Robust Dynamic Stability Assessment of Fuzzy logic Power System Stabilizers

M. Soliman*

Abstract— **Robustness of Type-I fuzzy logic power system stabilizers (FLPSSs) often lacks mathematical reasoning where the performance of such a stabilizer is often reviewed by transient response of the closed loop system. Necessary and sufficient conditions that guarantee robust dynamic stability of an FLPSS are presented. A small-signal model of an FLPSS is developed to study the dynamic stability of a single-machine infinite-bus power system. Such a small signal model is proved to be a conventional proportional-derivative (PD) controller whose parameters are expressed in terms of normalizing factors of FLPSS. The parameters of such a PD controller, are tuned to guarantee robust dynamic stability, thereafter normalizing factors can be directly computed. Synthesis of a robust PD controller is based on simultaneous stabilization of a finite number of extreme characteristic polynomials. Such polynomials are derived using Kharitonov theorem from an interval polynomial considered to reflect effect of loading conditions on characteristic polynomial coefficients. A convex region in the K_p-K_d parameter plane which guarantees robust stability is obtained using Routh-Hurwitz array. Such a region presents the pool for all robust normalizing factors of an FLPSS. Simulation results are presented to confirm the effectiveness of the proposed approach.**

Keywords: Dynamic stability, fuzzy logic PSS, Parameters tuning, Robust PD Control, Kharitonov polynomials.

I. Introduction

Over the past three decades or so, fuzzy logic control has emerged as a promising technique for PSS design [1-10]. Performance of an FLPSS is significantly affected by tuning its parameters (scaling factors). Recently, modern Evolutionary Algorithms (EA) algorithms including but not limited to Genetic Algorithms (GA), Particle Swarm Optimization (PSO) and Artificial Bee Colony (ABC) [7-10] are adopted for optimal adjustment of scaling factors, membership functions and the number of rules. Although the performance of the resulting FLPSS with a certain set of scaling factors is elegant, it often lacks systematic stability analysis and assessment. Optimality of such set is often realized via simulation and/or experimental results of both single and multimachine systems. This paper presents a method for computing all scaling factors of an FLPSS that can guarantee robust dynamic stability of a single machine infinite-bus system over wide range of operating conditions. Robustness of the proposed FLPSS is ensured by selecting appropriate set of controller parameters. A small signal model for an FLPSS is developed to accomplish robust dynamic stability study. Such a small signal model results in a conventional proportional-derivative (PD) controller. The controller parameters of an FLPSS are explicitly expressed in terms of gains of such a PD controller. An interval plant model is considered to reflect the effect of variation in generation patterns on the coefficients of the model. Robust PD controller design is reduced to simultaneous stabilization of finite number of extreme plants extracted from the interval plant model using Kharitonov theorem. Inequality constraints that describe the boundaries of the stability region, in K_p-K_d parameter plane, of each extreme plant are derived via Routh-Hurwitz criterion. Intersection of all the regions corresponding to all extreme plants gives the pool for all robust PD controller gains which in turn account for that of an FLPSS. Simple models are considered for the power system and for the FPLSS to demonstrate the principles of the proposed approach; however extension to more realistic models is straight forward.

The rest of this paper is organized as follows. Section II presents a brief literature of fuzzy logic controllers while the proposed small signal model of an FLPSS tags this section. Formulating power system model with uncertainties, due to changes in generation patterns, as an interval plant model is presented in Sec. III. Robust synthesis of a PD controller is considered in Sec. IV, where robust stability region is obtained with retrieval of the controller parameters of an FLPSS. Section V presents simulation results while Sec. VI concludes this work.

II. FLPSS Structure

An FLPSS comprises four basic parts: the fuzzifier, the knowledge base, the inference engine and the defuzzifier. The fuzzifier maps the crisp inputs into fuzzy variables using normalized membership functions and input gains. The fuzzy inference engine generates the proper control action based on the available rule base. Proper crisp value is derived from the fuzzy control action through the defuzzifier using normalized membership functions and output gains [11]. The speed deviation and its derivative are commonly used as inputs to an FLPSS. Instead of the speed deviation derivative as input, accelerating power is used as presented in [2] to minimize the torsional interactions [14]. An FLPSS out is injected to the summing point of the AVR. The common letters N, Z and P are used here to stand for the linguistic variables *negative*, *zero* and *positive* respectively. The universe of discourse of the input variables is assumed to bounded by $X_{\min}$ and $X_{\max}$. It is a common practice to determine these values from simulation information. If $X_{\max} = -X_{\min}$, this discourse can be normalized between +1 and -1 by

* M. Soliman is with Electrical Power and Machines Department, Faculty of Engineering at Shoubra, Benha University, Cairo, Egypt (e-mail: msoliman_28@yahoo.com, msoliman1512@gmail.com, Tel.: +2 0015 419 184, Fax: : +2 0222 022 310.

introducing a set of scaling factors to represent the actual signals such that: $k_\omega = 1/\Delta\omega_{\max}$, $k_a = 1/\Delta a_{\max}$ and $k_u = 1/u_{\max}$ where $\Delta a = p(\Delta\omega)$. These maximum values are usually determined from simulating the system under severe condition.

