Journal of Engineering and Technology for Industrial Applications

ITEGAM-JETIA

ISSN ONLINE: 2447-0228

Manaus, v.6 n.24, p. 15-20, July/Aug., 2020
DOI: https://doi.org/10.5935/jetia.v6i24.675

RESEARCH ARTICLE OPEN ACCESS

ROBUST COORDINATED DESIGN OF AVR+PSS USING QUANTUM PARTICLE SWARM OPTIMIZATION

Raimundo Nonato Diniz Costa Filho[1] and Vicente Leonardo Paucar[2]

[1] Federal University of Maranhão - UFMA. Balsas–Maranhão, Brazil.
[2] Federal University of Maranhão - UFMA. São Luís–Maranhão, Brazil.

[1]http://orcid.org/0000-0001-8926-2071, [2]http://orcid.org/0000-0002-7950-7693

Email: raimundo.diniz@ieee.org, lpaucar@ieee.org

ARTICLE INFO

Article History
Received: July 06th, 2020
Accepted: August 11th, 2020
Published: August 31th, 2020

Keywords:
Rotor Angular Stability,
Power System Stabilizer,
Automatic Voltage Regulator,
Quantum Particle Swarm Optimization.

ABSTRACT

Automatic Voltage Regulator (AVR) regulates the generator terminal voltage by controlling the amount of current supplied to the generator field winding by the exciter. Power system stabilizer (PSS) is installed with AVR to damp the low frequency oscillation in Electric power system (EPS). However, for years, PSS paired with high initial response AVR have served as an effective means of meeting sometimes conflicting system stability requirements. In this context, this work presented a methodology with the objective of tuning the parameters of AVR and PSS to improve all the rotor angular stability of an EPS. The tuning of RAT and ESP was modeled using a multi-objective problem. Applying the ε-constraint method and a PSO, based on the quantum behavior of the particles, called QPSO, it was possible to solve the problem presented. The AVR and PSS were tuned optimally in a 5-machine equivalent of the South/Southeast Brazilian system. The proposed methodology was compared with the specialized literature and presented better results both for stability to small disturbances and for transient stability.

I. INTRODUCTION

Rotor angular stability (electromechanical stability) refers to the ability of synchronous machines in the network to maintain synchronism under large (transient stability) or small (small-signal stability) disturbances and which may be directly associated with maintaining or restoring the balance between torque electromagnetic and the mechanical torque of each of the system's synchronous machines [1,2]. The study of electromechanical stability in Electrical Power Systems (EPS) is essential, since this problem can cause serious technical and economic problems for EPS [3,4].

The AVR (Automatic Voltage Regulator) and PSS (Power System Stabilizers), when properly tuned, are one of the most economical ways to improve electromechanical stability. In general, for these controllers to contribute positively to the electromechanical stability, the tuning of the AVR and PSS follows the following sequence: first step is to design the AVR and then, in a second step, adjust the parameters of the PSS [5].

The adjustment of the AVR and PSS parameters aims to satisfy transient stability performance and improve the damping of low frequency electromechanical oscillations [6]. However, the current AVRs have high gains that can affect and shift the oscillation modes to an unstable (or poorly stable) region, on the other hand, PSS can contribute, in a negative way, to the transient stability [7-9]. Thus, a coordinated design of these controllers is important, since the parameters obtained in the tuning of PSS, in order to improve the damping of the system, are not always adequate in the analysis of transient stability.

The tuning of these controllers is carried out separately using control techniques, such as [8,9] frequency response and [10,11] applies the idea of centralized control. With the advent of Artificial Intelligence (AI) techniques it was possible to apply them to solve the problem presented. The main techniques applied were genetic algorithms [7] and particle swarm optimization (PSO - Particle Swarm Optimization) [6].

The objective of the article is to apply a PSO, based on the quantum behavior of the particles, called QPSO (Quantum PSO)

[12], for tuning the parameters of AVR and PSS, in order to improve all electromechanical stability. The main features of QPSO are its fewer parameters to adjust, easy implementation and quality of solution. The effectiveness of the proposed approach has been demonstrated through computer simulation in a 5-machine equivalent of the South/Southeast Brazilian system.

II. APPLIED METHODOLOGY

II.1 AVR AND PSS MODELS

AVR regulates the generator terminal voltage by controlling the amount of current supplied to the generator field winding by the exciter. The AVR model, adopted in the simulations of this work, consists of the gain K_A and the time constant T_A of the regulator. The control device most used for the damping of electromechanical oscillations is the PSS. The basic function of a PSS is to add damping to the generator rotor oscillations by controlling its excitation using auxiliary stabilizing signal(s) [1]. The PSS consists of three blocks: a gain block (K_{pss}), a washout signal block (T_w) and phase compensation blocks (T_1-T_4). As a feedback signal for the PSS, variations in the angular velocity ($\Delta\omega$) of the PSS installation machines were used. The structures of these controllers are illustrated in Figure 1.

