Robust Stability Constraints for Optimal Lead Lag PSS Design Using Interval Approach

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Abstract. Electric vehicles have become much more common in our daily lives as a result of technological advancements. This may cause tremendous growth in the consumption of electrical energy. The globe is moving toward the alternative energy generation as a result of global warming and the depletion of fossil resources. Hence ingress of renewable energy into the power sector is inevitable resulting in unavoidable power system uncertainty. Consequently, synchronous generators must function in a wide range of unpredictably changing operational conditions. Hence, tuning of Power System Stabilizer (PSS) parameters over a wide range is required. This research provides a new way for constructing a lead-lag PSS that can effectively stabilize the system under wide operational scenarios. The PSS parameters are tuned using the simple stability conditions proposed to ensure power system stability, and the interval coefficients quantify the uncertainty in the system parameters under practical situations. To improve the proposed lead-lag PSS's performance, an objective function is defined. The Jaya algorithm is used to fine-tune the PSS parameters. The robustness of the proposed PSS design is confirmed by a case study of a single machine infinite bus (SMIB) power system. Simulation results reveal that the suggested lead-lag PSS is more successful than other well-known controllers in the literature when the system is induced with a step load disturbance for a wide set of operational states.

Keywords: Uncertainty · SMIB · Interval system · lead lag PSS · Jaya algorithm

1 Introduction

Power engineers are concerned with the mitigation of Low Frequency Oscillations (LFO) in a huge power system network. Because, the weak damping effect of the oscillations restrict the tie-line power flows and can even induce blackouts. The net damping effect is improved by adding an auxiliary device to the field system, such as a PSS [1]. The change in speed, accelerating power [2], or a combination of these two can be used as the stabilizer's input, while the stabilizer's output is the voltage provided to the field system. Demello [3] provides a framework for designing PSS for many of the existing approaches. On the other hand, classical PSS design is for a specific operating condition, therefore change in the operating state can lead to poor PSS performance and

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even system instability. As a result of the varying system conditions, tuning the PSS parameters over a wide range is required to assure power system stability. Furthermore, the design techniques must result in acceptable PSS performance for different operational conditions. However there exist many methodologies to tune the PSS parameters using linear control approaches such as linear quadratic regulator [4], pole placement [5], sliding mode control [6], linear matrix inequalities [7], quantitative feedback theory [8], H_2 or H_∞ [9] framework and non-linear methods like adaptive control [10], self-tuning [11] and heuristic dynamic programming [12] methods. Also, artificial intelligence and optimization techniques [13] were used to determine the PSS settings for wide range of operational scenarios.

However, several of the suggested solutions require a large amount of system variable data or extensive eigen value analysis. In addition, to deal with large load variation, the system has a separate controller for each loading state, such as heavy, nominal, or light to provide proper dynamic stability. As a result of this, the system's costs may rise. Artificial Intelligence approaches like fuzzy logic and neural networks provide promising results for nonlinear power system stability. But the drawback of these methods include the complexity of training for ANN and the need for extensive system knowledge for Fuzzy logic. However, system uncertainties can be dealt with adaptive and robust control techniques. In the adaptive method, system conditions are determined online and tune the controller parameters. But PSS settings may be improperly tuned due to time delays in the PSS, presence of noise, and loss of input data. However, in robust control, all possible practical operating conditions are considered offline and design a fixed controller hence, favourable in implementing for practical power systems. But, a robust control method like H_∞ attains a controller of higher-order and LMI technique needs to find the weight functions.

Although interval systems absorb all system uncertainties and store them in transfer function coefficients, this method has received little attention in the power systems community. However, the present PSS design methodologies that use interval systems employ kharitonov theorem [14]. But, according to it, the interval coefficients should be independent of each other hence, results may be conservative. On the other hand, stability of interval system employing PSO, tune the poles of eight kharitonov polynomials [15] necessitates a significant amount of calculation. To overcome the limitations and shortcomings of existing methodologies simplified inequality stability constraints are derived directly from interval polynomial without the requirement to formulate the Kharitonov polynomials in this research study. The Jaya optimization [16] algorithm is employed to fine-tune the PSS parameters while meeting the inequality stability constraints and reducing the stated objective function.