A. Fuzzy Rule Creation

Symmetrical rule base is commonly used for monotonically increasing systems (Drainkov et al., 1993). Each fuzzy rule takes the general form of "IF Antecedent THEN Consequent", e.g. IF $\Delta\omega$ is ***Z*** AND Δa is ***P*** THEN u is $\boldsymbol{\theta_6}$. TABLE I lists all rule entities of a 3-rule based FLPSS.

TABLE I. AN FLPSS RULES WITH SINGLETON OUTPUTS

		p(Δω)		
		N	***Z***	***P***
Δω	***N***	θ_1	θ_2	θ_3
	Z	θ_4	θ_5	θ_6
	P	θ_7	θ_8	θ_9

The three membership functions (MFs) *N*, *Z* and *P* are considered as triangular functions as shown in Fig.1. The firing strength of the i^{th} rule consequent is a scalar value (h_i) which is equal to the product of the two antecedent conjunction values. The appropriate crisp control is generated using center of gravity method. Consider that $\theta_i, i = 1,...,N$ represent the centroids of *N* MFs that are assigned to U_{pss}. Therefore, the crisp output of an FLPSS is computed as follows [12]:

$$U_{pss} = K_u \times \frac{\sum_{i=1}^{N} h_i\theta_i}{\sum_{i=1}^{N} h_i} = K_u a\Theta$$

where, $\alpha_i = \dfrac{h_i}{\sum_{i=1}^{N} h_i}$, $a = [\alpha_1 \quad \alpha_2 \quad \cdots \quad \alpha_N]$

and $\Theta = [\theta_1 \quad \theta_2 \quad \cdots \quad \theta_N]^T$.

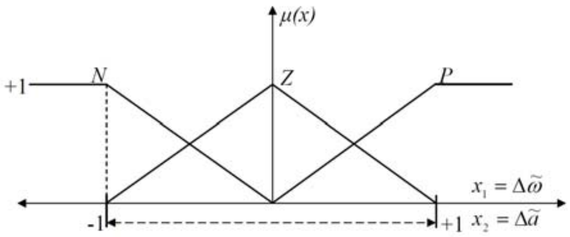

Figure 1. Triangular MFs considered for an FLPSS input variables.

The firing strength of the i^{th} rule (h_i) is calculated based on interpreting the conjunction "and" as a product of the values of the MFs corresponding to the measured quantities $\Delta\omega$ and Δa. For example, the firing strength of the shaded rule in Table 1 is given by $h_6 = \mu_Z(\Delta\tilde{\omega}) \times \mu_P(\Delta\tilde{a})$, where $\Delta\tilde{\omega}$ and $\Delta\tilde{a}$ are the normalized values of $\Delta\omega$ and Δa respectively, i.e., $\Delta\tilde{\omega} = K_\omega\Delta\omega$ and $\Delta\tilde{a} = K_a\Delta a$. In an FLPSS, the values $\theta_i, i = 1,..., N$ are set once and kept constant afterwards. As a common practice, the values of θ_i, $i = 1,...,9$ are set so that $\theta_1 = \theta_2 = \theta_4 = \vartheta^-$, $\theta_3 = \theta_5 = \theta_7 = \vartheta^0$ and $\theta_6 = \theta_8 = \theta_9 = \vartheta^+$. As a result, the output of an FLPSS turns out to have only three MFs whose centroids are ϑ^-, ϑ^0 and ϑ^+. In the following subsection, the FLPSS output MFs are assumed to be singletons.

