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SYNTHESIS AND ROBUSTNESS ANALYSIS OF DAMPING CONTROL SYSTEMS SUBJECT TO PARAMETRIC UNCERTAINITIES

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Abstract: This paper proposes the studied of a robust stability analysis technique applied in the design of a Power System Stabilizer (PSS) for damping of electromechanical oscillations in electric power systems. To representation of the dynamic model of the system were considered uncertainties associated with coefficients of the transfer function, such uncertainties represent changes in the operating conditions of the system and become motive to the investigation of robust control strategies. The design methodology is structured to minimize the total deviation from the desired performance for the closed-loop system, specified by a family of characteristic polynomials. The design by robust pole-placement technique was associated to the robust control techniques such as linear programming and Chebyshev's theorem, which incorporate restrictions on the plant parameters and on the performance specifications the same. Controllers designed per pole-placement technique through the Diophantine equation were used to comparison. To evaluate controllers performance were analyzed the control signal using the ISE (integral square error), a cost function that integrates the square of the error. The results shows the good performance of the proposal technique, mainly when occurs change in the system operation point, and the conventional controller loses performance

Keywords: Robust stability, robust performance, PSS, linear programming, Chebyshev's theorem.

INTRODUCTION

In the last years, there has been developed various control design techniques to electric power systems, and a major concern for this has been the low frequency oscillations, which limit the power transfer among systems, besides causing loss of synchronism among generators, taking them to instability. In this context, are designed Power Systems Stabilizers (PSS), which apart from to extend the power transfer limit in transient conditions, provide a stable and secure operation for the electric power system, when subjected to small perturbations (Oliveira, 2005).

However, many controllers designed by conventional techniques consider linearized models around an operating point, without consider the parametric uncertainties of system, compromising its performance and efficiency (Rogers, 2000). Thus, this problem can be to got around through use of the robust control techniques, which allow to design robust controllers able to remain the robust stability and performance of system when subjected to possible variations in its operation conditions.

Therefore, the design theses controllers have been extensively studied over the last few years (Bhattacharyya et al., 1995). For example, in (Keel, 1997), it is proposed a design methodology that takes into account the parametric uncertainties of system, represented by real intervals and designed via linear programming. In (Costa, 2013), it is proposed the PSS design based in a robust control strategy with emphasis in structured parametric uncertainties, which are treated as tools of interval analysis theory.

In this context, this paper presents the design of a robust PSS to an Electric Power System of type Single Machine Infinite-Bar (SMIB), using robust control techniques based in the linear programming technique and Chebyshev's Theorem for the determination of robust parameters of controller, whose purpose is dampen the electromechanical oscillations of system, when subject to parametric variations in the mechanic power of the machine, and compare the performance of robust controller with the performance of a controller obtained by conventional technique, for different operations points of the system.

SYSTEM SINGLE MACHINE INFINITE-BAR ADOPTED

Study of robust control technique, involving robust controllers' analysis and design to damping electromechanical oscillations, are, in general, realized through mathematic models that describe the electric power system behavior. In this paper, it is used the system single machine infinite-bar, developed in (Sauer, 1998), for the robust PSS design and is represented by a generator connected to an infinite-bus through a transmission line, including the Automatic Voltage Regulator (AVR), which is represented by a high gain KA and a very small time constant TA, both representing a fast excitation system.

To obtain the maximum efficiency in the damping of electromechanical oscillations of the electric power system, it is necessary to add any input signal in the PSS that represent precisely the electromechanical oscillations of system and is still in phase with the deviation of the angular velocity (Δω). So, in this work, it was adopted as input signal of controller the angular velocity deviation Δω, in pu.

Therefore, in (1) and (2) is represented the model of SMIB in state space, whose input and output are respectively the reference voltage at AVR, ΔVREF, and the angular velocity deviation of system, Δω.