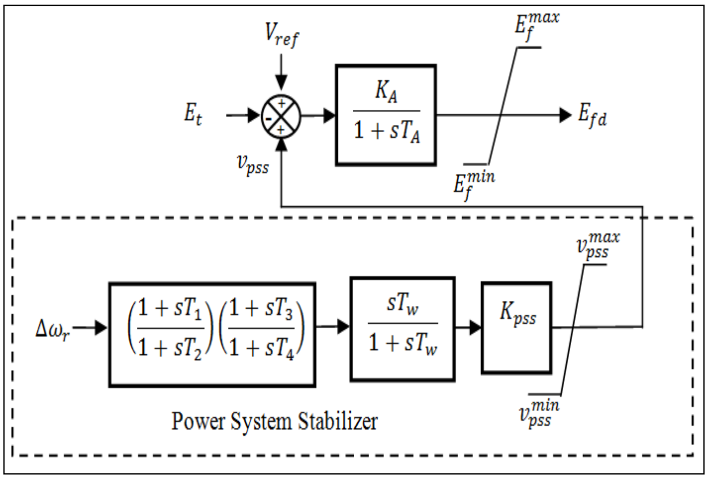

Figure 1: AVR and PSS models.
Source: Authors, (2020).

II.2 SMALL - SIGNAL STABILITY INDEX

The goal is to improve all electromechanical stability. This type of stability includes the analysis of stability to small disturbances and transient. The objective function used is based on indexes. These indexes are obtained through the analysis of stability to small disturbances and transient.

The analysis of stability to small disturbances involves the linearization of equations (1) around an operating point (x_0, r_0) obtained by a power flow program [1]:

$$\begin{bmatrix} \dot{\Delta x} \\ 0 \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta x \\ \Delta r \end{bmatrix} \tag{1}$$

Assuming that the Jacobian matrix J_4 is non-singular, the state matrix of the system can be obtained by eliminating the vector of the algebraic variables Δr:

$$\dot{\Delta x} = (J_1 - J_2 J_4^{-1} J_3)\Delta x = \boldsymbol{A}\Delta x \tag{2}$$

Where the symbol **A** represents the system state matrix.

The small disturbance stability assessment is based on the analysis of the eigenvalues of the system state matrix. The eigenvalues can be real or conjugated complex:

$$\lambda = \sigma \pm j\omega \tag{3}$$

The real part σ is related to the exponential growth of the response. The imaginary part, on the other hand, determines the oscillation frequency of the respective oscillation mode. The frequency of the oscillation mode in Hz is given by (4). The damping ratio for this frequency is given by (5).

$$f = \frac{\omega}{2\pi} \tag{4}$$

$$\zeta = \frac{-\sigma}{\sqrt{\sigma^2 + \omega^2}} \tag{5}$$

II.3 TRANSIENT STABILITY INDEX

The study of transient stability involves the representation of the EPS considering its nonlinearities. It is convenient to describe the behavior of the system with the angles of the generators expressed in relation to the center of inertia of all generators. The position of the Center of Inertia (COI) can be represented by a linear combination of the angles of all generators as follows in expression (6):

$$\delta_{COI} = \frac{1}{H_T}\sum_{i=1}^{N_g} H_i \times \delta_i \tag{6}$$

Where H_T is the sum of the inertia constants of all N_g generators in the system.

The accelerating power P_{ai} of generator i with respect to COI can be expressed by:

$$\begin{gathered} P_{ai} = P_{mi} - P_{ei} - \frac{H_i}{H_T} P_{COI} \\ P_{COI} = \sum_{i=1}^{N_g} (P_{mi} - P_{ei}) \end{gathered} \tag{7}$$

Where P_{mi} and P_{ei} are the mechanical and electrical powers of generator i, respectively.

$$\begin{gathered} F = \begin{bmatrix} P_{a1} = P_{m1} - P_{e1} - \frac{H_1}{H_T} P_{COI} \\ P_{a2} = P_{m2} - P_{e2} - \frac{H_2}{H_T} P_{COI} \\ \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \\ P_{aNg} = P_{mNg} - P_{eNg} - \frac{H_{ng}}{H_T} P_{COI} \end{bmatrix} \\ \Theta = \begin{bmatrix} \theta_1 = \delta_1 - \delta_{COI} \\ \theta_2 = \delta_2 - \delta_{COI} \\ \cdots\cdots\cdots\cdots\cdots\cdots \\ \theta_{Ng} = \delta_{Ng} - \delta_{COI} \end{bmatrix} \end{gathered} \tag{8}$$

