Different Trends on Power System Stabilizer

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Abstract: Power System are complex, hardly nonlinear and unpredictable fault locations. Furthermore, separated power systems are interconnected to each other. As a consequence, in large interconnected power systems small signal stability, especially local and inter-area modes of oscillation, become an increasing importance and cause power system instability. The Power System Stabilizer (PSS) are introduced as supplementary signal in Automatic Voltage Regulator (AVR) to damp such oscillations. In this paper a comprehensive review on PSS are introduced.

Keyword: power system stabilizer, fuzzy logic control, genetic algorithm, model reference model

1. Introduction

Power systems are growing in capacity with ever larger. Formerly separated power systems are interconnected to each other and the consequence is large power system. So modern power systems have evolved into systems of very large size. With growing generation and load capacity, different power plants and loads in a power system are added with even large capacity [1].

Furthermore, the unbundling of generation, transmission and supply is less oriented towards the physical nature of the synchronously interconnected power systems, which span a large area with interaction among the different sub network and the power plants. However, in the new environment with possible higher loading of transmission system the network operators may be forced to operate the system closer to its stability limit [2].

As a consequence, in large interconnected power systems small signal stability, especially inter-area oscillations, become an increasing importance. Inter-area oscillation is a common problem in large power system word wide. Many electric systems world-wide are experiencing increased loading on portions of their transmission systems, which can, and sometimes do, lead to poorly damped, low frequency inter-area oscillations.

The origin of inter-area oscillations can be illustrated by a spring-mass system, which is a mechanical analogue of a two area power system, see Fig. 1. The masses represent the aggregated inertias of the rotating generators and turbines of both areas, each having a well meshed grid inside the area. The spring corresponds to a relatively weak interconnection line. The two masses may oscillate against each other causing spring forces. The oscillations and of the two masses correspond to the local frequency deviations and in the two areas. The spring force is the analogue of the oscillating power exchange between the two areas.

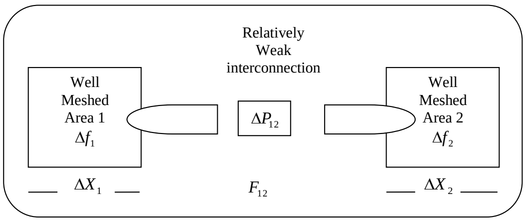

Fig. 1: Mechanical analogue (spring-mass system) inter-area oscillations

Power system stabilizers (PSSs) can provide supplementary control signal to the excitation system to damp these oscillations (local and interarea modes) and to improve dynamic performance [3], [4].

2. Survey and Comments

2.1 Conventional Power System Stabilizers (CPSS)

The conventional PSS (CPSS), a fixed parameter controller, is designed for single operating condition using linear control technique [4], the work in that paper is carried out to determine the parameters of power system stabilizers for a large generating power plant. Small signal and transient stability studies are reported which demonstrate the effectiveness of the stabilizers in enhancing the stability of inter-area as well as local plant modes of oscillation.

Power system stabilizers as undergraduate control design project in [5], this paper introduce the details of CPSSs design using root-locus, frequency-domain and state-space methods.

Damping of electromechanical modes using power system stabilizers in [6], the aim of that paper is to examine the effect of inclusion of a CPSS in improving the dynamic stability of different power system.

(1)

It consists of two lag-lead controllers with high pass filter that prevents steady change in speed from modifying the field voltage. The value of the washout time constant T_w should be high enough to allow signals associated with oscillations in rotor speed to pass unchanged. A high value of K_{STAB} is desirable from the viewpoint of transient stability.

The conventional PSS (CPSS), a fixed parameter controller, is designed for single operating condition using linear control techniques. Due to the nonlinear characteristics, wide range of operating conditions and unpredictability of perturbations in a power system, the fixed parameter PSS generally cannot maintain the same quality of performance under all conditions of operation.

2.2 Fuzzy Logic Based Power System Stabilizer (FLPSS)

A fuzzy logic power system stabilizer (FLPSS) have been found to be a good controller to damping oscillations rather than CPSS.