B. Small Signal Model of the 3-Rule Based FLPSS

After defuzzification, the crisp control output U_{pss} of an FLPSS is given by

$$\begin{aligned} U_{pss} = K_u \{ & \mu_N(\Delta\tilde{\omega}) \times \mu_N(\Delta\tilde{a}) \times \vartheta^- + \mu_N(\Delta\tilde{\omega}) \times \mu_Z(\Delta\tilde{a}) \times \vartheta^- \\ & + \mu_N(\Delta\tilde{\omega}) \times \mu_P(\Delta\tilde{a}) \times \vartheta^0 + \mu_Z(\Delta\tilde{\omega}) \times \mu_N(\Delta\tilde{a}) \times \vartheta^- \\ & + \mu_Z(\Delta\tilde{\omega}) \times \mu_Z(\Delta\tilde{a}) \times \vartheta^0 + \mu_Z(\Delta\tilde{\omega}) \times \mu_P(\Delta\tilde{a}) \times \vartheta^+ \\ & + \mu_P(\Delta\tilde{\omega}) \times \mu_N(\Delta\tilde{a}) \times \vartheta^0 + \mu_P(\Delta\tilde{\omega}) \times \mu_Z(\Delta\tilde{a}) \times \vartheta^+ \\ & + \mu_P(\Delta\tilde{\omega}) \times \mu_P(\Delta\tilde{a}) \times \vartheta^+ \} \end{aligned}$$

If we consider the dynamic stability of a power system, i.e. small signal stability where $|\Delta\omega| > \varepsilon \to 0^+$; thus the input MFs can be calculated as

$$\mu_N^{(0)}(\Delta\tilde{\omega}) = \mu_N^{(0)}(\Delta\tilde{a}) = 0, \quad \mu_Z^{(0)}(\Delta\tilde{\omega}) = \mu_Z^{(0)}(\Delta\tilde{a}) = 1,$$
$$\mu_P^{(0)}(\Delta\tilde{\omega}) = \mu_P^{(0)}(\Delta\tilde{a}) = 0$$

The small perturbed output control is given by

$$\Delta U_{pss} = K_u \begin{Bmatrix} \Delta\mu_N(\Delta\tilde{\omega}) \times \vartheta^- + \Delta\mu_Z(\Delta\tilde{\omega}) \times \vartheta^0 + \Delta\mu_P(\Delta\tilde{\omega}) \times \vartheta^+ \\ + \Delta\mu_N(\Delta\tilde{a}) \times \vartheta^- + \Delta\mu_Z(\Delta\tilde{a}) \times \vartheta^0 + \Delta\mu_P(\Delta\tilde{a}) \times \vartheta^+ \end{Bmatrix}$$

$$\Delta\mu_N(\Delta\tilde{\omega}) = -K_\omega\Delta\omega, \Delta\mu_N(\Delta\tilde{a}) = -K_a\Delta a, \Delta\mu_Z(\Delta\tilde{\omega}) = 0,$$
$$\Delta\mu_Z(\Delta\tilde{a}) = 0, \Delta\mu_P(\Delta\tilde{\omega}) = K_\omega\Delta\omega, \ \Delta\mu_P(\Delta\tilde{a}) = K_a\Delta a,$$

$$\begin{aligned} \Delta U_{pss} = K_u \{ & -K_\omega\Delta\omega \times \vartheta^- + K_\omega\Delta\omega \times \vartheta^+ \\ & - K_a\Delta a \times \vartheta^- + K_a\Delta a \times \vartheta^+ \} \end{aligned}$$

$$\Delta U_{pss} = \underbrace{K_u K_\omega(\vartheta^+ - \vartheta^-)}_{k_p}\Delta\omega + \underbrace{K_u K_a(\vartheta^+ - \vartheta^-)}_{k_d}\Delta a$$

$$\Delta U_{pss} = k_p\Delta\omega + k_d\Delta a$$

For a fixed structure FLPSS: $\vartheta^+ = 1$ and $\vartheta^- = -1$ which in turn leads to $k_p = 2K_uK_\omega$ and $k_d = 2K_uK_a$. Accordingly, it is verified that an FLPSS serves as a conventional PD controller when the power system undergoes small signal disturbance. As a result, the problem of selecting scaling factors of an FLPSS to guarantee robust dynamic stability is transformed into that of synthesizing a robust PD controller.

III. POWER SYSTEM UNCERTAINTY

The test system comprises a single-machine connected to an infinite-system through a tie lie line. Such infinite system may represent Thevenin's equivalent of a large interconnected power system. System dynamics are represented by four non-linear differential equations as given in [15]. System data are given in the Appendix. The block diagram for linearized model of such system as proposed by deMello and Concordia [13] is shown in Figure 1. The model parameters k_1-k_6 are load-dependent and have to be computed at each operating point that is fully described by both active and reactive powers P, Q. These parameters can be expressed as explicit functions in P and Q as derived in [15]. Open loop transfer function (TF) is in turn load-dependent and hence it is more convenient to accomplish the design. At any operating point, such TF has a general form given by:

