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Coordinated tuning of power system controllers using parallel genetic algorithms

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ABSTRACT

This work proposes a computational methodology for coordinated tuning of the power system controllers based on Genetic Algorithm which acts maximizing simultaneously two objective functions, representing each of them the damping of electromechanical oscillations and the improvement of the automatic voltage regulator responses, considering at the same time several critical operating conditions. The coordinated tuning procedure was posted as a multi-objective optimization problem, through the weighted sum technique. The controllers considered into the adjusting scheme correspond to the automatic voltage regulators, power system stabilizers and static var compensators to enhance the electromechanical and voltage response for a several critical operating conditions considered. The Genetic Algorithm was adapted for parallel computing in order to achieve both dynamic responses encompassing several critical operating conditions to reduce high computational efforts. Simulation results of the parallel implementation were more significant than the sequential version, and the proposed approach becomes an interesting alternative tool for operation planning and stability studies.

1. Introduction

Power Electric System (PES) is frequently affected by non-predicted disturbances, which cause outages of important transmission lines that modify its operating conditions and may appear low damped electromechanical oscillations, or even, the loss dynamic stability. Besides that, when PES operates with a high electric power demand, some regions can experiment a continued voltage degradation and, in many situations, can reach the voltage collapse, due to inadequate number of reactive power sources for critical operating scenarios [1,2].

Little variations in the power demand from generators to load centers produce small electromechanical oscillations. However, when large disturbances happened (e.g. main transmission lines outages, sudden disconnection of important group of generators, etc.) the amplitude of that oscillations can grow up and arrive to electromechanical and voltage instability. The main power system controllers that act, simultaneously, after a disturbance in order to control the electromechanical oscillations and voltage response of the synchronous generators are the Power System Stabilizers (PSSs) and the Automatic Voltage Regulators (AVRs), respectively. On the other hand, the voltage profile of the whole electric system is controlled by the FACTS devices, such as Static Var Compensators (SVCs), installed at specific substations, working like power reactive sources.

PSSs add supplementary signal to the reference voltage of the AVRs to damp quickly the electromechanical oscillations. The AVR in each generator acts when the monitored stator voltage varies away from the reference voltage when a certain disturbance happened. The AVR and PSS are located into the excitation system of each generator [1]. The SVCs are FACTS devices [3,4] installed in certain substations of the PES where they inject adequate reactive power from those substations to improve the local voltage positive affecting the voltage profile of the neighbor substations and the whole electrical system.

Computational methods for coordinated and simultaneous tuning of AVR and PSS have already been developed using numerical techniques [5–7] and meta-heuristic optimization approaches [8,9], major of them for damping quickly the electromechanical oscillations, and some of them to optimize the voltage response of the AVR. However, there are a few works related to the simultaneous adjusting of the AVR, PSS and SVC parameters in order to enhance the electromechanical and voltage stability [10–12], in frequency domain. So, this paper describes a computational coordinated method for, simultaneously, reducing the electromechanical oscillations, maximizing the minimum damping coefficient and improve the voltage response of the PES against to several critical operating conditions, and extends the work described in [12].

In this work the coordinated tuning of controllers was posted as a

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multi-objective optimization problem, where the response curve of AVR from the tuning procedure, simulated in time domain, was the first objective function; and, the PSS and SVCs were adjusted in frequency domain, through the maximization of damping ratio, considering several critical operating conditions [13]. The Genetic Algorithm (GA) was used due its proven effectiveness in global optimization of equation systems representing complex and non-linear dynamic systems [14]. So, in this work the GA was adequate for simultaneously optimization of both objective functions, AVR tuning in time domain and PSS and SVC adjusting procedure in frequency domain, considering at the same time several critical operating conditions, using the weighted sum technique, obtaining a kind of Multi-Objective GA (MOGA) [15]. The MOGA was also adapted for parallel computing in order to increase the research space and searching ability and also to reduce the computing time, because the resulting equation system to be optimized may to become a medium or large-scale optimization problem. The electric system used for validating the proposed coordinated tuning method was the New England, an academic and small-scale electric system. Additionally, the Pelican HPC MPI platform [16] was used for parallel computing in a cluster of PCs.

In this paper, the mathematical models of AVR, PSS and SVC are described in Section II. Section III details the tuning technique for each controller and the coordinated tuning proposed. Section IV itemizes the MOGA, based on Weighted Sum technique. Section V shows and explains the numerical results, and finally, in Section VI, the conclusions are described and a brief description of implementations being developed for future works.