2 Problem Formulation

For small signal stability, the system dynamics can be given by the equations that are linearized around the operational state, and Fig. 1 shows the block diagram of linearized equations known as the Heffron-Pilliphs model [3]. With the exception of k_3, all of the model parameters from k_1 to k_6 depend on load, Manson's rule can be used to compute the plant's transfer function G(s) without the controller and it is given as:

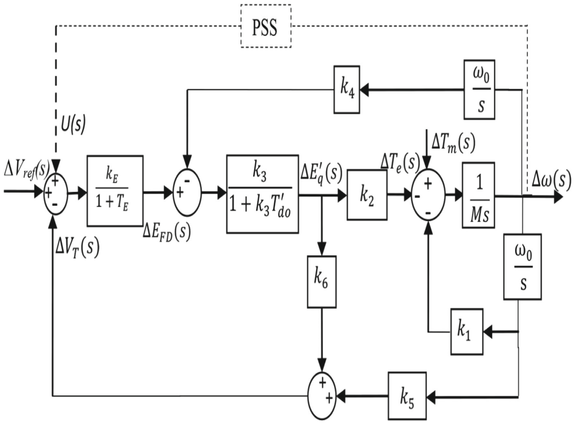

Fig. 1. SMIB power system linearized model

$$G(s) = \frac{\Delta\omega(s)}{\Delta V_{ref}(s)} = \frac{-bs}{a_4 s^4 + a_3 s^3 + a_2 s^2 + a_1 s + a_0} \tag{1}$$

The transfer function coefficients are:

$$\left.\begin{array}{l} a_4 = MTT_E; \quad a_3 = M(T + T_E); \quad a_2 = M + 314k_1TT_E + k_Ek_3k_6M \\ a_1 = 314k_1(T + T_E) - 314k_2k_3k_4T_E; \\ a_0 = 314(k_1 - k_2k_3k_4 - k_Ek_2k_3k_5 + k_Ek_1k_3k_6) \text{ and } b = k_Ek_2k_3 \end{array}\right\} \tag{2}$$

where $T = k_3 T'_{do}$

The field time constant, machine inertia constant, exciter time constant, and machine loading all influence the transfer function coefficients. As a result, as the system load changes over time, so do the transfer function coefficients. The coefficient upper and lower limits can be calculated by changing the loading condition throughout a specific range, i.e. $P \in [P_L, P_H]$ and $Q \in [Q_L, Q_H]$. Then the following polynomial in interval form can be used to approximate the transfer function.

$$G(s) = \frac{N(s,b)}{D(s,a)} = \frac{-[b^-, b^+]s}{[a_4^-, a_4^+]s^4 + [a_3^-, a_3^+]s^3 + [a_2^-, a_2^+]s^2 + [a_1^-, a_1^+]s + [a_0^-, a_0^+]} \tag{3}$$

where $a_i^- = \underset{P,Q}{min}(a_i); \quad a_i^+ = \underset{P,Q}{max}(a_i); \quad b^- = \underset{P,Q}{min}(b); \quad b^+ = \underset{P,Q}{max}(b) \, for \, i = 1, 2, 3, 4.$

The open loop system is unstable at particular operational points. As a result, a controller must be developed to keep the system stable under all operating conditions. This research work presents how to construct a fixed parameter robust Lead Lag PSS, as the operational state varies over a specific bound, such as $P \in [P_L, P_H]$ and $Q \in [Q_L, Q_H]$. The fixed polynomial stability conditions given by Nie and Xie [17] are used to develop the new simple stability conditions. The robust controller parameters are then designed for a specific bound of operational states for the SMIB system using the newly developed necessary and sufficient conditions.

