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ROBUST CONTROLLERS FOR DAMPING ELECTROMECHANICAL OSCILLATIONS USING METAHEURISTICS

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Abstract. *The increase in the demand for electric energy has made companies and companies invest in the EPS (electrical power system), making it more robust and, consequently, its more complex operation. These modifications influenced the emergence of problems related to electromechanical oscillations, which could lead to system instability. Of the several factors that influence the functioning of the EPS, stability is an important and fundamental point that impacts the safe and reliable operation of these systems. This work presents the design of a robust controller with the main objective of damping electromechanical oscillation modes (EOM) in power systems of three areas, seeking to achieve the robust stability of the system. Techniques for analysis and design of multivariate frequency domain controllers are used to verify the possibility of obtaining robust control with decentralized reduced-order controllers. In order for the controllers to achieve robustness, it is necessary to select the most significant input-output pairs for the system. For this purpose, analysis techniques were applied to a load-frequency system of three areas. The controller is of type* H_∞ *and the optimization method applied, to obtaining the robust control of the system with uncertainties, was the tabu search.*

Keywords: Electrical power system, Electromechanical oscillations modes, Robust control, Tabu search

1. **Introduction.** An electrical power system (EPS) is defined as a set of equipment that operates in a coordinated way for the continuous supply of electrical energy, obeying certain standards of quality and reliability, which require the EPS to work safely for a range of operating points, as well as being able to withstand undesirable events such as load disturbance, short circuits, among others.

Due to the growth in the number of generating units and the transmission system, there has been an increasing number of interconnections. The main purpose of the interconnections is to reduce the unavailability of electricity to consumers, allowing the exportation or importation of electricity from regions where there is an excess or temporary deficit of electricity. These interconnections increase system complexity more and therefore power systems suffer from operational problems caused by poorly damped oscillations, which can reach increasingly large regions of the system and can lead to large blackouts, if not properly damped.

In order for the EPS to operate reliably and safely, it is necessary for the system to operate with stability, adjusting total generation to load demand [1].

The reason why the system became unstable is the lack of synchronism of the generators, leading to the phenomenon of electromechanical oscillations [2-4]. These oscillations may limit transmission power as they decrease the stability margins of the power system.

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Therefore, the damping of these oscillations has become the prerequisite for a safe operation of an electrical system and the concern of engineers and operators [5]. Knowledge and analysis of the nature, types and frequencies of the oscillations is essential, so that effective control of the electromechanical oscillation modes can be obtained. The design of controllers for the damping of these oscillations should consider the changes in the operating conditions, the system transformation in the presence of failures, and the dynamics of the system, so when using linear techniques it has low performance of the controllers, due to the fact that these do not consider the dynamics of the system [5].

Considering all the inherent complexity of the system, in recent decades some researchers have used robust control techniques that are based on the time domain system or the frequency domain [6-11].

The robust control theory is used when it is desired to consider the existence of uncertainties or errors between the actual plant and its mathematical model in the design of the controller. This theory considers that the physical system to be controlled and the environment where it will operate cannot be modeled exactly. There is also the possibility of various types of interference, whether through sensor noise or unpredictable disturbances. This generates unexpected values that the controller should be able to handle. For the design of highly accurate controllers even in the presence of considerable uncertainties, it is convenient to resort to robust control systems.

These controllers must meet some control requirements such as system stability, maximum damping desired for dominant electromechanical modes, satisfactory response time and robustness in the face of uncertainties in the operation of the electrical system and load disturbances [12].

Thus, despite the existing technology in controller design, problems related to low-frequency oscillatory stability in electrical systems are still noticeable, and one of the causes is the inoperability or poor fit of these controllers, which are designed by classical techniques, which consider models linearity around an operating point without considering the uncertainties present in the system operation, limiting system stability and robust controller performance [2].

For this reason, this research aims to develop a robust controller of low order to dampen oscillations at low frequency produced by small perturbations, inherent to the operation of the system itself. The previous selection of the most effective input-output pairs for the application of the controllers is made from the RGA and unique values according to the model already found in the literature. The optimization method chosen to tune the best robust controller was the "tabu search" (TS) that will be implemented and presented in this work.

This paper is organized as follows. In Section 2, signal analysis for decentralized control is presented, together with the mathematical formulation regarding the robust control H_∞ criteria and how it can be applied to the tuning of robust PSS. In Section 3, the controller is designed. Subsequently, in Section 4, the application to a load-frequency system and results are presented and finally in Section 5, the conclusions are stated.