$$\begin{bmatrix} \Delta\delta \\ \Delta\omega \\ \Delta E_q^{'} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ \dfrac{-K_1}{2H} & \dfrac{-D_0}{2H} & \dfrac{-K_2}{2H} \\ -\dfrac{K_4+K_5K_a}{T^{'}_{do}} & 0 & -\dfrac{1+K_3K_6K_a}{K_3T^{'}_{do}} \end{bmatrix} \cdot \begin{bmatrix} \Delta\delta \\ \Delta\omega \\ \Delta E_q^{'} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \dfrac{K_a}{T^{'}_{do}} \end{bmatrix} \Delta V_{REF} \tag{1}$$

$$\Delta\omega = \begin{bmatrix} 0 & 1 & 0 \end{bmatrix} \cdot \begin{bmatrix} \Delta\delta \\ \Delta v \\ \Delta E_q^{'} \end{bmatrix} + \begin{bmatrix} 0 \end{bmatrix} \Delta V_{REF} \tag{2}$$

From (1) and (2), and according to (3) (Ogata, 2010), it is obtained the transfer function in the frequency domain, as shown in (4).

$$G(s) = C(sI - A)^{-1} + D \tag{3}$$

$$\frac{\Delta v}{\Delta V_{ref}} = \frac{b_1 s}{a_3 s^3 + a_2 s^2 + a_1 s + a_0} \tag{4}$$

Whose numerator and denominator parameters are determined from (5) and (9).

$$a_3 = 2HT^{'}_{do} \tag{5}$$

$$a_2 = \frac{2H}{K_3} + 2HK_6K_a + D_0 T^{'}_{do}\omega_0 \tag{6}$$

$$a_1 = \frac{D_0\omega_0}{K_3} + D_0K_6K_a\omega_0 + K_1T^{'}_{do}\omega_0 \tag{7}$$

$$a_0 = \frac{K_1\omega_0}{K_3} - K_2K_4\omega_0 - K_2K_5K_a\omega_0 + K_1K_6K_a\omega \tag{8}$$

$$b_1 = -K_2K_a \tag{9}$$

K_1 and K_6 represent the linearization coefficients and are functions of operating point and values of electromechanical parameters of electric power system. They are calculated according to (Sauer, 1998).

ROBUST STABILITY OF POLYNOMIALS FAMILY

Consider the notation G(s) for describe a plant that represent any dynamic system and the notation G(s,q) to emphasize the dependency of the plant coefficients in relation to the uncertain parameter vector q, as shown in (10).

$$G(s,q)=\frac{N(s,q)}{D(s,q)} \tag{10}$$

In the (10), N(s,q) e D(s,q) are uncertain polynomials of G(s,q), whose parameters are functions of q. Thus, for describe an uncertain polynomial, is convenient to write them according to (11) and (12).

$$N(s,q)=\sum_{i=0}^{n} b_i(q)s^i \tag{11}$$

$$D(s,q)=\sum_{i=0}^{n} a_i(q)s^i \tag{12}$$

Each uncertain parameter is restricted within pre-specified range of real closed intervals. Thus, according to (10), (11) and (12), it is defined (13) as a family of interval plants.

$$G(s,b,a)=\frac{\sum_{i=0}^{n}\left[b_i^{-},b_i^{+}\right]s^i}{\sum_{i=0}^{n}\left[a_i^{-},a_i^{+}\right]s^i} \tag{13}$$

According (13), check a decoupling of uncertainties between numerator and denominator, featuring G(s,b,a) as a plant with independent uncertain structure. In this context, a polynomial is stable if all its roots lie in the left half-plane of complex plan. So, G(a,b,a) is robustly stable if all polynomials of G(s,b,a) are stable, when there are small variations around its nominal value, respecting their minimum and maximum limits (Keel, 1997).

Therefore, applying robust control theory to SMIB and assuming a parametric variation in mechanic power of machine, it has a family of operating point, represented by function transfer of system, whose parameters vary within pre-specified real closed intervals and represent the operating range of electric power system under study, as shown in (14).

$$\frac{\Delta v}{\Delta V_{ref}}=\frac{\left[b_1^{-},b_1^{+}\right]s}{s^3+\left[a_2^{-},a_2^{+}\right]s^2+\left[a_1^{-},b_1^{+}\right]s+\left[a_0^{-},a_0^{+}\right]} \tag{14}$$

ROBUST CONTROL TECHNIQUES

The robust control technique applied to the PSS design uses two different procedures associated with linear programming technique. The first is the tool developed in (Keel, 1997), which consider the uncertainties relating to changes in the operating point of system and formulate a linear inequalities set that describe a polytope. The second procedure is the use of Chebyshev Theorem, developed in (Boyd, 2003), which provide maximum stability region, characterized by a ball of center x_c and radium R defined by polytope. The center and radium this bull is called Chebyshev center and radium, whose norm is Euclidean.