$$G_p(s) = \frac{-b_1 s}{a_4 s^4 + a_3 s^3 + a_2 s^2 + a_1 s + a_0} \tag{1}$$

The coefficients a_0, a_1, a_2 and b_1 vary according to a vector ρ which consists of two independent quantities (machine loading P and Q), *i.e.*, $\rho = [P \quad Q]^T$ while a_3 and a_4 are always constant and independent of machine loading. The vector ρ takes values in a *rectangular* whose vertices are given by $(\underline{P} \quad \underline{Q}), (\underline{P} \quad \overline{Q}), (\overline{P} \quad \underline{Q})$ and $(\overline{P} \quad \overline{Q})$. Simply, any change in P and/or Q leads to corresponding changes in a_0, a_1, a_2 and b_1. So as P and Q vary over their prescribed intervals, Equation 1 describes a family of plants rather than a nominal plant. Since a_0, a_1, a_2 and b_1 depend simultaneously on ρ, this family of plants can not be exactly described by an interval plant, but as a subset of the following interval plant:

$$\mathcal{G}_p(s) = \frac{-[\underline{b}_1 \quad \overline{b}_1]s}{[\underline{a}_4 \quad \overline{a}_4]s^4 + [\underline{a}_3 \quad \overline{a}_3]s^3 + [\underline{a}_2 \quad \overline{a}_2]s^2 + [\underline{a}_1 \quad \overline{a}_1]s + [\underline{a}_0 \quad \overline{a}_0]} \tag{2}$$

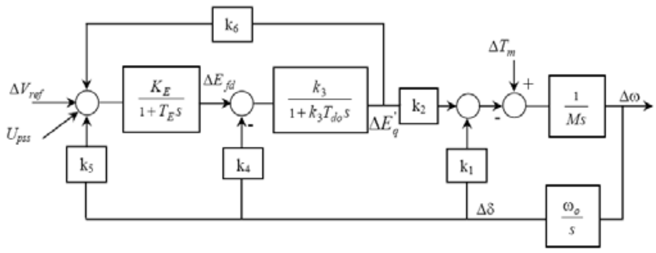

Figure 2. Block diagram of the linearized model [1]

As result, if this interval plant is robustly-stable, the family of plants is robustly-stable as well. However, instability of such interval plant does not imply instability of the family of plants. The bounds of each coefficient in this interval plant can easily be computed.

IV. DESIGN OF ROBUST PD-BASED PSS

Hurwitz stability of an interval polynomial like that given by (3) is often examined via Kharitonov theorem [16-17]. The positive feedback control system shown in Figure 3 has the following characteristic polynomial:

$$D(s) - (K_p + K_d s)N(s) = 0 \tag{3}$$

The influence in operating point has been addressed using the interval plant model described in the previous section. According to Kharitonov, it suffices to insure simultaneous stabilization of the following extreme plants only, i.e.

$$D_i(s) - (k_p + k_d s)N_j(s) = 0, \quad i = 1,2,3,4, \quad j = 1,2 \tag{4}$$

$$\Delta_1(k_p, k_d, s) = \underline{a}_4 s^4 + \overline{a}_3 s^3 + (\overline{a}_2 + k_d \underline{b}_1)s^2 + (\underline{a}_1 + k_p \underline{b}_1)s + \underline{a}_0$$
$$\Delta_2(k_p, k_d, s) = \underline{a}_4 s^4 + \underline{a}_3 s^3 + (\overline{a}_2 + k_d \underline{b}_1)s^2 + (\overline{a}_1 + k_p \underline{b}_1)s + \underline{a}_0$$
$$\Delta_3(k_p, k_d, s) = \overline{a}_4 s^4 + \overline{a}_3 s^3 + (\underline{a}_2 + k_d \underline{b}_1)s^2 + (\underline{a}_1 + k_p \underline{b}_1)s + \overline{a}_0$$
$$\Delta_4(k_p, k_d, s) = \overline{a}_4 s^4 + \underline{a}_3 s^3 + (\underline{a}_2 + k_d \underline{b}_1)s^2 + (\overline{a}_1 + k_p \underline{b}_1)s + \overline{a}_0$$
$$\Delta_5(k_p, k_d, s) = \underline{a}_4 s^4 + \overline{a}_3 s^3 + (\overline{a}_2 + k_d \overline{b}_1)s^2 + (\underline{a}_1 + k_p \overline{b}_1)s + \underline{a}_0$$
$$\Delta_6(k_p, k_d, s) = \underline{a}_4 s^4 + \underline{a}_3 s^3 + (\overline{a}_2 + k_d \overline{b}_1)s^2 + (\overline{a}_1 + k_p \overline{b}_1)s + \underline{a}_0$$
$$\Delta_7(k_p, k_d, s) = \overline{a}_4 s^4 + \overline{a}_3 s^3 + (\underline{a}_2 + k_d \overline{b}_1)s^2 + (\underline{a}_1 + k_p \overline{b}_1)s + \overline{a}_0$$
$$\Delta_8(k_p, k_d, s) = \overline{a}_4 s^4 + \underline{a}_3 s^3 + (\underline{a}_2 + k_d \overline{b}_1)s^2 + (\overline{a}_1 + k_p \overline{b}_1)s + \overline{a}_0$$