2. Signal Analysis for Decentralized Control.

A power system with n units, m control and r output signals is described by

$$y(j\omega) = G(j\omega)u(j\omega) \tag{1}$$

where $G(j\omega)$ is the matrix of frequency response transfer functions (MFTfr). From the definition of controllability presented by [13], one can define the "controllability" of an oscillation mode (OM) as the ability of the system to dampen the OM to achieve acceptable performance with inputs and limited outputs. In the same way, one can define the "observability" of an OM as the contribution of OM in the system response. The zeros of a system can cause significant controllability and observability of modes and controller design [14]. The only way to avoid undesirable zeros is with the previous selection of inputs and outputs suitable for application of controllers. For the analysis of controllability and modal observability of multivariable systems in the frequency domain, the "singular values" of the MFTfr are used, which for the case of the matrix $G(j\omega)$ are defined by

$$\sigma_i(j\omega) = \sqrt{\lambda_i\left(G^H G\right)} = \sqrt{\lambda_i\left(G G^H\right)}, \quad i = 1, \ldots, k \tag{2}$$

where λ_i is the ith eigenvalue of the matrix, G^H is the conjugate and transposed matrix of G and $k = \min(m, r)$. Defining $\overline{\sigma}$ as the largest singular value, $\underline{\sigma}$ as the smallest and the relation $\gamma = \overline{\sigma}/\sigma$ as the condition number, the following properties of interest are described [14]:

- $\overline{\sigma}$ in the frequency of an OM represents the degree of observability of the mode in the response of the system and $\underline{\sigma}$ represents the degree of controllability of the mode. OM low damped and strongly observable values have large peaks in the $\overline{\sigma}$ graph. The peaks of $\overline{\sigma}$ are associated with the robustness of the system. Robust systems feature small peaks.
- A depression on the graph of $\underline{\sigma}$ indicates the existence of an influent zero at said frequency.
- High condition number ($\gamma > 10$) indicates difficulty in control, especially if $\underline{\sigma} << 1$.
- The norm I_2 of G is $\overline{\sigma}(G)$. Also, $\|G^{-1}\| = 1/\underline{\sigma}(G)$.
- The "cutoff frequency", ω_c, is defined as the frequency where $\overline{\sigma} = 1$, when $\overline{\sigma}$ is decreasing.

Consider the power system $G(j\omega)$ with controllers $H(j\omega)$, reference inputs R and disturbances, d:

$$y = (I + GH)^{-1} GR + (I + GH)^{-1} G_d d \tag{3}$$

where $S = (I + GH)^{-1}$ is the sensitivity matrix and $T = SG$ is the matrix of closed loop transfer functions of the system. These matrices are used to analyze the performance of the controlled system.

Consider a variation on the reference R, assuming $d = 0$. Then it results in $\|y\|/\|R\| = \overline{\sigma}(T) = \overline{\sigma}(G)/\underline{\sigma}(I+GH)$. Also, knowing that $\underline{\sigma}(I+GH) \geq \underline{\sigma}(GH) - 1$ and that $\underline{\sigma}(GH) \geq \underline{\sigma}(G)\underline{\sigma}(H)$, results in

$$\overline{\sigma}(T) \leq \frac{\overline{\sigma}(G)}{\underline{\sigma}(G)\underline{\sigma}(H) - 1} \tag{4}$$

Similarly, considering only the effect of the disturbance on the output, we find that $\|y\|/\|d\| \leq \overline{\sigma}(G_d)/(\underline{\sigma}(G)\underline{\sigma}(H) - 1)$. These results show that $\underline{\sigma}(G)$, which depends on the selection of inputs and outputs, should be large to reduce $\overline{\sigma}(T)$ and the effect of the disturbances, facilitating the action of the controller. If $\underline{\sigma}(G) << 1$ in the frequency range of the oscillation modes, it will be almost impossible to control the system with decentralized controllers. This explains why $\underline{\sigma}(G)$ is considered as the degree of controllability of the system.