The vector of the rotor angles and the accelerating power of the generators in relation to the COI are relevant measures that can be used to detect the instability of the system in the time domain [13]. It is possible to define the vectors *F* (formed by the accelerating powers of the synchronous generators in relation to the COI) and Θ (formed by the angles of the synchronous generators in relation to the COI) to develop the index used in the evaluation of the transient stability [13]. In this way, the stability of the system can be determined by using the internal product (9).

$$Dot = F * \Theta^t = F_1 * \Theta_1 + \cdots + F_{Ng} * \Theta_{Ng} \qquad (9)$$

II.4 COORDINATED TUNING OF AVR AND PSS

The ε-constraint method was introduced by Haimes for problems involving two objective functions [14]. In this method, one of the objectives is chosen as the only objective to be optimized, while the others are incorporated into the set of restrictions of the problem. Mathematically, the ε-constraint method can be written as follows, if the function to be minimized is $f_2(x)$, then the other objective functions are treated as problem inequality constraints, that is [15,16]:

$$\begin{gathered} \min f_2(x) \\ subject\ to\ f_i(x) \leq \varepsilon_i, i = 1, \cdots, p, i \neq 2, x \in X \end{gathered} \qquad (10)$$

Where $\varepsilon = (\varepsilon_1, \cdots, \varepsilon_p) \in R^p$ and is defined by the user.

This method is the most appropriate to be used for the AVR and PSS tuning problem in order to improve the angular stability, since in this multi-objective problem there are two purposes considered: to improve the stability to small disturbances and the transient stability. However, in practical applications, when analyzing stability to small disturbances, a minimum damping level is required for all electromechanical oscillation modes (e.g, ζ_o = 5%) [17], so in this case it can be considered as objective function an index which expresses, in numerical values, the situation of the system after a major disturbance has occurred (such as short circuit) and the other objective function, in the case of stability to small disturbances, will be incorporated into the set of problem constraints, as shown in Figure 2.

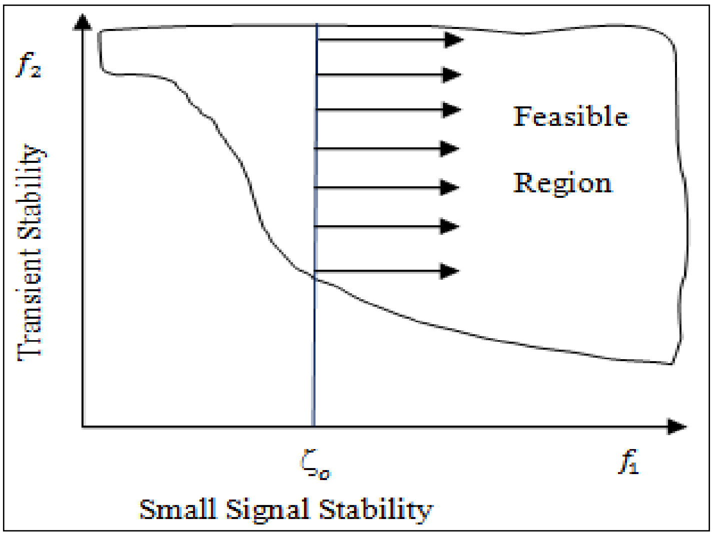

Figure 2: AVR and PSS models.
Source: Authors, (2020).

The index to represent stability to small-signal stability is given by the objective function f_1. Where, *NP* is the number of operation points considered in the analysis of small-signal stability and ζ_{NPmin} is the smallest damping ratio of the closed-loop system at the *NP* operation point.

$$f_1 = \min(\zeta_{1min}, \zeta_{2min}, \cdots, \zeta_{NPmin}) \qquad (11)$$

The objective function f_2 refers to the problem of transient stability.

$$f_2 = \int_0^{t_{sim}} Dot \times dt \qquad (12)$$

The problem can be formulated mathematically according to equation (13):

minimize f_2
Subject to

$$\begin{gathered} f_1 \geq \zeta_o \\ K_{A_{min}} \leq K_A \leq K_{A_{max}} \\ T_{A_{min}} \leq T_A \leq T_{A_{max}} \\ K_{pss_{min}} \leq K_{pss} \leq K_{pss_{max}} \\ T_{i_{min}} \leq T_i \leq T_{i_{max}}, \qquad i = 1, \cdots, 4 \end{gathered} \qquad (13)$$

Where ζ_o is the minimum damping considered when tuning the AVR and PSS at all points of operation.