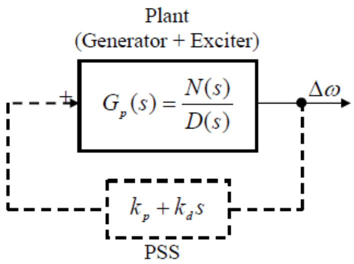

Figure 3. Equivalent block diagram for the closed loop system.

These eight extreme polynomials can be reduced to only four polynomials if and only if the controller parameters assume positive values which in turn ensure the positivity of all scaling factors. This reduction falls out directly from the fact that the coefficients $(a_2 + k_d b_1)$ and $(a_1 + k_p b_1)$ have their upper bounds as $(\overline{a}_2 + k_d \overline{b}_1)$ and $(\overline{a}_1 + k_p \overline{b}_1)$ respectively and have their lower bounds as $(\underline{a}_2 + k_d \underline{b}_1)$ and $(\underline{a}_1 + k_p \underline{b}_1)$ respectively providing both k_p and k_d are nonnegative. In general, negativity of k_p and/or k_d cause sign change in such coefficients which makes it obligatory to consider all extreme plants. Consequently, polynomials $\Delta_1, \Delta_2, \Delta_7$ and Δ_8 are trustily discarded. Stability of remnant polynomials, i.e. $\Delta_3, \Delta_4, \Delta_5$ and Δ_6 are examined using RH array. Stability of a nominal polynomial is firstly examined to derive general stability constraints; thereafter extreme polynomials have to satisfy these constraints. Consider the nominal closed loop polynomial as follows:

$$a_4 s^4 + a_3 s^3 + (a_2 + b_1 k_d)s^2 + (a_1 + b_1 k_p)s + a_0 = 0 \tag{5}$$

Then construct RH table as follows:

$$\begin{array}{l|lll}
s^4 & a_4 & a_2 + b_1 k_d & a_0 \\
s^3 & a_3 & a_1 + b_1 k_p & \\
s^2 & R_{11} = a_2 a_3 + a_3 b_1 k_d - a_1 a_4 - a_4 b_1 k_p & a_0 a_3 & \\
s^1 & R_{11} = (a_2 a_3 + a_3 b_1 k_d - a_1 a_4 - a_4 b_1 k_p)(a_1 + b_1 k_p) - a_0 a_3^2 & & \\
s^0 & a_0 a_3 & &
\end{array}$$

Noticeably, positivity of R_{11} implies that of R_{21} and hence it is sufficient to enforce the positivity of R_{11} , *i.e.*

$$(a_2 a_3 + a_3 b_1 k_d - a_1 a_4 - a_4 b_1 k_p)(a_1 + b_1 k_p) - a_0 a_3^2 > 0$$

Therefore;

$$k_d > (a_4/a_3)k_p + (a_1 a_4 - a_2 a_3)/(a_3 b_1) + (a_0 a_3/b_1)/(a_1 + b_1 k_p) \tag{6}$$

This condition must be satisfied for the four extreme polynomials as follows:

$$
\begin{aligned}
k_d^3 &> (\overline{a}_4/\overline{a}_3)k_p + (\underline{a}_1\overline{a}_4 - \underline{a}_2\overline{a}_3)/(\overline{a}_3\underline{b}_1) + (\overline{a}_0\overline{a}_3/\underline{b}_1)/(\underline{a}_1 + \underline{b}_1 k_p) \\
k_d^4 &> (\overline{a}_4/\underline{a}_3)k_p + (\overline{a}_1\overline{a}_4 - \underline{a}_2\underline{a}_3)/(\underline{a}_3\underline{b}_1) + (\overline{a}_0\underline{a}_3/\underline{b}_1)/(\overline{a}_1 + \underline{b}_1 k_p) \\
k_d^5 &> (\underline{a}_4/\overline{a}_3)k_p + (\underline{a}_1\underline{a}_4 - \overline{a}_2\overline{a}_3)/(\overline{a}_3\overline{b}_1) + (\underline{a}_0\overline{a}_3/\overline{b}_1)/(\underline{a}_1 + \overline{b}_1 k_p) \\
k_d^6 &> (\underline{a}_4/\underline{a}_3)k_p + (\overline{a}_1\underline{a}_4 - \overline{a}_2\underline{a}_3)/(\underline{a}_3\overline{b}_1) + (\underline{a}_0\underline{a}_3/\overline{b}_1)/(\overline{a}_1 + \overline{b}_1 k_p)
\end{aligned} \tag{7}
$$