2.1. **Frequency interactions.**

The relative gain array (RGA) is important for analysis of multivariate systems and will be used for a prior selection of inputs and outputs for decentralized control. The RGA is defined by

$$\wedge(G(j\omega)) = \begin{bmatrix} \lambda_{11} & \cdots & \lambda_{1m} \\ \vdots & \ddots & \vdots \\ \lambda_{r1} & \cdots & \lambda_{rm} \end{bmatrix} \tag{5}$$

where $\lambda_{ij} = g_{ij}b_{ij}$ and b_{ij} is the element ij of G (generalized inverse matrix of G), defined by $G^* = \left(G^H G\right)^{-1} G^H$ for $m \leq r$, $rank(G) = m$ or $G^* = G^H \left(GG^H\right)^{-1}$ for $r \leq m$, $rank(G) = r$.

It is known that λ_{ij} is an interaction measure between input j and output i [14]. It is also verified that λ_{ij} is a measure of the effect that the control of the remaining variables has on the gain between u_j and y_i [15].

Using its properties, the RGA can be used to select the most effective input-output pairs. However, the use of RGA alone for this selection has some limitations. The biggest limitation is the impossibility to select the most effective output between signals of the same unit, for example, speed and electric power in a generator [15] or, in a general way, signals with some relation between them.

In [16], a technique was proposed that combines RGA and singular values in the selection of the most effective input-output pairs for the application of decentralized controllers. This technique proves to be very efficient and reliable for signal selection.

2.2. **Decentralization.** A set of inputs and outputs is completely decentralized if $\wedge(G) = I$. However, this equality only occurs if the matrix G is triangular, which is not the case with power systems. However, the set results in $\wedge(G(j\omega)) \cong I$ for $\omega = \omega_c$ [14]. The closer the identity matrix results to $\wedge(G(j\omega_c))$ the more independent the input-output pairs and consequently the smaller interactions will occur between the controllers.

2.3. **Selecting inputs and outputs.** The selection of pairs for the application of decentralized controllers is performed according to the procedure proposed by [16].

Initially all inputs and output signals are used to determine the RGA in the frequency $\omega = 0$. This matrix eliminates the ineffective signals or inputs that provoke undesirable interactions.

Next, considering that p controllers are sufficient to dampen the oscillation modes with robust system control, all sets with p inputs and p outputs are formed. Then these sets are tested to verify the decentralization at frequency $\omega = \omega_c$. Sets with strong interactions between units (poor decentralization) are discarded.

Having made the selection of inputs and outputs, the controllers are designed according to Section 3.

3. Decentralized Robust Controllers Design.

Controllers are designed taking account of modeling errors. These errors, called uncertainties, occur because the nonlinearities, parameter changes with load variations, and exclusion of generator dynamics, excitation systems, etc. are not included in the model. The multiplicative uncertainties are reflected in the output, as represented in Figure 1 [17], where $\Delta_0 W_0(s) = (G' - G)\, G^{-1}$ is the matrix of relative uncertainties and G' is the transfer matrix of the actual system.

The diagonal matrix $W_0(s)$ represents the upper limits of the uncertainties in the control channels.

We have $G'(s) = (I + \Delta_0 W_0)G(s)$. $S' = (I + G'H)^{-1}$ is the sensitivity matrix of the real system. Then, $S' = [I + (I + \Delta_0 W_0)GH]^{-1} [I + GH]S$. Assuming that the range of frequencies of greatest interest occurs if $\underline{\sigma}(GH) >> 1$, results:

$$\overline{\sigma}\left(S'\right) \leq \frac{\gamma(G)\gamma(H)}{\underline{\sigma}\left(I + \Delta_0 W_0\right)} \tag{6}$$

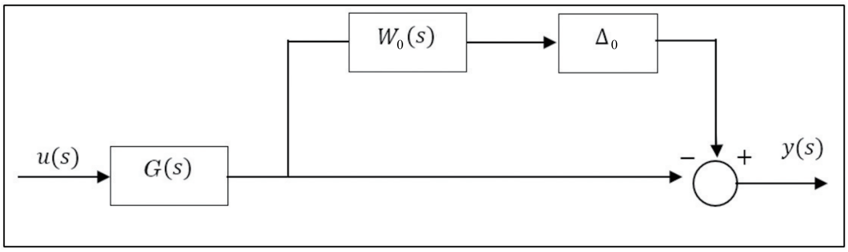

Figure 1. Block diagram of the real power system

From (6) we conclude that the decentralized control will not contribute to the deterioration of the sensitivity of the system if $\gamma(H) = 1$, that is, when identical controllers are used in the various channels. The same result is obtained for uncertainties in the input, which means that the system becomes more robust for faults in the controllers when these are identical.