III. QPSO ALGORITHM

III.1 PSO

PSO is a global optimization method developed by Kennedy and Eberhart [18]. It was developed from collective intelligence and is based on research on the behavior of bird flock and fish schools. The first step of the algorithm is to generate the *N* particles that will form the swarm with their respective positions. Each particle is initialized with a position and speed at random. The algorithm updates the velocity and position vectors until the maximum number of iterations is reached. To update the velocity vector of each particle, the expression (14) is used. To update the position vector of each particle, equation (15) [19] is used.

$$\begin{aligned} V_{ij}^{t+1} = w * V_{ij}^t + C_1 * r_1 * \left(P_{best_{ij}}^t - X_{ij}^t\right) + C_2 * r_2 \\ * \left(G_{best_j}^t - X_{ij}^t\right) \end{aligned} \qquad (14)$$

$$X_{ij}^{t+1} = X_{ij}^t + V_{ij}^{t+1} \qquad (15)$$

Where $i = 1,2, \ldots, N$, and *N* is population size; $j = 1,2, \ldots, dim$, and *dim* is the dimension of the problem; V_{ij}^{t+1} is the current particle speed; X_{ij}^t is the current position of the particle; $P_{best_{ij}}^t$ is the best position found by the particle *ij*; $G_{best_j}^t$ is the best position found among all particles *i*; *t* is the number of iterations; *w* is the inertia weight; C_1 and C_2 are generally acceleration coefficients; r_1 and r_2 are random numbers uniformly distributed in the interval [0,1]; X_{ij}^{t+1} is the position of each particle *i-j* in the iteration *t+1*; V_{ij}^{t+1} is the velocity vector of particle *i-j* in the iteration *t+1*.

III.2 QPSO

The QPSO algorithm is based on the quantum behavior of particle movements, so it is a type of algorithm with probabilistic characteristics, since the state of a particle is represented by the wave function ψ(x, t), instead of the position and speed as in the conventional model (PSO).

Based on the trajectory analysis, the reference [20] demonstrated that, to guarantee the convergence of the PSO, each particle must converge to its local attractor p_{ij}^{t}, whose coordinates are:

$$p_{ij}^{t} = \varphi_{ij} \times P_{best_{ij}}^{t} + (1 - \varphi_{ij}) \times G_{best_{j}}^{t} \quad (16)$$

Where φ_{ij} is a random number uniformly distributed over (0.1).

In the QPSO algorithm, the dynamic behavior of each particle is widely divergent compared to the classic PSO, and the exact position and velocity values cannot be determined simultaneously. In this scenario, it is only possible to find the particle at position X_{ij}, at time t, using the probability density function $|\psi(x,t)|^2$, which depends on the potential field in which the particle is located [12]. Using the Monte Carlo method, one can obtain the *jth* component of the position of particle i in the iteration $(t + 1)$ through the expression (17) [12,20].

$$\begin{cases} X_{ij}^{t+1} = p_{ij}^{t} + \alpha \times |C_j^t - X_{ij}^t| \times \ln\left(\dfrac{1}{u_{ij}^{t+1}}\right), if\ rand \geq 0.5 \\ X_{ij}^{t+1} = p_{ij}^{t} - \alpha \times |C_j^t - X_{ij}^t| \times \ln\left(\dfrac{1}{u_{ij}^{t+1}}\right), if\ rand < 0.5 \end{cases} \quad (17)$$

Where uij is a random number uniformly distributed over (0.1) and C_j is the best average position, which can be calculated by averaging the best individual positions of all particles.

$$C_j^t = \frac{\sum_{i=1}^{N} P_{best_{ij}}^{t}}{N}, (1 \leq j \leq dim) \quad (18)$$

The expansion and contraction coefficient α (sometimes represented by β [20]) controls the convergence speed of the algorithm during the search process. Behavior in the literature is suggested in a linearly decreasing manner and obeys equation (19) [12].

$$\alpha^t = \alpha_0 + (\alpha_1 - \alpha_0) \times \frac{(t_{max} - t)}{t_{max}} \quad (19)$$

Where t_{max} is the maximum number of iterations, α_1 and α_0 are the final and initial values of the parameter α and t is the current iteration.