Using this technique, it is possible obtain a PSS able to ensure the robust stability of electric power system in a wide operating point range (Ramos et al., 2002). Thus, by extending (14) the system G(s) of order n to be controlled, and assuming a controller C(s) of order r to be designed, it is obtained (15) and (16), respectively.

$$G(s)=\frac{b_n s^n+b_{n-1}s^{n-1}+\ldots+b_0}{a_n s^n+a_{n-1}s^{n-1}+\ldots+a_0} \tag{15}$$

$$C(s)=\frac{n_r s^r+n_{r-1}s^{r-1}+\ldots+n_0}{d_r s^r+d_{r-1}s^{r-1}+\ldots+d_0} \tag{16}$$

From (17), the closed loop system is represented as in (18).

$$G_{mf}(s) = \frac{G(s)}{1 + C(s)G(s)} = \frac{\dfrac{n_G(s)}{d_G(s)}}{1 + \dfrac{n_G(s)}{d_G(s)}\dfrac{n_C(s)}{d_C(s)}} = \frac{n_G(s)d_C(s)}{d_G(s)d_C(s) + n_G(s)n_C(s)} \tag{17}$$

$$G_{mf}(s) = \frac{n_{mf}(s)}{d_{mf}(s)} \tag{18}$$

The goal this technique is to displace the poles of G(s), or equivalently, the roots of d_{mf} (s) to a desired region. It highlights that this techniques has not any effect on the plant zeros (roots of G(s)), although introduce news zeros in the function transfer of closed loop system. On the other hand, the poles of G(s) and C(s) are displaced to roots of d_{mf}(s), whose characteristic polynomial is represented by Eq. (19).

$$d_{mf}(s) = (b_n n_r + a_n d_r)s^{n+r} + (b_n n_{r-1} + b_{n-1} n_r + a_n d_{r-1} + a_{n-1} d_r)s^{n+r-1} + \ldots + (b_0 n_0 + a_0 d_0) \tag{19}$$

Thus, the robust controllers parameters must be chosen to satisfy the performance specifications, construed in desired localizations of poles of closed loop system, containing a set of n+r desired poles, according to Eq. (20).

$$\delta(s) = \delta_{n+r} s^{n+r} + \delta_{n+r-1} s^{n+r-1} + \ldots + \delta \tag{20}$$

Where δ(s) is described by interval vector [δ] = [δ-, δ+].

Thereat, for G_{mf}(s) to present robust stability and performance, the Eq. (19) must represent the same roots of Eq. (20), this is, both must present the same performance, as shown in Eq. (21).

$$d_{mf}(s) = \delta(s) \tag{21}$$

According to (Keel, 1997) and Eq. (21), for the robust controller design is formulated a linear inequalities set, which restricted the plant and desired polynomial coefficients in the defined intervals, as shown in Eq. (22). Thus, the closed loop system has its poles within the roots space of interval desired polynomial, ensuring the robust stability (Lordelo and Ferreira, 2002).

$$\begin{bmatrix} \delta_{n+r}^{-} \\ \delta_{n+r-1}^{-} \\ \cdot \\ \cdot \\ \cdot \\ \delta_0^{-} \end{bmatrix} \le \begin{bmatrix} b_n n_r + a_n d_r \\ b_n n_{r-1} + b_{n-1} n_r + a_n d_{r-1} + a_{n-1} d_r \\ \cdot \\ \cdot \\ \cdot \\ b_0 n_0 + a_0 d_0 \end{bmatrix} \le \begin{bmatrix} \delta_{n+r}^{+} \\ \delta_{n+r-1}^{+} \\ \cdot \\ \cdot \\ \cdot \\ \delta_0^{+} \end{bmatrix} \tag{22}$$

Using the linear programming technique and Chebyshev theorem, are calculated the robust controller coefficients and the radium R, according to Eq. (23) and Eq. (24). The Eq. (25) represents the parameter array to be calculated and optimized by linear programming.

$$\max F(x_c, R) \tag{23}$$

Sujeito á:

$$A_i x_c + \|a\| R \le b_i \tag{24}$$

$$x = \begin{bmatrix} x_c \\ R \end{bmatrix} \tag{25}$$

Where: $A_c = \begin{bmatrix} A_i & \|a\| \\ -A_i & \|a\| \\ 0_{1xi} & -1 \end{bmatrix}$ e $B_c = \begin{bmatrix} b_{i\max} \\ -b_{i\min} \\ 0 \end{bmatrix}$.