Introducing the uncertainties in the block diagram and arranging them to separate the block from uncertainties Δ_0, are obtained $M(s) = -W_0(s)T(s)H(s)$. Usually, the $W_0(s)$ matrix is represented by $\omega_0(s)I$, where $\omega_0(s)$ is a weight, considering a single upper bound, representing the worst case, associated with all control channels [17]. This weight is described by $\omega_0(s) = (\zeta s + \zeta_0)/[(\zeta/\zeta_\infty)s + 1]$, where ζ_0 is the relative uncertainty at steady state, $1/\zeta$ is approximately the frequency where relative uncertainty reaches 100% and ζ_∞ is the magnitude of the weight at high frequencies.

Assuming that the matrix M and the perturbations Δ are stable, then the $M\Delta$ system is stable for all perturbations with $\overline{\sigma}(\Delta) \leq 1$, $\forall\omega$, if and only if [14]

$$\mu(M(j\omega)) < 1, \forall\omega \tag{7}$$

where $\mu(M)$ is the singularly structured value of M.

It is known that $\mu(M) \leq \overline{\sigma}(M)$ and that equality occurs when the uncertainty matrix, Δ, is full, which must occur with modeling errors and exclusion of dynamics from generators, transmission network, etc.

Therefore, it is considered as a necessary and sufficient condition for the robust stability of the system, with $\overline{\sigma}(\Delta) \leq 1$, $\forall\omega$, the condition:

$$\overline{\sigma}(M(j\omega)) < 1, \forall\omega \tag{8}$$

It is assumed that the controller is of known structure (decentralized and of reduced order). To achieve robustness, the parameters of the controller $H(s)$ are adjusted to solve the following problem of optimization:

$$\min\left[\sup\left(\overline{\sigma}(M(j\omega))\right)\right] \tag{9}$$

subject to

$$\gamma(H) = 1$$

$$\eta s_{s\max,s\min}$$

where η is the vector of 1 adjustable parameters of H, which are set between practical limits. So if identical controllers are used on all selected channels, the project is reduced to an unrestricted optimization problem.

Consider $M = W_0TH$ (the negative signal does not affect the result). Then, (8) reduces to $\overline{\sigma}(M) = \omega_0\overline{\sigma}(TH) \leq \omega_0\overline{\sigma}(T)\overline{\sigma}(H) < 1$, or

$$\overline{\sigma}(T) < \frac{1}{\omega_0} \cdot \frac{1}{\overline{\sigma}(H)}, \forall\omega \tag{10}$$

For identical controllers, $\overline{\sigma}(H) = \underline{\sigma}(H) \leq 1/\overline{\sigma}\left(H^{-1}\right)$, which is substituted in (10), results in

$$\overline{\sigma}(T) < \frac{\overline{\sigma}\left(H^{-1}\right)}{\omega_0}, \forall\omega \tag{11}$$

Then, the computationally more practical procedure for designing the robust controller is to adjust H to minimize $\overline{\sigma}(T)$, satisfying (11). If this inequality is not satisfied, then the robustness, for the uncertainties established, cannot be reached with the proposed structure for the controller.

The function to be minimized is not an explicit expression. Therefore, it is advisable to use an optimization technique that does not need to calculate derivatives. The direct optimization method called "tabu search" is chosen due to its adaptation to the problem. Tabu search is a high-level heuristic procedure for solving optimization problems, it can be used to guide any process that employs a set of moves to transform one solution into another and that provides an evaluation function to measure the attractiveness of those moves. The orientation of this method is highly flexible and often motivates the creation of new types of movements and evaluation criteria to take advantage of its adaptability to different problem structures and strategic goals. The two basic elements of the TS metaheuristic are the definitions of search space and neighborhood structure [18].

4. **Application to a Load-Frequency System.** The system model is represented by

$$\begin{aligned}\dot{X} &= AX + Bu\\ y &= CX\end{aligned}$$

where

$$\begin{aligned}X^T &= \left|f_1 x_{E1} P_{G1} P_{tie1} f_3 x_{E3} P_{G3} P_{tie2} f_2 x_{E2} P_{G2}\right|\\ u^T &= \left|P_{C1} P_{C3} P_{C2}\right|\\ y^T &= \left|f_1 P_{tie1} f_3 P_{tie2} f_2\right|\end{aligned}$$

where f_i, x_i, P_{Gi} and P_{tiei} are respectively frequency, output signal of the speed regulator, power turbine mechanics and exchange power of the turbogenerator of area i, in incremental values. P_{Ci} is the control input of the speed controller of the area i.