IV. RESULTS

The purpose of this section is to show the results obtained by applying the proposed methodology to an equivalent system in South-Southeast Brazil. All state matrices were obtained using the PacDyn software [21]. The values of angles and accelerating power, in the analysis of transient stability, were obtained using the ANATEM [22]. Several functions have been written in MATLab (Matrix Laboraty) language to allow communication between the programs PacDyn and ANATEM. The limits of the PSS parameters are: 0.01≤Kpss≤ 50; 0.001≤ (T1, T2, T3, T4) ≤ 2. The value of the constant T_w was 3 seconds. The limits of the AVR parameters are 20≤KA≤400 and 0.01≤TA≤0.2. In the analysis of transient stability, it is important to consider the output limits of the AVR and PSS [1], the limits considered in all simulations were ± 10p.u and ± 0.25p.u for the AVR and PSS, respectively [8]. The QPSO parameters [12] adopted in the simulations are: population size = 50; maximum number of iterations = 60, α_1 = 1 and α_0 = 0.5.

IV.1 TEST SYSTEM

This system is a seven-bus, five-machine equivalent model of the Southern/Southeastern Brazil system. The synchronous generators were represented by a fifth-order model. The order of the open loop system is 29x29. For the application of the methodology, there are five different operation points or cases, taken from [23] and shown in Table 1. It is observed that the lowest damping value occurs at operation point 5 with -16.58% and frequency oscillation of 0.796 Hz. Through the analysis of the residues, 2 PSS was installed in the system, a PSS in the Segredo generator (bus 3) and the other PSS in the Itaipu generator (bus 4).

The large disturbance considered in the project was an application of a three-phase short circuit on bus 5 with duration of 115 ms followed by the opening of line 5-1. The simulation time (t_{sim}) considered was 5 seconds and the damping required for all operating points was ζ_0 = 10%.

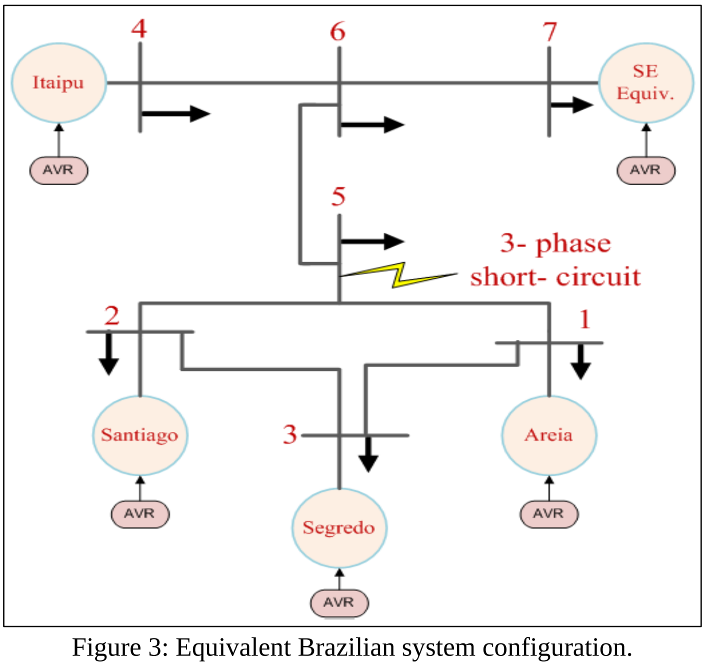

Figure 3: Equivalent Brazilian system configuration.
Source: Authors, (2020).

Table 1: Operating conditions.

Case #	X_{5-6} pu	X_{6-7} pu	Mode 1 f(Hz)	Mode 1 ζ(%)	Mode 2 f(Hz)	Mode 2 ζ(%)
1	0,39	0,57	0,858	-11,90	0,935	3,83
2	0,50	0,57	0,855	-12,10	0,918	3,50
3	0,80	0,57	0,851	-12,66	0,877	2,77
4	0,39	0,63	0,830	-14,04	0,931	4,04
5	0,39	0,70	0,796	-16,58	0,926	4,18

Source: Authors, (2020).

After applying the QPSO algorithm, the PSS and AVR parameters were obtained, which are presented in Table II. The map of closed-loop poles is illustrated in Figure 8. It is observed that, for all operating points, closed-loop poles have damping above the required (ζ_0 = 10%) in the project (case 1- ζ_{min} = 13.95%; case 2- ζ_{min} = 13.90%; case 3- ζ_{min} = 13.79%; case 4- ζ_{min} = 13.95% and case 5- ζ_{min} = 13.96%). The closed-loop pole map considering the 5 operating conditions is shown in Figure 4. Through the application of the presented methodology, it was possible to stabilize the system with respect to transitory stability and, at the same time, improve the damping levels of all the considered operation points.