$F(x_c,R)$ is an arbitrary linear function in x and R, xc is the vector with the controller variable to be optimized, considered the Chebyshev center, and R represent the Chebyshev radium, b_{imin} and b_{imax} are respectively the inequalities relative to lower and upper limits of system. The array A_i corresponds to open loop plant coefficients and $\|a\|$ is the norm of coefficients of A_i.

Robust controller design via linear programming

For the robust PSS design, consider that the generator will operate supplying active powers in the range P_0= [0.63, 0.77] pu, keeping Q_0= 0.00 pu. This way, the interval transfer function of SMIB is showed in Eq. (26). The Table 1, Table 2, Table 3 and Table 4 show respectively the nominal operating points of system, transmission line and transformer dates, automatic voltage regulator dates and generator nominal dates, both in pu.

$$\frac{\Delta v}{\Delta V_{ref}} = \frac{[-3.748,-3.262]s}{s^3 + [11.37,11.62]s^2 + [94.61,95.35]s + [949.2,955.3]} \tag{26}$$

Table 1 – Nominal operating points of system

$P_0(pu)$	$Q_0(pu)$	$V_\infty(pu)$
0.70	0.00	1.00

Table 2 – Transmission line and transformer dates

$X_{LT}(pu)$	$R_{LT}(pu)$	$X_T(pu)$	$R_T(pu)$
0.40	0.00	0.15	0.00

Table 3 – Automatic Voltage Regulator dates

K_a	$T_a(seg)$
100	0.00

Table 4 – Generator nominal dates

$R_a(pu)$	$X_d(pu)$	$X_q(pu)$	$X_d^{'}(pu)$	$T^{'}_{do}(seg)$	$H(seg)$	D_0
0.00	1.2	0.7	0.3	6.0	4.0	0.013333

For requirements of design, the interval values of damping coefficients and undamped natural frequency are ξ_d = [0.15, 0.25] e ω_n= [9.05, 9.07], respectively. The adoption of interval values theses parameters allow increase the damping of dominant oscillatory mode.

Thus, using the poles displacement technique, the PSS designed takes the form of Eq. (27) for the closed loop system, such that the closed-loop desired polynomial is of the form of Eq. (28), where a=5ωn represents a non-dominant pole, whose characteristic not influence in the system behavior.

$$ESP(s) = \frac{n_2 s^2 + n_1 s + n_0}{d_2 s^2 + d_1 s + d_0} \tag{27}$$

$$\delta_d(s) = \left(s^2 + 2\xi\omega_n s + \omega_n^{\,2}\right)(s + a) \tag{28}$$

Therewith, considering the interval values of ξ_d and ω_n, we have the interval desired polynomial, according to Eq. (29).

$$\delta_d(s) = s^5 + \delta_{4d}s^4 + \delta_{3d}s^3 + \delta_{2d}s^2 + \delta_{1d}s + \delta_{0d} \tag{29}$$

Where:

$\delta_{4d} = [100.2{,}101.8]$, $\delta_{3d} = [3451{,}3605]$, $\delta_{2d} = [45610{,}50350]$,

$\delta_{1d} = [206700{,}256200]$, $\delta_{0d} = [1504000{,}1531000]$

Applying the robust control technique shown in Eq. (23) to Eq. (25), we have the robust PSS design, illustrated in Eq. (30). The Eq. (31) represents the PSS design through a conventional technique using the Diophantine Equation, like in (Lordelo, 2014), for comparison purposes, and the Eq. (32) represents the value of Chebyshev Radium, which delimit the maximum stability region of system for the controller designed.

$$ESP(s)_{robusto} = \frac{622s^2 - 7500s + 3792}{s^2 + 71.11s + 7969} \tag{30}$$