As a result, robust stability of the interval plant is guaranteed *iff*

$$k_d \in \bigcap\nolimits_{i=3,4,5,6} k_d^i \tag{8}$$

V. COMPUTATION OF ALL ROBUST FLPSS PARAMETERS

Usually, a power system operates at different load levels and various generation patterns. It is assumed that uncertainty in the power system model is only due to constantly variations in load levels. However, the proposed technique can rigorously account for different types of uncertainties such as uncertainty in the parameters of the generator and tie line reactance. Machine loading in terms of active and reactive powers (P, Q) are assumed to vary over real compact intervals given by $P \in [0.2 \quad 1.0]$, $Q \in [-0.2 \quad 0.5]$. Interval coefficients of the proposed interval plant can precisely computed as follows:

$$\underline{a}_i = \min_{\substack{P\in[\underline{P} \ \ \overline{P}],\\ Q\in[\underline{Q} \ \ \overline{Q}]}} a_i, \qquad \overline{a}_i = \max_{\substack{P\in[\underline{P} \ \ \overline{P}],\\ Q\in[\underline{Q} \ \ \overline{Q}]}} a_i, \qquad i = 0,1,\ldots,4 \tag{9}$$

Using a fine grid on P and Q intervals, the bounds of the interval plant coefficients can be calculated using these min-max equalities as follows:

$a_4 = [1 \quad 1], a_3 = [20.463 \quad 20.463], a_2 = [22.413 \quad 87.206],$

$a_1 = [131.52 \quad 792.93], a_0 = [569.89 \quad 1763.7], b_1 = [2.439 \quad 11.574]$

Marginal stability of the four extreme polynomials is governed by the following four equality constraints:

$$
\begin{aligned}
k_d^{3cr} &= 0.049k_p - 6.56 + 14792/(131.5 + 2.44k_p), \\
k_d^{4cr} &= 0.049k_p + 6.7 + 14792/(793 + 2.44k_p), \\
k_d^{5cr} &= 0.049k_p - 7.0 + 1008/(131.5 + 11.57k_p), \\
k_d^{6cr} &= 0.049k_p - 4.2 + 1008/(793 + 11.57k_p)
\end{aligned} \tag{10}
$$

These critical stability equality constraints are plotted in Figure 4; remarkably the boundaries of robust stability region are sufficiently governed by critical stability constraints of Δ_3 and Δ_4 only where:

$$k_d^{cr} = \begin{cases} 0.049k_p - 6.56 + 14792/(131.5 + 2.44k_p) & k_p \le 187.5 \\ 0.049k_p + 6.70 + 14792/(793 + 2.44k_p) & k_p > 187.5 \end{cases} \tag{11}$$

This robust stability region describes the basin of all robust stabilizing parameters, i.e. k_ω, k_a and k_u of an FLPSS. For example if k_u is set to 0.5, then $k_\omega = k_p$ and $k_a = k_d$; generally $k_\omega = 0.5k_p / k_u$ and $k_a = 0.5k_d / k_u$.

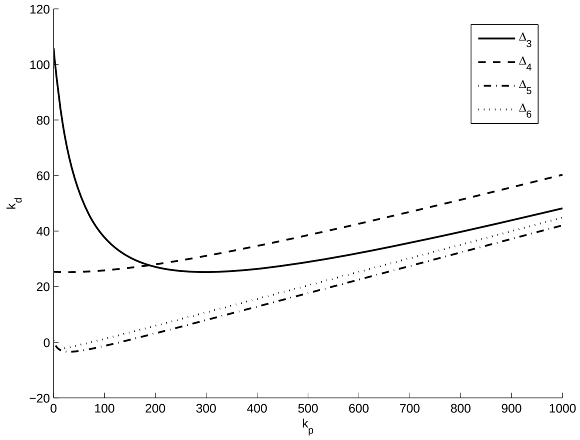

Figure 4. Region of robust stability in k_p-k_d parameter plane.

VI. SIMULATION RESULTS

The data of test system and its nonlinear model is given in the Appendix.