Fuzzy logic power system stabilizer introduced in [7], [8]. These two papers proposed fixed parameters fuzzy power system stabilizer using speed and power output deviations as the controller input variable. The complete range for the variation of each of the two controller inputs is represented by a 7×7 decision table, i.e. 49 rules as shown in Table 1.

Fig. 1-2 shows membership function for seven linguistic variables *LN, MN, SN, Z, SP, MP, LP* which stand for large negative, medium negative, small negative, zero, small positive medium positive and large positive respectively.

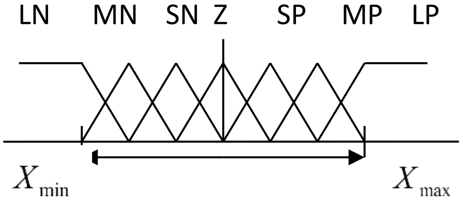

Fig 2.: Membership function for seven linguistic variables

Table 1: Fuzzy-logic PSS rules

Eq. (1) shown the transfer function of CPSS.

$$G_{PSS}(S) = \left(K_{STAB}\right)\left[\frac{sTw}{1+sTw}\right]\left[\frac{1+sT1}{1+sT2}\right]\left[\frac{1+sT3}{1+sT4}\right]$$

Δώ Δω	LN	MN	SN	Z	SP	MP	LP
LN	LN	LN	LN	LN	MN	SN	Z
MN	LN	LN	MN	MN	SN	Z	SP
SN	LN	MN	MN	SN	Z	SP	MP
Z	MN	MN	SN	Z	SP	MP	MP
SP	MN	SN	Z	SP	MP	MP	LP
MP	SN	Z	SP	MP	MP	LP	LP
LP	Z	SP	MP	LP	LP	LP	LP

Implementation and laboratory test results for a fuzzy logic based self-tuned power system stabilizer in [9], this paper describes the implementation of a fuzzy logic based self-tuned controller to improve the stability of electric power systems. The stabilizing signal is computed using the standard fuzzy membership function depending on the speed/acceleration state of the generator in the phase plane.

Direct adaptive fuzzy power system stabilizer introduced in [10], in this paper a fuzzy power system stabilizer (FPSS) is developed using the concept of fuzzy basis functions. The linguistic rules, regarding the dependence of the plant output on the controlling signal, are used to build the initial FPSS. Based on the Lyapunov's direct method, an adaptation rule is developed in order to make the FPSS adaptive to change in operating conditions of the power system.

A self-organizing fuzzy power system stabilizer is proposed in [11], the authors in this paper proposed PSS consists of output look-up table that made by fuzzy rule base, and learning algorithm based on the principle of sliding mode. The control system is composed of two look-up tables which are created from a fuzzy rule base with two inputs, and a signal output. The first look-up table is the main controller and the other is self-organizing part on sliding mode control for updated the first look-up table controller. A variable-structure adaptive.

2.3 Adaptive PSS with Neural Network Predictor and Neural Network Controller

An adaptive neural network-based controller using indirect adaptive control method has been developed in [12], [13], [14]. It combines the advantages of neural networks with the good performance of the adaptive control. This controller employs the learning ability of the neural networks in the adaptation process and is trained each sampling period. The controller consists of two sub-networks. Based on the inputs and outputs of the plant, one network, adaptive neuro-identifier (ANI), identifies the power plant in terms of its internal weights and predicts the dynamic characteristics of the plant. The second sub-network, an adaptive neuro-controller (ANC), provides the necessary control action to damp the oscillations of the power plant. The success of the control algorithm depends upon the accuracy of the identifier in predicting the dynamic behavior of the plant. The ANI and ANC are initially trained off-line over a wide range of operating conditions and a wide spectrum of possible disturbances. After the off-line training stage, the controller is hooked up in the system. Further updating of the ANI and ANC is done on-line every sampling period. On-line updating enables the controller to track the plant variations as they occur and to provide control signal accordingly. The two sub-networks are trained in each sampling period using an on line of the back-propagation algorithm.