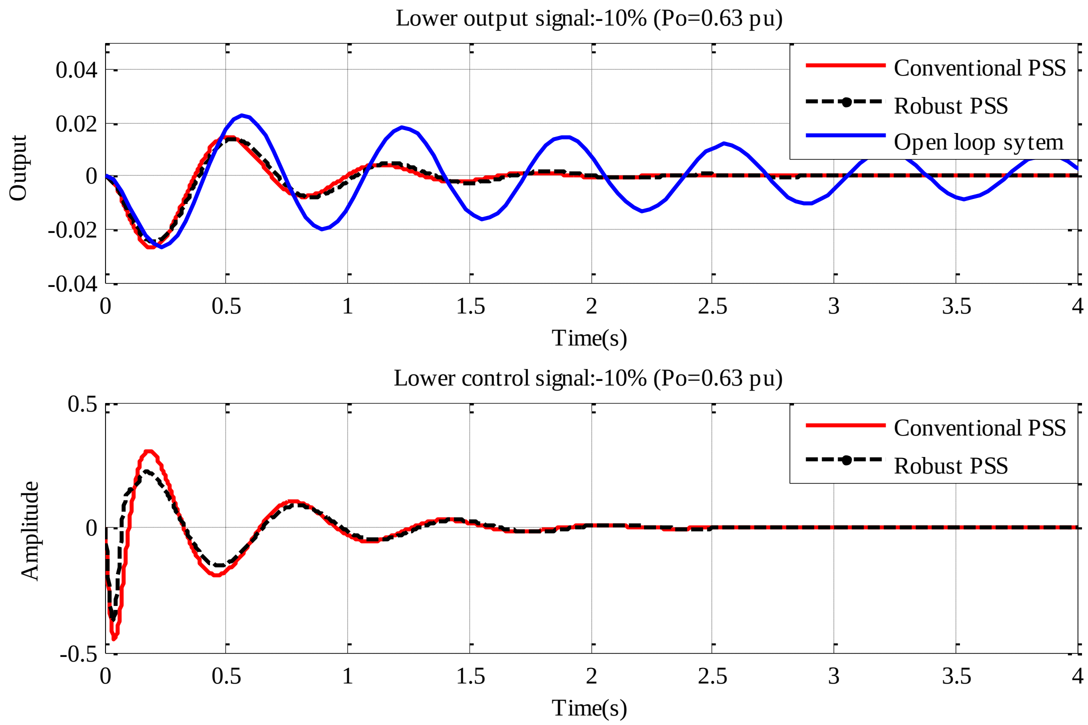
$$ESP(S)_{convencional} = \frac{814.2s^2 - 9094s + 11660}{s^2 + 128.1s + 8020} \tag{31}$$