3 Development of New Stability Constraints

Consider a real polynomial of n[th] order in interval form:

$$P(s,p) = p_n s^n + p_{n-1}s^{n-1} + -- + p_1 s + p_0 \tag{4}$$

where the coefficient p_j defined in terms of system parameters is always within the lower and higher limits as the variables changes due to system uncertainty as:

$$p_j = \left[p_j^-, p_j^+\right] \mathit{for}\ j = 1, 2, 3 \ldots n.$$

The polynomial degree is considered to be constant throughout the interval family and referred as an interval polynomial. If the family of polynomials given by Eq. (4) is Hurwitz then the interval polynomial is said to be stable. The new stability constraints for this interval polynomial (4) are constructed using the simple stability conditions of a fixed polynomial developed by Nie and Xie [17]. They are as follows:

3.1 Lemma 1: The polynomial *P(s, p)* in interval form as given in Eq. (4) is Hurwitz for all $p_j \in \left[p_j^- p_j^+\right]$ *where* $j = 0, 1, 2, 3 \ldots n$ if and only if they satisfy the following necessary conditions.

$$p_j > 0\ \mathit{and}\ p_j p_{j+1} > p_{j-1}p_{j+2} \tag{5}$$

The above necessary conditions are further simplified into fixed coefficients as follows:

$$\left.\begin{array}{ll} p_j^+ \geq p_j^- > 0 & \mathit{for}\ j = 0, 1, 2, 3 \ldots n \\ p_j^- p_{j+1}^- > p_{j-1}^+ p_{j+2}^+ & \mathit{for}\ j = 1, 2, 3 \ldots n-2 \end{array}\right\} \tag{6}$$

3.2 Lemma 2: The polynomial *P(s, p)* in interval form as given in Eq. (4) is Hurwitz for all $p_j \in \left[p_j^- p_j^+\right]$ *where* $j = 0, 1, 2, 3 \ldots n$ if and only if they satisfy the following sufficient conditions.

$$p_j > 0\ \mathit{and}\ 0.4655 p_j p_{j+1} > p_{j-1}p_{j+2} \tag{7}$$

The above sufficient conditions in interval form are further simplified into the fixed coefficients as follows:

$$\left.\begin{array}{ll} p_j^+ \geq p_j^- > 0 & \mathit{for}\ j = 0, 1, 2, 3 \ldots n \\ 0.4655 p_j^- p_{j+1}^- > p_{j-1}^+ p_{j+2}^+ & \mathit{for}\ j = 1, 2, \ldots n-2 \end{array}\right\} \tag{8}$$

Hence, the robust stability conditions for a fifth order SMIB power system are as follows:

$$\left.\begin{array}{l} p_0^+ \geq p_0^- > 0;\ p_1^+ \geq p_1^- > 0;\ p_2^+ \geq p_2^- > 0;\ p_3^+ \geq p_3^- > 0; \\ p_4^+ \geq p_4^- > 0\ \mathit{and}\ p_5^+ \geq p_5^- > 0 \\ \frac{p_0^+ p_3^+}{p_1^- p_2^-} < 0.4655;\ \frac{p_1^+ p_4^+}{p_2^- p_3^-} < 0.4655\ \mathit{and}\ \frac{p_2^+ p_5^+}{p_3^- p_4^-} < 0.4655 \end{array}\right\} \tag{9}$$

The newly obtained necessary and sufficient stability conditions, given by Eq. (9) are applied to design an optimal Lead Lag PSS for a wide operating SMIB power system.

4 Designing a Lead Lag PSS for a Wide Operating SMIB Power System

As a case study the SMIB power system is taken with the machine data from [18]. Over the following ranges, the active power (P) and reactive power (Q) are considered to alter independently. i.e., $P \in [0.4, 1.0]$ and $Q \in [-0.1, 0.5]$, with the desired step size to get 1024 operational states. This includes almost all commonly seen operating circumstances. The interval coefficients are obtained from minimum and maximum values of each coefficient and are given by:

$$\left.\begin{array}{l} a_4 = [1, 1];\; a_3 = [22, 22];\; a_2 = [80, 106]; \\ a_1 = [574, 996];\; a_0 = [1030, 2550];\; b = [4.6, 11.55] \end{array}\right\} \quad (10)$$