A Neural network-based power system stabilizer using power flow characteristics proposed in [15], in this paper a neural network-based power system stabilizer (Neuro-PSS) is designed for a generator connected to a multi-machine power system utilizing the nonlinear power flow dynamics. The Neuro-PSS consists of two neural networks: Neuro-Identifier and Neuro-Controller. The low frequency oscillation is modeled by the Neuro-Identifier using the power flow dynamics, then generalized back-propagation algorithm is developed to train the Neuro-Controller to generalized delta to the Neuro-Controller for training.

Generalized neuron-based adaptive PSS for multi-machine environment introduced in [16]. Taking advantage of the characteristics of a generalized neuron (GN), that requires much smaller training data and shorter training time. the PSS in this paper consists of a Generalized neuron (GN) as an identifier, which predicts the plant dynamics one step ahead, and (GN) as a controller to damp low frequency oscillations. Results of studies with a GN-based PSS on a five-Machine power system show that it can provide good damping of both local and interarea modes of oscillations.

A Neural network-based PSS suitable for on-line training [17]. This paper proposed PSS consists of a neuro-identifier and a neuro-controller which have been developed based on Functional Link Network (FLN) model which eliminates the need of hidden layer while retaining the nonlinear mapping capability of the neural network by using enhanced inputs. A recursive on-line training algorithm has been utilized to train the two neural networks.

An adaptive PSS based on recurrent neural network in [18], [19]. The architecture of the proposed adaptive PSS has two recurrent neural networks. One functions as a tracker to learn the dynamic characteristics of the power plant and the second one functions as a controller to damp the oscillations caused by the disturbances. The proposed approached in this paper, the weights of the neural network are updated on-line.

2.4 Adaptive Neuro-Fuzzy PSS

Characteristics of neural networks and fuzzy logic complement each other in respect of their pros and cons. That offers the possibility of using a hybrid neuro-fuzzy approach in the form of an adaptive network based Fuzzy Logic controller (FLC) whereby it is possible to take advantage of the positive features of both neural networks and Fuzzy Logic. Such a system can automatically find appropriate set of rules and membership functions.

An online adaptive neuro-fuzzy PSS for multi-machine systems in [20], [21]. An Adaptive neuro-fuzzy inference system (ANFIS) based PSS developed. ANFIS PSS uses controller whose membership functions and consequences are tuned online by the back-propagation method. Recursive least square [RLS] method with variable forgetting factor is used to obtain the coefficient vector of the generating system model. The structure of the proposed controller is shown in Fig. 3. The controller consists of two subsystem— the identifier for the generator and the ANFIS PSS. The parameters of the identifier are updated based on the error between the estimator generator speed deviation ($\Delta \hat{\omega}$) and its actual value ($\Delta\omega$), while the parameters of the ANFIS PSS are tuned by back propagating the error signal between ($\Delta \hat{\omega}$) and its desired value ($\Delta\omega_d$).

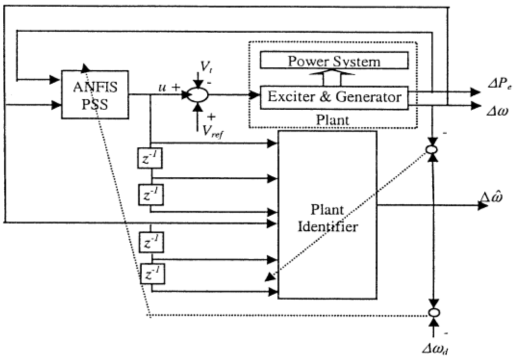

Fig. 3: Adaptive Neuro-Fuzzy Power System Stabilizer (ANFIS PSS) [20].

A fuzzy logic based PSS with learning ability in [22], [23], [24]. In the research reported in this paper, both the FLC and ANN have been employed together to design a new PSS, Adaptive-Network-Based Fuzzy Logic PSS (ANF PSS). The proposed ANF PSS employs a multilayer adaptive network. The network is trained directly from the input and the output of the generator unit. Learning is based on the error evaluated by comparing the output of the ANF controller and a desired controller, self-optimizing pole-shifting has been chosen as the desired controller. The algorithm combines the advantages of the artificial neural networks (ANNs) and fuzzy logic control (FLC) schemes.