$$R = 15.9712 \tag{32}$$

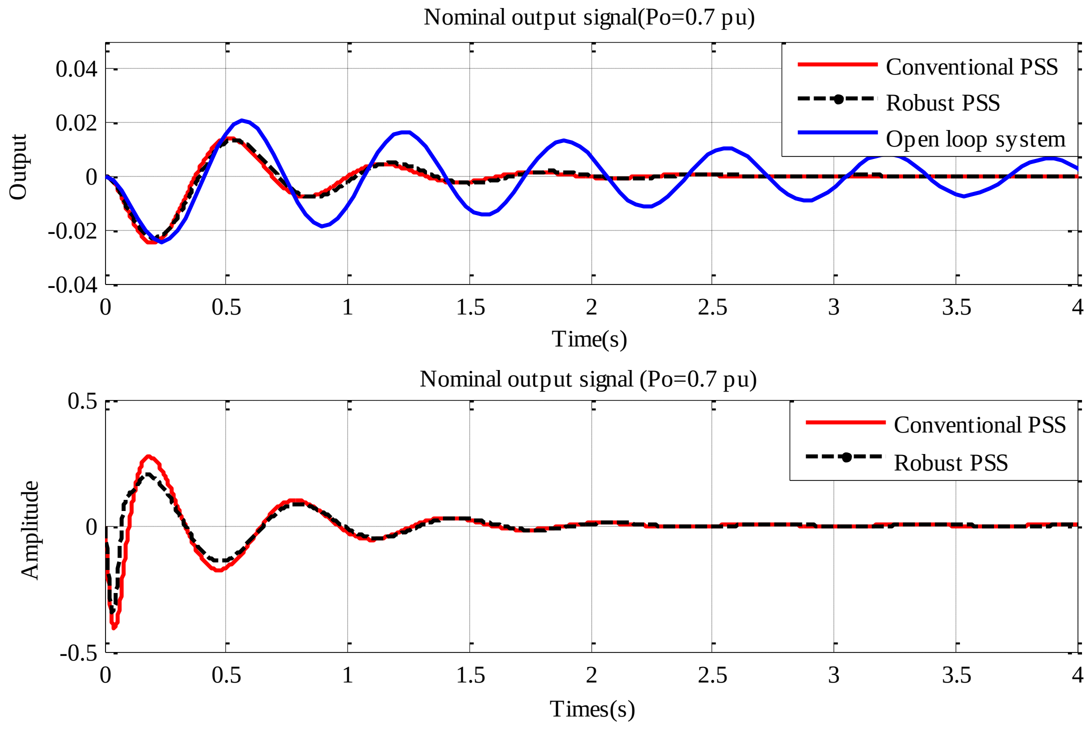
RESULTS

For the robust controller design is used a polytope with three vertex relating to three different levels of operating points of machine. One vertex was adopted using the operation condition of base or nominal case, that is represented as interval center, and the other two were built considering variations of –10% and +10% in the operation condition of base case. It highlights that the variation occur in the mechanic power of machine.

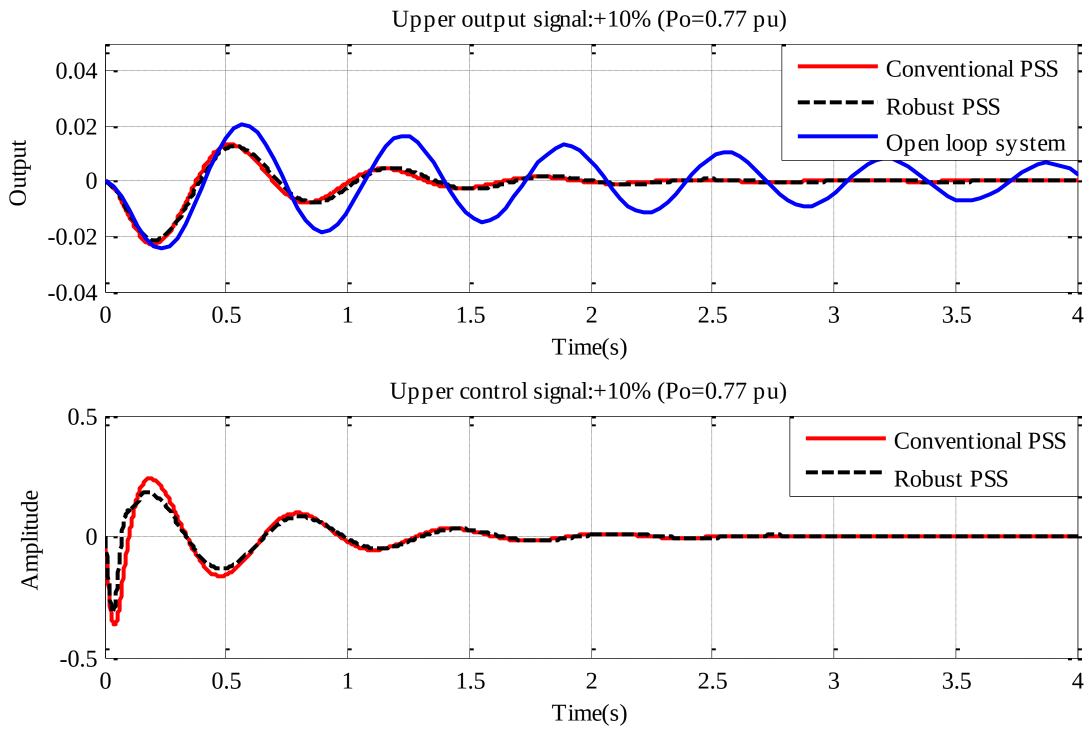
For analysis of robust PSS performance, it was applied a signal of kind step on the system input. The Fig. 1 presents the dynamic performance of system output, in open loop, closed loop, with conventional and robust PSS, for the three operation points and the dynamic performance of control signal for the two controllers. It is observed that the open loop system machine Infinite-Bar presents little damped oscillation modes which are justified by large oscillations represented in the blue curve.



a) Lower operating Condition



b) Nominal operating condition



c) Upper operating condition

Figure 1 – Dynamic performance of output and control signal

It was observed that with the introduction of conventional and robust PSS, the system presented damping of electromechanical oscillations, satisfying the desired performance specifications of system. The test proposed considered three operation points and for each point was analyzed the output of system and control signal of PSS. It was observed that, although outputs of system not present substantial differences, control effort of robust PSS was lower when compared to conventional PSS, which was evident when analyzed the criterion of integral square error (ISE).