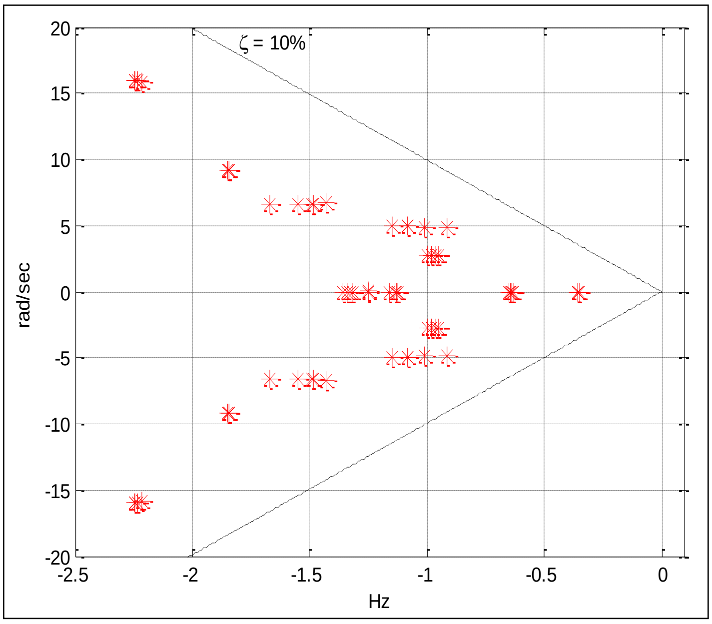

Figure 4: Closed-loop pole map.
Source: Authors, (2020).

Table 2: Optimal control parameters.

	K_A		T_A		
AVR_3	74.5110		0.2000		
AVR_4	157.9200		0.0705		
	K_{pss}	T_1	T_2	T_3	T_4
PSS_3	45.618	0.0612	0.0010	0.2552	0.0010
PSS_4	31.295	0.6882	0.0010	0.2667	0.0013

Source: Authors, (2020).

IV.2 UNCOORDINATED DESIGN OF AVR+PSS

Originally, the AVR of generators 3 and 4 have values of K_A and T_A equal to 30 p.u and 0.05 s, respectively. The transfer functions of the PSSs obtained through the classic design have been removed from reference [23] (named in design article C). The minimum damping values obtained through the use of PSSs in Segredo and Itaipu are: case 1- ζ_{min} = 9.54%; case 2- ζ_{min} = 9.66%; case 3- ζ_{min} = 8.81%; case 4- ζ_{min} = 9.03% and case 5- ζ_{min} = 7.17%.

For comparison, a three-phase short circuit was applied to bus 5 in 0.200 seconds and removed in 0.312 seconds followed by the opening of line 5-1. Figures 5 and 6 show the behavior of the angle (with respect to generator 7) and the voltages of all the generation buses with the PSS of generators 3 and 4 designed by the classic control, respectively. In contrast, Figures 7 and 8 show the behavior of the angle (with respect to generator 7) and the voltages of all the generation buses with the PSS and AVR of generators 3 and 4 tuned by the QPSO algorithm, respectively. Note that the response of the angles of the generators and voltage of the generation buses obtained by applying the proposed methodology is better than that obtained by the classical control theory.

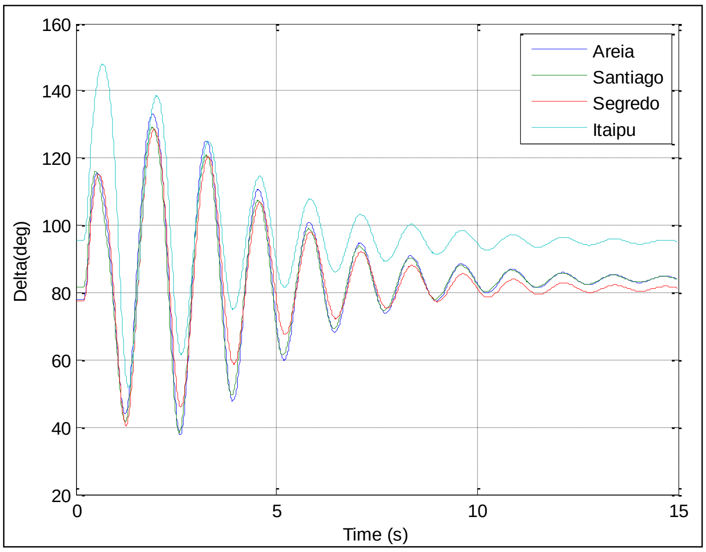

Figure 5: Generators rotor angle - classic design.
Source: Authors, (2020).