A rule-based fuzzy PSS tuned by a neural network [25], A fuzzy logic power system stabilizer (FPSS) has been developed using speed and active power deviations as the controller input variables. The inference mechanism of the fuzzy logic controller is represented by a (7 X 7) decision table, i.e. 49 then rules. There is no need for a plant model to design the FPSS. Two scaling parameters have been introduced to tune the FPSS. These scaling parameters are the outputs of a neural network which gets the operating conditions of the power system as inputs. This mechanism of tuning the FPSS by the neural network, makes the FPSS adaptive to changes in the operating conditions.

2.5 Robust PSS

A simple robust PSS is designed that can properly function over a wide range of operating conditions and extend the machine load ability. The lead compensator design is achieved by drawing the root loci for a finite number of extreme characteristics polynomials. Such polynomials are obtained, using the kharitonov theorem [26], to reflect wide loading conditions on characteristics equation coefficient. The PSS proposed in [26], belong to the class of robust controller. It has the following advantages:

- It is based on simultaneous stabilization of exactly.
- The control design is intuitive since it the resulting controller has a low order.
- Based on the root locus technique.

Power system stability agents using robust wide area control introduced in [27], in this paper, a supervisory level power system stabilizer (SPSS) using wide area measurement is proposed. H_∞ controllers using selected wide area measurements are embedded into the SPSS control loop to accommodate power system nonlinear dynamic performance and model uncertainties.

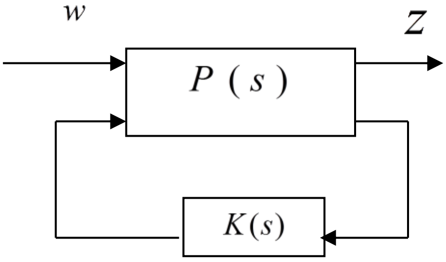

Fig. 4: H_∞ control Linear Matrix Inequalities (LMI) model

A general H_∞ robust control problem is depicted in Fig.4, where $P(s)$ and $K(s)$ are state-space realizations of the open-loop power system and robust controller, respectively, and w and z denote the disturbance input and the output associated with the H_∞ performance, respectively.

2.6 Adaptive Power System Stabilizer

An Adaptive control has the ability to modify its behavior depending on the performance of the closed-loop system. The basic function of the adaptive control may be described as:

i. Identification of unknown parameters, or measurement of a performance index.
ii. Decision of the control strategy
iii. On-line modification of the controller parameters.

Depending on how these functions are synthesized, different types of adaptive controllers are obtained. Various adaptive control techniques have been proposed for excitation control.

Two distinct approaches, *direct adaptive control* and *indirect adaptive control* can be used to control a plant adaptively. In the direct adaptive control, Fig. 5, the parameters of the controller are directly adjusted to reduce some norm of the output error [28] ,[29] ,[30] ,[31]. In the indirect control, Fig. 2-6, the parameters of the plant are estimated as the elements of a vector at any instant k, and the parameters vector of the controller is adapted based on the estimated plant vector [32] ,[33] ,[34] ,[35] ,[36], [37] [38].