The plant's open-loop interval transfer function is determined by substituting Eq. (10) into Eq. (3) as follows:

$$G(s) = \frac{[-4.6, -11.55]s}{[1, 1]s^4 + [22, 22]s^3 + [80, 106]s^2 + [574, 996]s + [1030, 2550]} \quad (11)$$

The minimum damping ratio (ζ_{min}) is computed for 1024 operational states to demonstrate the open-loop system's damping characteristics and it is presented in Fig. 2.

ζ_{min} is very low for certain operational states illustrating the weak dampening, causing the system to unstable in the face of uncertainty. To robustly stabilize the system for 1024 operational states a lead lag PSS as given by Eq. (12) is considered in this research study.

$$G_c(s) = K\frac{(1 + sT_1)}{(1 + sT_2)} \quad (12)$$

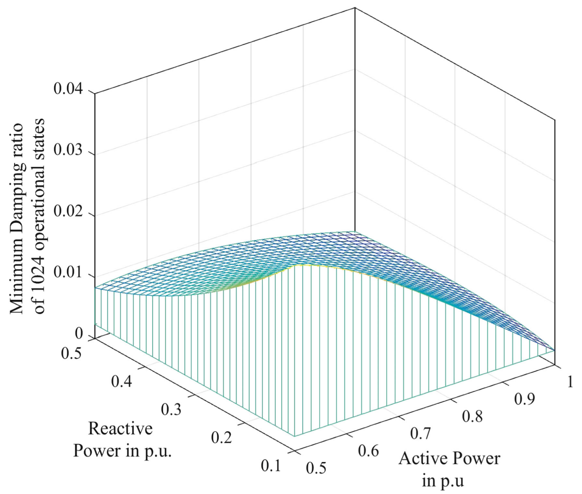

Fig. 2. The open loop system minimum damping ratio of 1024 operational states

where K is the controller gain and T_1, T_2 are the time constants. However, from [3], T_2 is taken as 0.05 to give satisfactory dynamic response. Consequently, the following equation gives the plant's closed-loop transfer function:

$$\begin{aligned} T(s) \\ = \frac{[-4.6, -11.55] * (1+0.05s) * s}{\begin{array}{l}[1, 1] * 0.05 * s^5 + ([22, 22] * 0.05 + [1, 1])s^4 + ([80, 106] * 0.05 + [22, 22])s^3 \\ \quad + ([574, 996] * 0.05 + ([80, 106] + [4.6, 11.55] * K * T_1)s^2 \\ \quad + ([1030, 2550] * 0.05 + [574, 996] + [4.6, 11.55]K)s + [1030, 2550]\end{array}} \end{aligned} \tag{13}$$

The closed-loop transfer function characteristic equation is obtained from above as follows:

$$\begin{aligned} D(s, a) &= [0.05, 0.05]s^5 + [2.1, 2.1]s^4 + [26, 27.3]s^3 \\ &\quad + [108.7 + 4.6 * K * T_1, 155.8 + 11.55 * K * T_1]s^2 \\ &\quad + [625.5 + 4.6 * K, 1123.5 + 11.55 * K]s + [1030, 2550] \end{aligned} \tag{14}$$

Apply the new stability conditions from Eqs. (9) to Eq. (14), the inequality constraints are determined as follows:

$$Constraint\ 1: \frac{(2550) * (27.3)}{[(625.5 + 4.6 * K) * (108.7 + 4.6 * K * T_1)]} - 0.4655 < 0 \tag{15}$$

$$Constraint\ 2: \frac{[1123.5 + 11.55 * K] * 2.1}{[108.7 + 4.6 * K * T_1] * 26} - 0.4655 < 0 \tag{16}$$

$$Constraint\ 3: \frac{[155.8 + 11.55 * K * T_1] * 0.05}{26 * 2.1} - 0.4655 < 0 \tag{17}$$