A. Robust stability test

Robust stability of the closed loop system at different operating points varying over $P \in [0.2 \quad 1.0]$ and $Q \in [-0.2 \quad 0.5]$ is the essential objective of this paper. As depicted in Figure 4, there are different values of k_p and k_d that can robustly stabilize the entire range of operating conditions. An applicant controller parameters are chosen as $k_p = 50$ and $k_d = 60$. The roots of the closed loop characteristic polynomials of 1024 plants are computed where the minimum damping factor of each plant is shown in Figure 5. Remarkably, all plants have damping factors that are less than -0.5sec^{-1}.

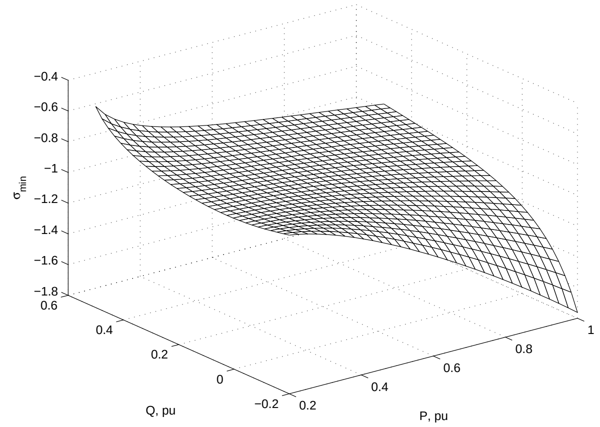

Figure 5. Minimum damping factors for 1024 plants covering the full operating range $[0.2 \quad 1.0] \times [-0.2 \quad 0.5]$ with K_p =50, K_d=60

B. Transient Stability tests

The transient stability is examined by simulating the nonlinear model of the considered system. The performance of the candidate controller is tested for a heavy load with leading power factor operating point given by P=1.0 and Q=-0.15 *pu* when the system undergoes a 0.1 pu step change in the mechanical torque for 0.1 sec. the system response is shown in Figure 6. The candidate controller considers the same output limits and the same filtering conditions as presented in [15]. The controller output is limited within the standard PSS output limits ±0.1 that can not affect the profile of the terminal voltage dramatically. Remarkably, conventional PSS fails to maintain system stability while the proposed design achieves good damping characteristics.

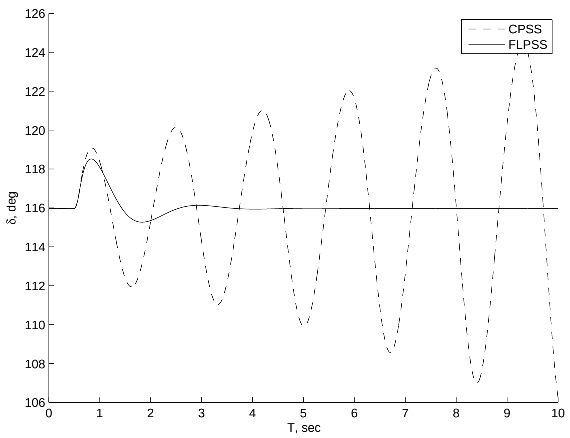

Figure 6. Rotor angle response for 0.1pu step change in T_m.

VII. Conclusions

Robustness of conventional fuzzy logic power system stabilizers (FLPSSs) always lacks mathematical reasoning where the performance of such a stabilizer is often reviewed by transient response of the closed loop system. Necessary and sufficient conditions that guarantee robust dynamic stability of an FLPSS are presented. A small-signal model of an FLPSS is developed to study the dynamic stability of a single-machine infinite-bus power system. Such a small signal model is proved to be a conventional proportional-derivative (PD) controller whose parameters are expressed in terms of normalizing factors of FLPSS. The parameters of such a PD controller, are tuned to guarantee robust dynamic stability, thereafter normalizing factors can be directly computed. Synthesis of a robust PD controller is based on simultaneous stabilization of a finite number of extreme characteristic polynomials that are derived using Kharitonov theorem. A convex region in the K_p-K_d parameter plane which guarantees robust stability is obtained using Routh-Hurwitz array. Such a region presents the pool for all robust normalizing factors of an FLPSS. Simulation results are presented to confirm the effectiveness of the proposed approach.