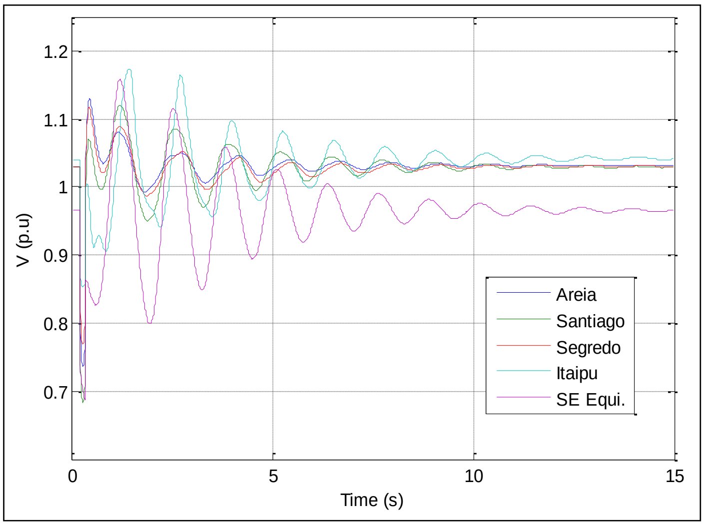

Figure 6: Generation bus voltage - classic design.
Source: Authors, (2020).

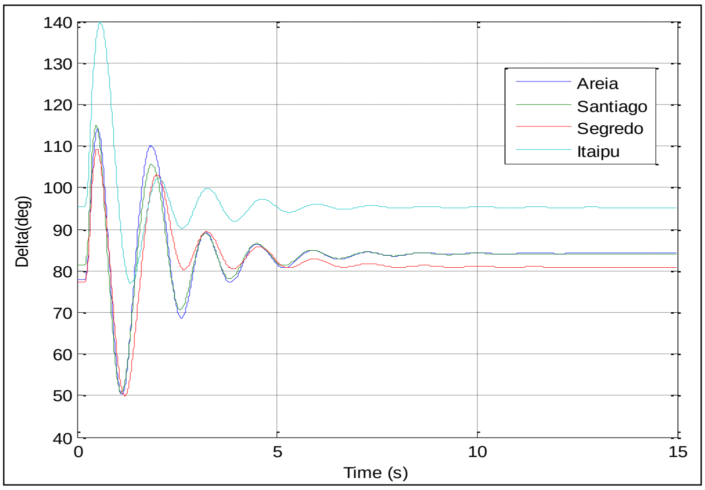

Figure 7: Generators rotor angle - QPSO.
Source: Authors, (2020).

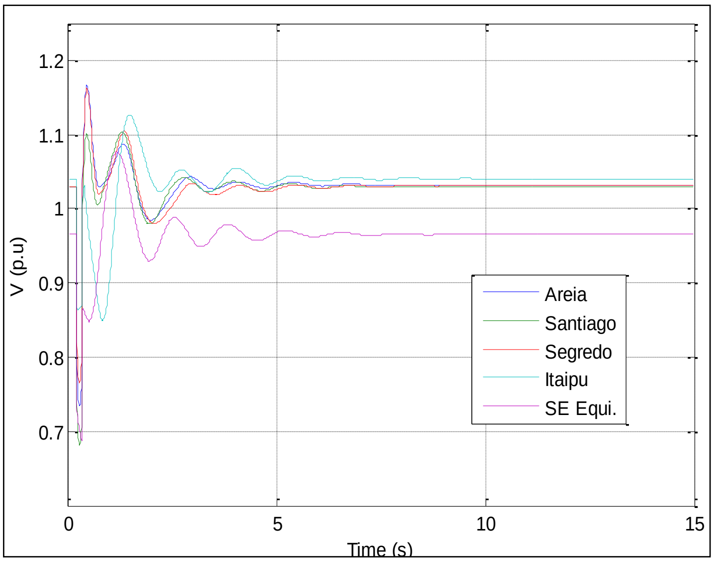

Figure 8: Generation bus voltage - QPSO.
Source: Authors, (2020).

V. CONCLUSIONS

This paper presented a methodology with the objective of tuning the parameters of AVR and PSS to improve all the electromechanical stability of an Electric Power System (EPS). The tuning of AVR and PSS was modeled using a multi-objective problem. Applying the ε-constraint method and a PSO, based on the quantum behavior of the particles, called QPSO, it was possible to solve the problem presented. The AVR and PSS were tuned optimally in a 5-machine equivalent of the South/Southeast Brazilian system. The proposed methodology was compared with the specialized literature and presented better results both for stability to small disturbances and for transient stability.