$$Constraint\ 4: \ - 625.5 - 4.6 * K < 0 \tag{18}$$

$$Constraint\ 5: \ - 108.7 - 4.6 * K * T_1 < 0 \tag{19}$$

The parameters of the lead lag PSS are minimized using the below objective function as:

$$J_{min} = abs(K) + abs(T_1) \tag{20}$$

The optimum parameters are found by minimizing Eq. (20) while meeting the set of inequality constraints defined by Eqs. (15)–(19). To compute the parameters of lead lag PSS, the proposed algorithm is constructed in MATLAB and uses the Jaya optimization technique. The following are the PSS parameters:

$$K = 5.3164, \ and \ T_1 = 4.9624 \tag{21}$$

5 Jaya Optimization Technique

Design variables are more prevalent in real time design challenges and settings. Furthermore, the impact of them to achieve the target is substantial and the program developer demands for global minima, even though the objective function may stick in local minima. Hence conventional approaches are inefficient for tackling such issues since they only compute local optima. As a result, an intelligent strategy is necessary for efficiently handling limited design problems. In this research work Jaya Optimization algorithm

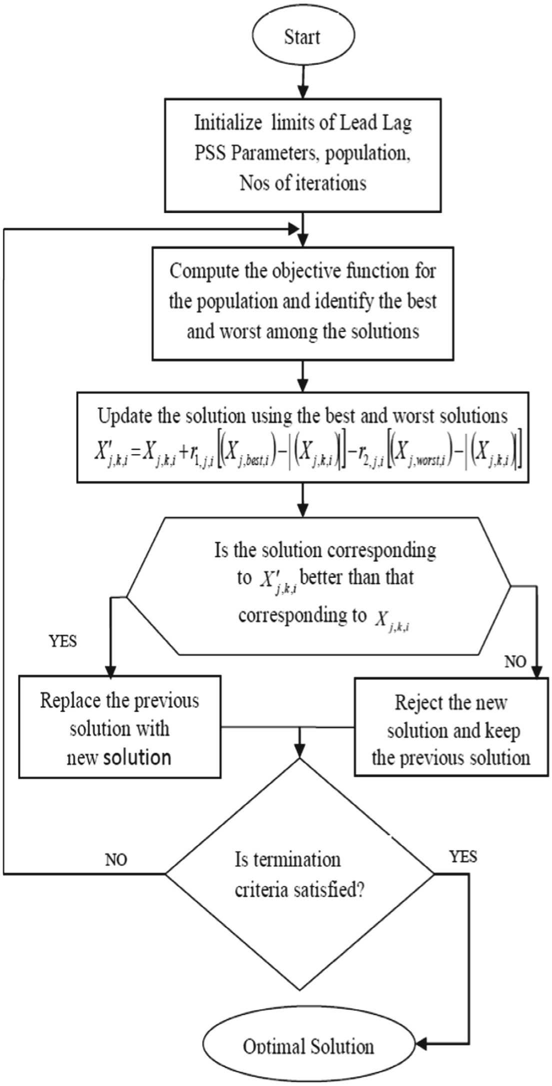

Fig. 3. Jaya Algorithm Flow Chart

is employed since it is free of algorithm specific parameters and reduces the computational efforts. Constraints handling was done by adopting penalty method. The flow chart shown in Fig. 3 presents the algorithm steps to attain the optimal solution.

6 Simulation Results and Discussions

For heavy, nominal and light operating states, the system is simulated using the Heffron-Philiphs model as given by Fig. 1 in MATLAB-SIMULINK. The efficiency of the proposed methodology is evaluated for each of the three scenarios by subjecting the system to 10% mechanical step disruptions. Figures 4, 5, and 6 depict the plant's speed deviation responses, respectively. The addition of PSS to the machine improves its dynamic stability.

The proposed lead lag PSS has a shorter settling time than the other prominent controllers in the literature even though peak values more or less same. Therefore, under various loading situations, the proposed Lead Lag PSS effectively dampens system oscillation for the provided disturbance. Therefore, under all operational situations, the proposed method outperforms the other controllers in terms of dynamic performance for the system's uncertainties.