According to [16], this system has three modes of the inter-area type, which implies the use of controllers in the three areas to cushion these modes. The eigenvalues associated to these modes are

$$\lambda_1 = -0.1759 \pm j3.0010, \quad \lambda_2 = -0.1199 \pm j4.0102, \quad \lambda_3 = -0.1893 \pm j4.6410.$$

As shown in [16], using the most effective signals P_{tie1} and P_{tie2}, but the frequency signals have significant effects, especially in their own areas. It was also verified that with two or three of these simple signals one could only obtain reasonable decentralizations, making robust control impossible. In this work, we consider output composite signals, represented by

$$y_2^T = \left|P_{tie1} + Bf_1, P_{tie2} + Bf_3, -P_{tie2} + Bf_2\right|, \quad B = 0.417$$

The RGA at $\omega_C = 6$ rad/s resulted in

$$\Lambda = \begin{bmatrix} 1.063 - j0.036 & 0 & -0.063 + j0.036\\ -0.004 - j0.003 & 1.004 - j0.103 & 0 + j0.106\\ -0.059 + j0.039 & -0.004 - j0.103 & 1.063 - j0.142 \end{bmatrix}$$

It is then verified that the signals of y_2 with the inputs, u, result in pairs with a decentralization very good. The graphs of $\overline{\sigma}$ and $\underline{\sigma}$ of the description $y_2 = G_2(j\omega)u$ are shown in Figure 2.

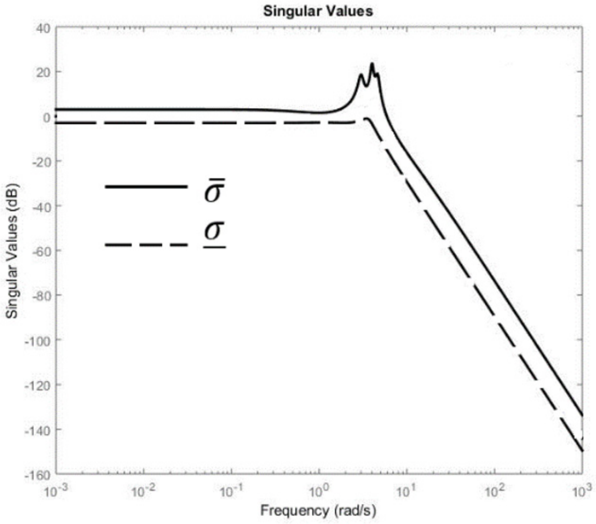

FIGURE 2. Values of $\overline{\sigma}$ and $\underline{\sigma}$ of $G_2(jw)$

The three areas are somewhat similar, justifying the use of identical controllers. Thus, it is suggested to apply identical controllers of type $h_i = K(1 + sT_1)/(1 + sT_2)$ in each area. The parameters of the controllers are adjusted to minimize the M function, also decreasing the $\overline{\sigma}(T)$. In this problem we used a function elaborated by the author, which uses tabu search optimization method. In this work, the search space was restricted to values that improve the objective function, thus reaching the best result faster than other methods with simulated annealing (SA) and two evolutionary algorithms: genetic algorithm (GA), and particle swarm optimization (PSO) [19,20].

After analyzing the results of each parameter found by the method, it used the one that presented the lowest value of the objective function M together with a greater robustness of the system, obeying at the same time the practical restrictions, since $T_1/T_2 = 0.1$. Therefore, the parameters used from this function will be $K = 0.4$; $T_1 = 0.009$ s; $T_2 = 0.09$ s.

The graphs of $\overline{\sigma}(T)$ the obtained controller and of $\overline{\sigma}\left(H^{-1}/\omega_0\right)$ to $\omega_0 = (0.25s + 0.15)/(0.5s + 1)$ are shown in Figure 3.