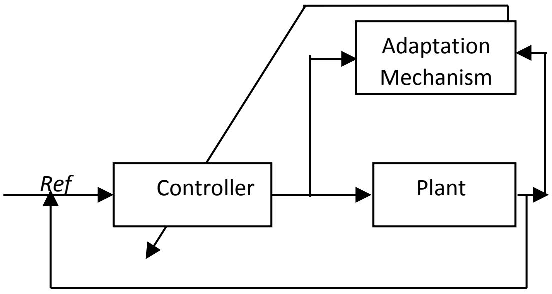

Fig. 5: Direct adaptive controller structure

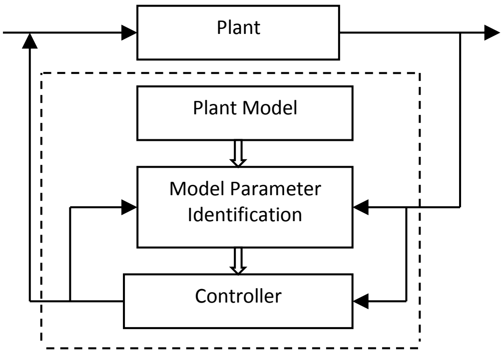

Fig. 6: Indirect adaptive controller structure

2.7 Direct Adaptive FPSS

Direct adaptive fuzzy power system stabilizer (DFPSS) for a one machine-infinite bus system is designed in [39]. The linguistic rules regarding the dependence of plant output on the control signal are used to build the initial controller, based on the Lyapunov's direct method, an adaptation rule is developed to make the PSS adaptive to changing system conditions.

In the simulations study for the DFPSS, the DFPSS is superiority to the MB-PSS to damping the local oscillation when applied to single machine infinite bus. The author applied the DFPSS to multi-machine power system, the simulation results shows the performance of DFPSS is worse than MB-PSS.

Therefore, it is our opinion that the simulation results which applied to single machine infinite bus is not enough to measure the performance of PSS, hence the study should be extend to multi-machine power system.

The disadvantage of the DFPSS is suffers robustness problem due to use of the integration in the adaptation equations.

2.8 Direct Variable Structure Adaptive Fuzzy Power System Stabilizer (DVSFPSS)

Direct variable structure adaptive fuzzy power system stabilizer (DVSFPSS) applied to single machine infinite bus and multi-machine power system is designed in [40]. The use of a particle swarm optimization based algorithm has made it possible to tune the controller's gains such that the sum of the squares of the speed deviations is minimized.

. The designing of the DVSFPSS is used the variable structure algorithm that does not suffer robustness problems such as DFPSS in section (2.6) because they are free of integrations.

The simulation results of power system at different operating conditions with three different fault locations and due one generator trip, show that the DVSFPSS is superiority to damping inter-area oscillation than MB-PSS.

2.9 An Indirect Adaptive Fuzzy Power System Stabilizer (IDFPSS)

An indirect adaptive fuzzy power system stabilizer (IDFPSS) is proposed in [41]. It consists of A fuzzy identifier and a feedback linearizing controller. The IDFPSS, it uses the actual speed and the actual speed deviation as inputs to the fuzzy identifier (obtained online and assumed to be measured from the output of the plant). The output of the fuzzy identifier is the estimates of the unknown nonlinearities of the model. These are used in a feedback linearization algorithm to provide the necessary damping in the power system.

The objective is to damp local and inter-area oscillations that occur following power system disturbance and increasing the power transfer capability. To solve the problem of long-term low damping oscillation phenomena and increasing the power transfer capability, a method is presented to design IDFPSS for damping inter-area power oscillations at three different positions of the three phase to ground fault. The method is based on the multi-machine power system. Dynamic simulations using a 4-machine 2-area system power model are presented in order to show the effectiveness of the IDFPSS over IEEE standard multi-band power system stabilizer (MB-PSS). The gains of the controller are tuned via a particle swarm optimization routine to ensure system stability and minimum sum of the squares of the speed deviations.

Simulation results of the bench-mark problem of a 4-machine 2-area system in [41] have confirmed the superiority of the IDFPSS compared to the conventional one CPSS.

2.10Robust Adaptive FPSS (RFPSS)

The proposed controller adopts a dynamic inversion approach [41]. Since feedback linearization is practically imperfect, robustifying and adaptive components are included in the control law to compensate for modelling errors and achieve acceptable tracking errors. Two fuzzy systems are implemented. The first system models the nominal values of the system's nonlinearity. The second system is an adaptive one that compensates for modelling errors. A feedback linearization-based control law is implemented using the identified model. The gains of the controller are tuned via a particle swarm optimization routine to ensure system stability and minimum sum of the squares of the speed deviations. A bench mark problem of a 4-machine 2-area power system is used to demonstrate the performance of the proposed controller and to show its superiority over other conventional stabilizers used in the literature**.**

The RFPSS improve the transient and the dynamic performance of the overall multi-machine power system.