Appendix

Data of a single-machine infinite-bus system:

$X_d = 1.6\ pu, X_q = 1.55\ pu, X_d^{'} = 0.32\ pu, T_{do}^{'} = 6\sec., M = 10\sec,$

$K_E = 25, T_E = 0.05\sec., E_{fd}^{\min} = -5\ pu, E_{fd}^{\max} = 5\ pu,\ V^{\infty} = 1\ pu,$

$\omega_o = 2\pi \times 50\ rad/\sec.$

Nonlinear model:

$$\dot{\delta} = \omega_o \omega$$
$$\dot{\omega} = \left(T_m - (E_q^{'} I_q + (X_q - X_d^{'}) I_d I_q)\right) / M$$
$$\dot{E}_q^{'} = -\left(E_q^{'} + (X_d - X_d^{'}) I_d - E_{fd}\right) / T_{do}^{'}$$
$$\dot{E}_{fd} = \left(K_E V_{ref} + U_{pss} - K_E V_T - E_{fd}\right) / T_E$$
$$R_e I_d - (X_e + X_q) I_q + V^{\infty} \sin\delta = 0$$
$$R_e I_q + (X_e + X_d^{'}) I_d + E_q^{'} + V^{\infty} \cos\delta = 0$$

References

[1] O. Malik and K. El-Metwally, "Fuzzy logic controllers as power system stabilizers", In M. El-Hawary (ed.), Electric power applications of fuzzy logic, New York, IEEE Press, 1998.

[2] K. El-Metwally, and O. Malik, "Application of fuzzy-logic stabilizers in a multimachine environment," IEE Proc. Generation, Transmission and Distribution, vol. 143, no. 3, pp. 263-268, 1996.

[3] K. El-Metwally and O. Malik, "Parameter tuning for fuzzy logic control", Proc. IFAC World Congress on Automation and Control, pp. 581-584, Sydney 1993.

[4] P. Hong, and K. Tomosovic, "Design and Analysis of an Adaptive Fuzzy Power System Stabilizer," IEEE Trans. Energy Conversion, vol. 11, no. 2, pp. 455-461, June 1996.

[5] T. Abdelazim and O. P. Malik, "An adaptive power system stabilizer using on-line self-learning fuzzy systems," Proc. of IEEE/PES General Meeting, vol. 3, pp.1715–1720, Toronto, ON, Canada, 13-17 July 2003.

[6] A. L. Elshafei, K. El-Metwally, and A. Shaltout "A variable-structure adaptive fuzzy-logic stabilizer for single and multi-machine power systems," Control Engineering Practice, vol. 13, no. 4, pp. 413-423, 2004.

[7] M. A. Abido, and Y. L. Abdel-Magid, "Tuning of a fuzzy logic power system stabilizer using genetic algorithms," IEEE Intr. Conf. Evolutionary Computations, pp. 595–599, 13-16 Apr. 1997.

[8] M. Dubey, "design of genetic algorithm based fuzzy logic power system stabilizers in multimachine power system," intr. Conf. Power System Tech. and IEEE Power India conf. Joint, pp. 1-6, 12-15 Oct. 2008.

[9] K. R. Sudha, V. S. Vakula, and R. Vijayasanthi, "Particle swarm optimization in fine tuning of pid fuzzy logic power system stabilizer," ieee intr. Conf. Advances in computing, control &telecommucations tech., pp. 356–358, 28-29 Dec. 2009.

[10] O. Abedinia, B. Wyns, and A. Ghasemi, "Robust fuzzy PSS design using ABC," 10th intr. Conf. Environment and electrical engineering (EEEIC), pp.1-4, 2011.

[11] D. Drainkov, H. Hellendoorn, and M. Reinfrank, An introduction to fuzzy control, Berlin: Springer, 1993.

[12] B. Kosko, fuzzy engineering, Englewood Cliffs: Prentice-Hall, 1997.

[13] F. P. DeMello and C. Concordia, "Concepts of synchronous machine stability as affected by excitation control," IEEE Trans. Power Apparatus and Systems, vol. 88, no. 4, pp. 316-329, April 1969.

[14] E. V. Larsen and D. A. Swann, "Applying power system stabilizers: Parts I-III," IEEE Trans. Power Apparatus and Systems, vol. 100, no. 6, pp. 3017-3046, June 1981.

[15] H. M. Soliman, A.L. Elshafei, A. Shaltout, and M. F. Morsi, "Robust Power System Stabilizer," IEE Proc. Generation, Transmission and Distribution, vol. 147, no. 5, pp.285–291, Sept. 2000.

[16] V. L. Kharitonov, "Asymptotic stability of an equilibrium position of a family of systems of linear differential equations," *Differential'nye Uravnenya*, vol. 14, no. 11, pp. 2086-2088.

[17] S. P. Bhatacharyya, H. Chapellat, and L. H. Keel, Robust Control: the parametric approach, Prentice-Hall, 1995.