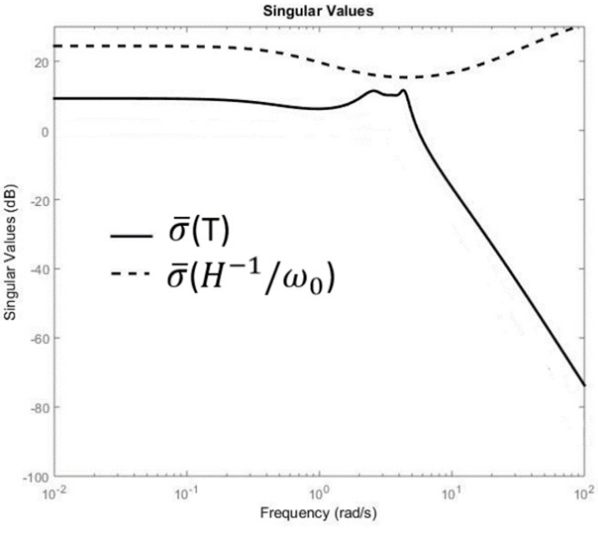

FIGURE 3. Graphs of $\overline{\sigma}(T)$ for the proposed control and $\overline{\sigma}\left(H^{-1}/\omega_0\right)$

Figure 3 confirms that robust system control was obtained using decentralized first-order controllers.

Analyzing Figure 4, it can be concluded that the optimization method used presented an excellent result, in addition to guaranteeing a greater damping of the system, when compared to the result obtained by the "genetic algorithms" method in [8].

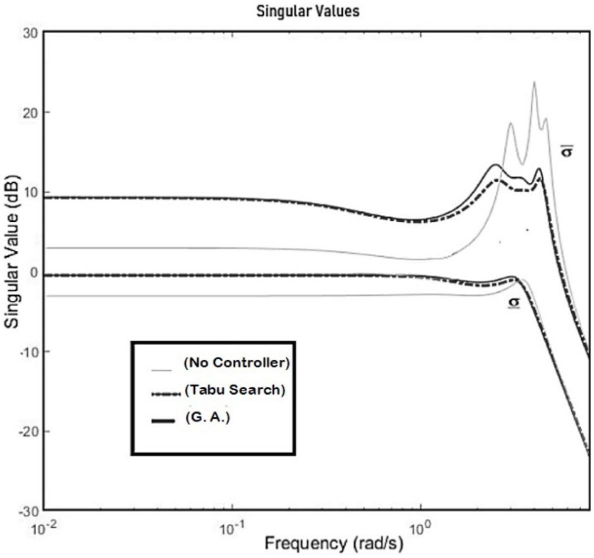

Figure 4. Singular values of the system without controller, with controller obtained by genetic algorithms and by tabu search

Therefore, it can be confirmed that the proposed procedure, using RGA for pre-selection of exits and inputs, leaving the final selection to be performed with the use of singular values is adequate and efficient for application in the system of load-frequency, and was instrumental in facilitating the efficient choice of a low-order and decentralized controller.

Finally, following all the steps proposed in this work, we conclude that the controller works properly for the proposed system, in addition to having the necessary robustness for this system.

5. **Discussion and Conclusions.** In this work we used the tabu search method to develop a robust, decentralized and small-order controllers design, and it was applied in a load-frequency system.

Initially, it used singular values, which allow to apply frequency techniques in systems with multiple inputs and multiple outputs. The RGA matrix indicates the degree of interaction between the inputs and outputs of the system, indicating how much the controller can be decentralized. The use of the two techniques allows simultaneously selecting all the most effective input and output pairs, aiming to dampen the most critical electromechanical oscillations modes and obtain a decentralized controller. This methodology can be applied to any system, regardless of size.

This technique stands out in relation to the traditional techniques of robust control H_∞, especially in large systems, as it results in a low order controller, applied directly to the system without any reduction of the model, whereas in traditional methods the resulting controller is centralized and of order higher than the order of the system, being necessary the reduction of the original system model and later the reduction of the own controller.

After selection of the most significant inputs and outputs, as well as the definition of the controller type, the tabu search optimization method was used to find its parameters, aiming for a higher damping. This method presented quite satisfactory results, finding optimal parameters for the controllers, and showing an improvement, when compared to the results in the literature.

REFERENCES

[1] P. Kundur, *Power System Stability and Control*, McGraw-Hill, 1994.

[2] G. Rogers, *Power System Oscillation*, 1st Edition, Kluwer Academic Publishers, Boston, 2000.