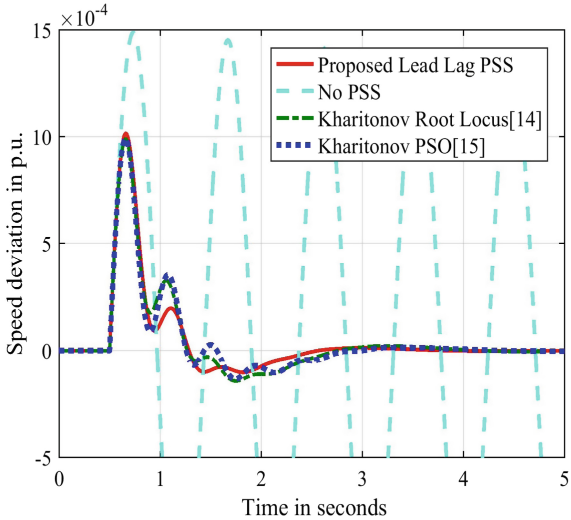

Fig. 4. Speed deviation response at heavy load for 10% step mechanical disturbance

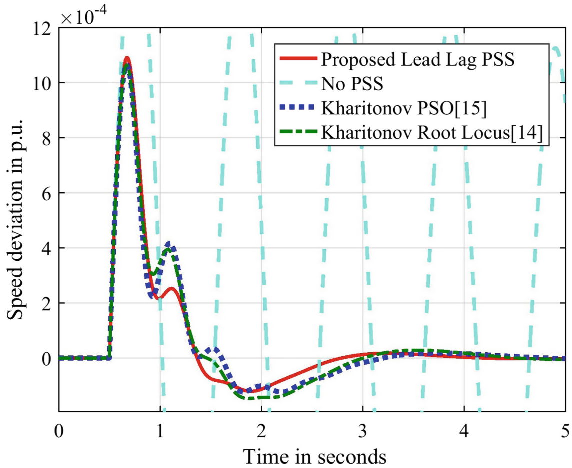

Fig. 5. Speed deviation response at nominal load for 10% step mechanical disturbance

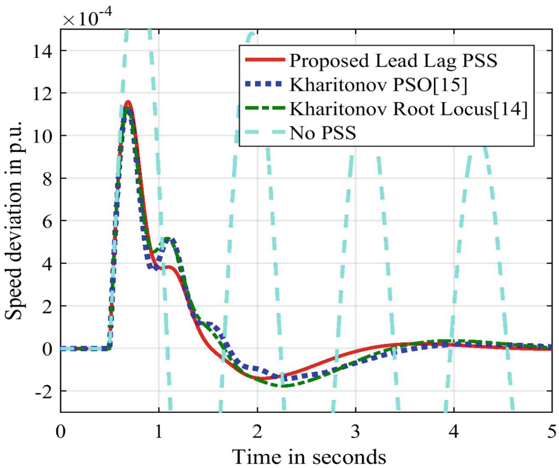

Fig. 6. Speed deviation response at light load for 10% step mechanical disturbance

7 Conclusion

In the proposed control scheme the PSS parameters are attained by satisfying the five simple stability constraints and minimizing the stated objective function using the JAYA optimization algorithm. Robust stability conditions are obtained directly from the closed loop transfer function of SMIB power system given in interval polynomial form. Whereas for PSS [15] the controllers parameters are tuned using the objective function that comprises eight kharitonov polynomials. The PSO optimization technique was employed to determine the design variables. Moreover for PSS [14], the root locus is obtained for eight extreme kharitonov polynomial and controller values are determined. Hence computational efforts reduce greatly with the proposed control scheme since there is no need of formulating the kharitonov polynomials and tuning the PSS parameters. The attained PSS parameters stabilizes the system for wide operational states and simulation results exhibit the efficiency of the proposed lead lag PSS compared to the notable PSS techniques.

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