & O. P. Malik, "Design of a neural adaptive PSS using dynamic back-propagation method," Electrical power and energy systems 22 (2000) 29-34.
[68] Y. Park, & et al., "A wide range operation PSS design with neural network using power flow charactristics," IEEE, pp. 294-298, 1996.
[69] P. Pugliese, & et al., "Intelligent control of inter-area oscillations in power systems," IEEE, pp. 737-741, 1996.
[70] Y. Hsu, & C. Chen, "Tuning of PSSs using an artificial neural network," IEEE Trans. Energy Con., vol. 6, no. 4, pp. 612-619, December 1991.
[71] Y. Zhang, & et al., "An artificial neural network based adaptive PSS," IEEE Trans. Energy Con., vol. 8, no. 1, pp. 71-77, March 1993.
[72] A. S. Yilmaz, & et al., "An analysis of relative performance of state variables in the design of PSS through neural networks," IEEE, pp. 1052-1056, 1998.
[73] M. A. Abido, & Y. L. Abdel-Magid, "Radial basis function network based PSSs for multi-machine power systems," IEEE, pp. 622-626, 1997.
[74] R. Segal, & et al., "Radial basis function network adaptive PSS," IEEE Trans. Power Sys., vol. 15, no. 2, pp. 722-727, May 2000.
[75] M. L. Kothari, & et al., "Orthogonal least squares learning algorithm based rasial basis function network adaptive PSS," IEEE, pp. 542-547, 1997.
[76] J. He, & O. P. Malik, "An adaptive PSS based on recurrent neural networks," IEEE Trans. Energy Con., vol. 12, no. 4, pp. 413-418, December 1997.
[77] U. Boonprasert, & et al., "Support vector regression based adaptive PSS," IEEE, pp. 371-374, 2003.
[78] T. Hiyama, "Development of fuzzy logic PSS and further studies," IEEE, pp. 545-550, 1999.
[79] P. Hoang, & K. Tomsovic, "Design and analysis of an adaptive fuzzy PSS," IEEE Trans. Energy Con., vol. 11, no. 2, pp. 455-461, June 1996.
[80] A. Ishigame, & et al., "Design of electric PSS based on fuzzy control theory," IEEE, pp. 973-980, 1992.
[81] G. V. Moodley, & et al., "Fuzzy logic PSS in multi-machine stability studies," IEEE, pp. 843-848, 1996.
[82] Y. Lee, and et al., "Design of single-input fuzzy logic control PSS," IEEE Proc of TENCON'02, pp.1901-1904, 2002
[83] T. Hiyama, & et al., "Advanced PID type fuzzy logic PSS," IEEE Trans. Energy Con., vol. 9, no. 3, pp. 514-520, September 1994.
[84] S. Chen, & et al., "The PSS design using optimal path estimation method," IEEE, pp. 194-199, 1998.
[85] J. Lu, & et al., "A fuzzy logic-based adaptive PSS for multimachine systems," Electric power systems research 60 (2001) 115-121.
[86] J. Shi, & et al., "Comparison of fuzzy logic based and rule based PSS," IEEE, pp. 692-697, 1992.
[87] T. H. Ortmeyer, & T. Hiyama, "Frequency response characteristics of the fuzzy polar PSS," IEEE, pp. 333-338, 1994.
[88] A. M. Sharaf, & et al., "A dW-Pa rule-based PSS design using multi-layer zonal bang-bang control," IEEE, pp. 707-712.

[89] M. A. Abido, & Y. L. Abdel-Magid, “Hybridizing rule-based PSSs with genetic algorithms,” IEEE Trans. Energy Con., vol. 14, no. 2, pp. 600-607, May 1999.
[90] S. Robak, & et al., “Comparison of different control structures for lyapunov-based PSS,” IEEE, pp. 229-234, 2001.
[91] D. M. Lam, & H. Yee, “A study of frequency responses of generator electrical torques for PSS design,” IEEE Trans. Power Sys.., vol. 13, no. 3, pp. 1136-1142, August 1998.
[92] M. A. Johnson, & et al., “Prony analysis and power system stability some recent theoretical and applications research,” IEEE, pp. 1918-1923, 2000.
[93] D. J. Trudnowski, & et al., “An application of prony methods in PSS design for multi-machine systems,” IEEE Trans. Power Sys., vol. 6, no. 1, pp. 118-126, February 1991.
[94] R. Gupta, & et al., “Design of decentralized PSS for multi-machine power system using periodic output feedback technique,” IEEE Int. Conf. on control, automation, robotics and vision, Singapore, pp. 1676-1681, December 2002.
[95] C. A. Jacobson, & et al., “Towards a dissipativity framework for PSS design,” IEEE Trans. Power Sys., vol. 11, no. 4, pp. 1963-1968, November 1996.
[96] H. Ni, & et al., “Power system stability agents using robust wide area control,” IEEE Trans. Power Sys., vol. 17, no. 4, pp. 1123-1131, November 2002.
[97] N. C. Pahalawaththa, & U. D. Annakkage, “An optimum gain scheduling PSS,” IEE Int. Conf. on advances in power system control, operation and management, Hong Kong, pp. 211-216, November 1991.
[98] H. Wu, & G. T. Heydt, “Design of delayed input wide area PSS using the gain scheduling method,” IEEE, pp. 1704-1709, 2003.
[99] I. Kamwa, & et al., “Multi-loop PSSs using wide area synchronous phasor measurements,” IEEE Proc of American control conf, Philadelphia, Pennsylvania,pp.2963-2967,June 1998
[100] A. J. Urdaneta, & et al., “Tuning of PSSs using optimization techniques,” IEEE Trans. Power Sys., vol. 6, no. 1, pp. 127-134, February 1991.
[101] M. Fathizadeh, & et al., “Power system stabilizer design for maximum stability margin,” IEEE, pp. 168-174.
[102] G. P. Chen, & et al., “Optimization technique for the design of a linear optimal PSS,” IEEE Trans. Energy Con., vol. 7, no. 3, pp. 453-459, September 1992.
[103] H. Shu, & T. Chen, “Robust digital design of PSSs,” IEEE Proc of American control conf, Albuquerque, New Mexico, pp.1953-1957, June 1997.