[3] P. M. Anderson and A. A. Fouad, *Power System Control and Stability*, Wiley, 2008.

[4] B. S. Munir, A. Trisetyarso, M. Reza and B. S. Abbas, Application of artificial neural networks for power system oscillation prediction, *ICIC Express Letters*, vol.13, no.9, pp.815-822, 2019.

[5] A. C. Castro, *Decentralized Low-Order Robust Controller Design for Damping of Oscillations in Electrical Power Systems (Projeto de controladores robustos descentralizados de ordem reduzida para amortecimento de oscilações em sistemas elétricos de potência)*, Ph.D. Thesis, Tese apresentada à Universidade Federal da Paraíba, João Pessoa, PB, Brasil, 2006 (in Portuguese).

[6] G. E. Boukarim, S. Wang, J. H. Chow, G. N. Taranto and N. Martins, A comparison of classical, robust and decentralized control designs for multiple power system stabilizers, *IEEE Trans. Power Systems*, vol.15, no.4, pp.1287-1292, 2000.

[7] H. Chen, Z. Guo and H. Bai, Wide-area robust H2/H1 control with pole placement for damping inter-area oscillations, *Proc. of IEEE Power Engineering Society General Meeting*, Montreal, 2006.

[8] B. G. da S. Filha, A. C. de Castro, F. A. Moreira and J. M. Araujo, Design of a robust H_∞ controller for a load-frequency power system, *International Journal of Innovative Computing, Information and Control*, vol.12, no.1, pp.321-331, 2016.

[9] A. C. Castro, J. M. Araújo, E. T. F. Santos, F. G. S. Silva and C. S. de Araújo, A novel technique for designing decentralized stabilizers for robust control in power systems using an H_∞ criterion, *International Journal of Innovative Computing, Information and Control*, vol.7, no.3. pp.1387-1396, 2011.

[10] K. Charles, N. Urasaki, T. Senjyu, M. Lotfy and L. Liu, Robust load frequency control schemes in power system using optimized PID and model predictive controller, *Energies*, vol.11, no.11, DOI: 10.3390/en11113070, 2018.

[11] S. Oucheriah, Robust adaptive output feedback controller for a quadratic boost converter, *ICIC Express Letters, Part B: Applications*, vol.10, no.9, pp.789-795, 2019.

[12] S. P. Bhattacharyya and L. H. Keel, Robust control: The parametric approach, in *Advances in Control Education 1994*, A. Ichikawa and K. Furuta (eds.), Oxford, Pergamon, DOI: 10.1016/B978-0-08-042230-5.50016-5, 1995.

[13] M. V. Wal and B. Jager, A review of methods for input/output selection, *Automatica*, vol.37, pp.487-510, 2001.

[14] S. Skogestad and I. Postlethwaite, *Multivariable Feedback Control Analysis and Design*, John Wiley & Sons, 2005.

[15] J. V. Milanovic and A. C. S. Duque, The use of relative gain array for optimal placement of PSS, *IEEE Trans. Power Systems*, vol.16, pp.992-996, 2001.

[16] A. C. Castro and C. S. Araújo, Signal analysis for decentralized control in power systems (Análise de sinais para controle descentralizado em sistemas de potência), *Proc. of the Brazilian Congress of Automatica (Anais do XIV Congresso Brasileiro de Automática)*, pp.1188-1193, 2002 (in Portuguese).

[17] J. J. Cruz, *Multivariable Robust Control (Controle Robusto Multivariável)*, Editora Universidade de São Paulo, 1996 (in Portuguese).

[18] Glover, Tabu search: A tutorial, *Interfaces*, vol.20, no.4, pp.74-94, 1990.

[19] B. G. da Silva Filha, A. C. de Castro, F. A. Moreira, I. S. L. Tebexreni and J. M. Araújo, Comparative study on heurist optimization techniques in the design of robust power systems stabilizers using H_∞ criterion, *International Journal of Innovative Computing, Information and Control*, vol.16, no.5, pp.1485-1495, 2020.

[20] M. A. Abido, Robust design of multimachine power system stabilizers using simulated annealing, *IEEE Trans. Energy Conversion*, vol.15, no.3, pp.297-304, 2000.

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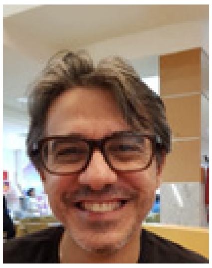

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