Based on the system output and control signal of PSS, was done the analysis of performance index and cost benefit of the controllers, through of ISE function, calculated according to Eq. (33).

$$J_{ISE} = \int_0^t e^2(t)dt \tag{33}$$

The Fig. 2 presents the cost function of system output and control effort to the three operation points. Note that, throughout the operating range, the value of ISE for the output signal and control effort is smaller for the robust PSS compared to conventional PSS. In other words, the robust PSS provided a best performance in the damping of system electromechanical oscillations and a lower control effort, may reduce in long term costs with natural frictions which these systems are submitted, or rather, reduction in the energy consumption.

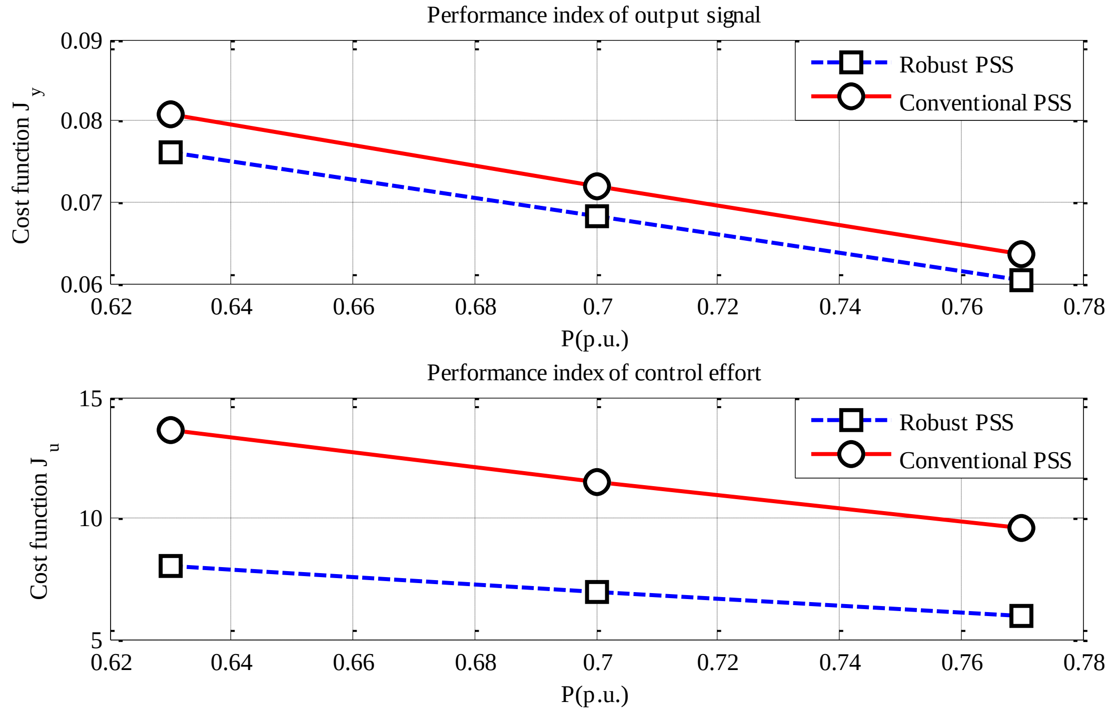


Figure 2 – Cost function of the output signal and cost function of the control signal

CONCLUSION

This paper proposed the application of a robust stability analysis technique integrated to linear programming technique for the design of a fix order robust PSS, through pole robust displacement for damping of electromechanical oscillations of system machine Infinite-Bar, with type interval uncertainties in their parameters.

Through the results presented, we note that the two controllers ensured the system robust stability and both presented a good performance when occur variations in the operating conditions of system. But, the robust controller presented a very satisfactory performance with a lower control effort. The performance index analysis and cost benefit of the two controllers, through the ISE function, was done to show the efficiency of robust PSS.

However, the applicability of the methods proposed for other physical system still needs further investigation which includes the comparison between conventional and advanced methodology, when analyzed the dynamic performances of system with parametric variations.

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