VI. REFERENCES

[1] P. Kundur, Power System Stability and Control. New York: McGraw Hill, 1994.

[2] A. Gómez-Expósito, A. J. Conejo and C. Cañizares, Electric Energy System: Analysis and Operation. CRC Press, 2008.

[3] D. N. Kosterev, C. W. Taylor and W. A. Mittelstadt, "Model validation for the august 10, 1996 WSCC system outage," IEEE Transactions on Power System, vol. 14, no. 3, pp. 967-979, Aug. 1999.

[4] V. X. Filho, L. A. S. Pilotto, N. Martins, A. R. C. Carvalho and A. Bianco, "Brazilian defense plan against extreme contingencies," in Proc. IEEE Power Eng. Soc. Summer Meet., vol. 2, pp. 834-839, 2001.

[5] K. T. Law, D. J. Hill and N. R. Godfrey, "Robust controller structure for coordinated power system voltage regulator and stabilizer design," IEEE Transactions on Control System Technology, vol. 2, no. 3, pp. 220-232, Sep. 1994.

[6] E. R. C. Viveros, G. N. Taranto and D. m. Falcão, "Tuning of generator excitation system using meta-heuristics," in Proc. IEEE Power Eng. Soc. Gen. Meet.., pp. 1-6, 2008.

[7] B. Selvabala and D. Devaraj, "Co-ordinated design of AVR-PSS using multiobjective genetic algorithm," Swarm, Evolutionary and Memetic Computing, vol. 6466, pp. 481-493, June 2010.

[8] G. J. W. Dudgeon, W. E. Leithead, A. Dysko, J. O'Reilly and J. R. McDonald, "The effective role of AVR and PSS in power systems: frequency response analysis," IEEE Transactions on Power System, vol. 22, no. 4, pp. 1986-1944, Nov. 2007.

[9] A. Dysko, W. E. Leithead and J. O'Reilly, "Enhanced power system stability by coordinated PSS design," IEEE Transactions on Power System, vol. 25, no. 1, pp. 413-422, Feb. 2010.

[10] H. Bourlès, S. Peres, T. Margotin and M. P. Houry, "Analysis and design of a robust coordinated AVR/PSS," IEEE Transactions on Power System, vol. 13, no. 2, pp. 568-575, May 1998.

[11] H. Quinot, H. Bourlès and T. Margotin, "Robust coordinated AVR+PSS for damping large scale power systems," IEEE Transactions on Power System, vol. 14, no. 4, pp. 1446-1451, Nov. 1999.

[12] J. Sun, W. Fang, V. Palade, X. Wu and W. Xu, "Quantum-behaved particle swarm optimization with gaussian distributed local attractor point," Applied Mathematics and Computation, vol. 218, no. 7, pp. 3763-3775, Dec. 2011.

[13] C. Fu and A. Bose, "Contingency ranking based on severity indices in dynamic security analysis," IEEE Transactions on Power System, vol. 14, no. 3, pp. 980-986, Aug. 1999.

[14] Y. Y. Haimes, L. Lasdon and D. Wismer, "On a dicrierion formulation of the problem of integrated systems identification and systems optimization," IEEE Transactions on Systems, Man, Cybernetics, vol. SMS-1, pp. 296-297, July 1971.

[15] Y. Sawaragi, H. Nakayama and T. Tanino, Theory of Multiobjective Optimization. Academic Press, Orlando, Florida, 1985.

[16] G. Mavrotas, "Effective implementation of the ϵ-constraint method in multi-objective mathematical programming problems," Applied Mathematics and Computation, vol. 213, no. 2, pp. 455-465, July 2009.

[17] S. Gomes Jr., N. Martins and C. Portela , "Computing small-signal stability boundaries for large-scale power systems," IEEE Transactions on Power System, vol. 18, no. 2, pp. 747-752, May 2003.

[18] J. Kennedy and R. C. Eberhat, "Particle swarm optimization," Proceedings of IEEE International Conference on Neural Networks, vol. 4, pp. 1941-1948, Nov. 1995.

[19] H. S. Lopes e R. H. C. Takahashi, Computação Evolucionária em Problemas de Engenharia, Omnipax, 2011.

[20] L. S. Coelho, "Novel gaussian quantum-behaved particle swarm optimiser applied to electromagnetic design," IET Science, Measurement & Technology, vol. 1, no. 5, pp. 290-294, Sep. 2007.

[21] PacDyn 8.1 User Manual, Cepel, Nov. 2008.

[22] ANATEM User Manual, Cepel, Nov. 2001.

[23] 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 Transactions on Power System, vol. 15, no. 4, pp. 1287-1292, Nov. 2000.