2.11 Tuned Fuzzy Power System Stabilizer (TFPSS)

The structure of the TFPSS is depicted in Fig. 7. It consists of two fuzzy systems [42][43]. One of them appears in the main feedback loop and contributes in the excitation signal (FPSS). The other fuzzy system acts as a supervisory system (FLS) that tunes the scaling factors of the first one. Two scaling factors are used to adjust the range of inputs and one scaling factor is to adjust the output of the FPSS as the operating condition of the system change. The speed deviation is scaled with $\Delta\omega' = k_p \Delta\omega$ and the derivative of speed deviation is scaled with $\Delta\dot{\omega}' = k_d \Delta\dot{\omega}$ and the output of the FPSS is scaled with $u' = K_u\, u$. The electrical active power of each generator is selected as an input signal to represent the operating condition of each machine. The FLS with one input (P_e) and three outputs (scaling factors) designed this way is referred to as the tuner. The rule base for each tuner consists of two rules. Typical rules are given below.

***Rule 1**: If (P_e is SP) then (K_p is LP) and (K_d is LP) and (K_u is SP).*

***Rule 2:** If (P_e is LP) then (K_p is SP) and (K_d is SP) and (K_u is LP).*

The operating conditions are divided into two levels; namely: heavy and light active power. The range of the heavy power is from 0.5 to 1.2 pu. The range of the light power is from 0.1 to 0.49 pu. It means that there are two sets of values for the scaling factors (K_P, K_d, K_u) corresponding to the two operating conditions. These values of the scaling factors that appear in the rule base are set by particle swarm optimization (PSO) based on a nonlinear simulation of three-phase to ground faults at different locations and generator trip.

The inputs of FPSS are fuzzified using normalized triangle membership functions. . For each input variable, seven labels are defined as shown in [43]. LN, MN, SN, Z, SP, MP and LP stand for Large Negative, Medium Negative, Small Negative, Zero, Small Positive, Medium Positive, Large Positive. The value $x_{\max}$ and $x_{\min}$ represent maximum and minimum variation of the input and output signals. The values are selected based on simulation information. A decision table is constructed consisting of 49 rules [43]. An example of the ith rule is:

If $\Delta\omega$ is SN and $\Delta\dot{\omega}$ is MP then u is SP

A symmetrical fuzzy rule set is used to describe the FPSS behavior as shown

The center of area method is used for defuzzification.

For the inputs of FLS, trapezoidal membership functions are used and for the outputs, triangle membership functions are used. The rule base for the FLS is derived based on experience. The whole stabilizer obtained is referred to as the tuned fuzzy power system stabilizer (TFPSS) and is shown in Fig. 7.

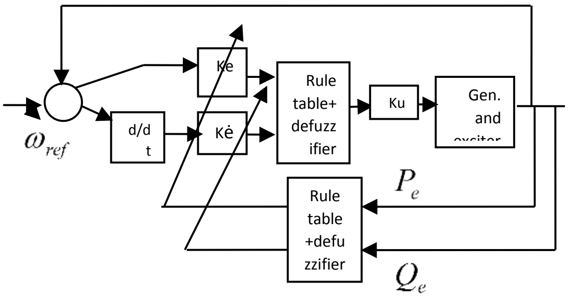

Fig. 8: Structure of the proposed TPSS

Comparing the TFPSS to the multi-band power system stabilizer (MB-PSS), simulation results based on a typical four-machine two-area system have confirmed that the TFPSS has been superior. The TFPSS can cope with large disturbance at different locations.

2.12: Model Reference Adaptive PSS

The authors in [44] are focused on the use of model reference adaptive control approach which described by eq. (1) and (2). The concept on the reference model will assure the control action, to tracking the controlled plant output which is generated by the adaptive algorithm. Adaptive gains are obtained as a combination of the "proportional constant" term and with the σ-term extended "integral time constant" term. The σ-term is introduced to avoid divergence of the integral time constant gain. The necessary condition for asymptotic tracking is derived by means of hyperstability theory. The benefits of the model reference adaptive power system stabilizer were evaluated as objectively as possible by means of a theoretical analysis, numerical simulations and laboratory realizations. Damping of the electromechanical oscillations in the entire operating conditions was investigated. Obtained results show the improved damping in the entire operating conditions and the increase the damping of electrotechnical oscillations. The results of the work in [44] will help by the development of the model reference power system stabilizer which superior than conventional power system stabilizer (CPSS). The model reference PSS has many advantages when compared with conventional PSS. The improvement is satisfactory damping in all operating condition.

$$\dot{x}_m(t) = A_m x_m(t) + B_m u_m(t) \ldots\ldots\ldots.(1)$$

$$y_m(t) = C_m x_m(t) \ldots\ldots\ldots\ldots\ldots\ldots..(2)$$

where $x_{(t)m}$is the reference model's state vector, $u_m(t)$is the reference model's command vector, $y_m(t)$ is the reference model's output vector, and A_m, B_m and C_m are matrices of appropriate dimensions. The model is supposed to be stable .

The dimension of the reference model's state may be less than the dimension of the plant state .The output tracking error is defined as

$$e_y(t) = y_m(t) - y_p(t) \ldots\ldots\ldots\ldots(3)$$

2.13 PSS Parameters Optimization Using Immune Genetic Algorithm

The aim of the paper in [] is to search for optimal parameters of PSS by optimization technique, immune genetic algorithm (IGA) to guarantee the power system stability when subjected to disturbance at different operating conditions. It is applied on a single machine infinite bus (SIMB) power system model as in Fig. 9.

The design steps could be formulated as the following constrained optimization technique, where the constrains are PSS parameter bounds:

$$0.01 \le K_s \le 20$$
$$0.01 \le T_1 \le 0.5$$
$$0.01 \le T_2 \le 0.5$$

The author in [] chosen to minimize the error and the oscillation of the angular speed. According to the cost function (Integral Time Absolute Error) :

$$ITAE = \int t|\Delta\omega|dt \ldots\ldots\ldots\ldots (4)$$

Simulation results shows that IGA has great effect to damping electrotechnical oscillations and achieve better performance than traditional GA.

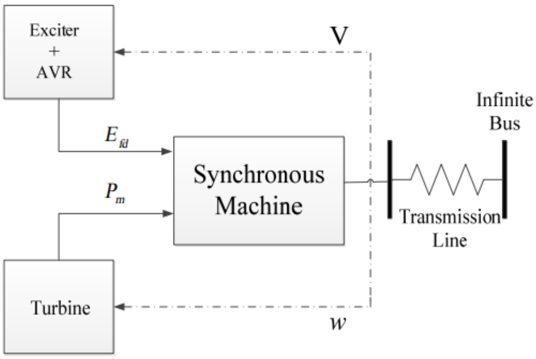

Fig. 9: SMIB Power System

Conclusion:

Power system stabilizers have been proven very effective controller in enhancing stability of power system. types of PSSs have been investigated, and their advantages and disadvantages have become clearer. Based on this survey have been developed to help the researcher to choose the most suitable configuration to damping electromechanical oscillations.

CPSS use linear model with transfer functions which designed at certain operating condition, could work around a particular operating condition of the system for which these transfer functions are obtained, they are not able to provide satisfactory results over wider ranges of operating conditions.

This problem is overcome by fuzzy logic system-based technique for the design of PSSs. Fuzzy. Suggests a direct adaptive fuzzy PSS, an indirect adaptive fuzzy PSS, a robust adaptive fuzzy PSS and tuned fuzzy PSS.

The Model reference adaptive PSS shows optimal performance to damping electromechanical oscillations over CPSS for different operating conditions.

The optimization techniques such swarm optimization technique and genetic algorithm could be used to search for optimal parameter of PSS.

The feature in this survey encourage power system engineers to replace CPSSs with adaptive PSSs.

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