2. Models

2.1. AVR model

Fig. 1 represents the first order model of the AVR considered in this work that corresponds to a variant derived from the IEEE ST1A scheme [17]. The gain K_A and the time constant T_A are the parameters to be adjusted by the proposed tuning procedure.

V_{REF} is the voltage reference of the AVR. The voltage terminal (V_T) of each generator should be close of V_{REF} at widely operating conditions. The AVR output signal is the Field Voltage, E_{FD}, regards to the necessary reactive power from the excitation circuit in order to regulate V_T.

2.2. PSS model

Fig. 2 describes the PSS model [17]. The PSS input signal is the angular speed of the generator rotor (ω), in the present work. The time constant of the washout block, T_W, is considered known and was set to 3 s (T_W = 3 s). The gain of the PSS, K_S, and the two parameters of the lead-lag blocks, α and ω, are the PSS parameters to be tune through the proposed tuning algorithm. The PSS adds a complementary signal, V_S, into the voltage reference, V_{REF}, of the corresponding AVR.

Where T_1 and T_2, are functions of α and ω, and these parameters are calculated through the following mathematical expressions:

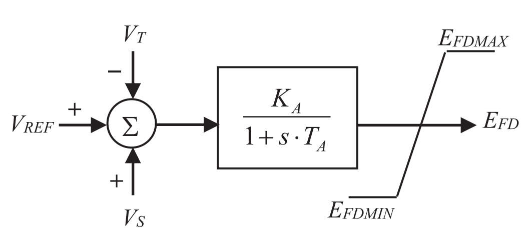

Fig. 1. First order AVR model.

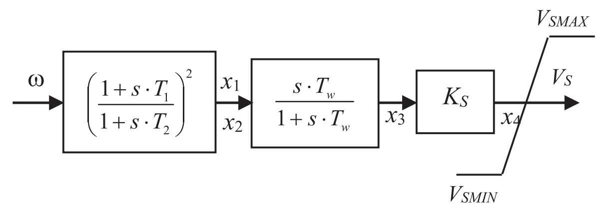

Fig. 2. PSS model.

$$T_1 = \frac{\sqrt{\alpha}}{\omega}$$
$$T_2 = \frac{1}{\omega\cdot\sqrt{\alpha}} \tag{1}$$

PSS constitutes a lead-lag compensator which provides the maximum phase compensator defined by the following equation [18]:

$$\sin(\varphi_m) = \frac{\alpha - 1}{\alpha + 1} \tag{2}$$

where the supplementary angular deviation ϕ_m is the maximum compensation phase, which is approximately 55° with α = 10, according (2); and, ω corresponds to the angular frequency of the dominant electromechanical mode, in Eq. (1). The PSS output signal, V_S, is a supplementary voltage that is added to V_{REF}, such as shown in Fig. 1.

2.3. SVC model

Fig. 3 illustrates the dynamic model of the SVC voltage regulator, and the proposed adjustment method seeks the optimal value for the gain K_C and the time constant T_C [19].

SVC monitors the bus voltage (V_C), of the substation where the static compensator is installed. V_C is compared to the voltage reference, V_{CREF}, of the SVC voltage regulator, and the resulting error ($V_{CREF} - V_C$) feeds the lag block and produces the output signal B_C, which represents the necessary susceptance of the SVC that generates the feasible reactive power to be injected into the substation, and then improve the voltage profile of the neighbor substations.

2.4. PES model

The well-known state space equations [1] represents suitably the PES, for dynamic and voltage stability studies, at any operating condition:

$$\begin{bmatrix} \frac{dx}{dt} \\ 0 \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \cdot \begin{bmatrix} x \\ u = V_{REF} \end{bmatrix} \tag{3}$$

The sub-matrices J_1, J_2, J_3, J_4 in the Eq. (3) form the expanded *Jacobian* of the PES [1], and represents the open-loop operation of the PES. The close-loop state matrix, A_{CLOSE}, is calculated applied the Gaussian reduction on the matrix Eq. (3), where the sub-matrix J_1 contains the mathematical equations of all power system controllers to be adjusted, such as AVR, PSS and SVC devices. Then, the mathematical expression (4) shows the calculation of the A_{CLOSE} matrix [1]:

$$A_{CLOSE} = J_1 - J_2 \cdot J_4^{-1} \cdot J_3 \tag{4}$$

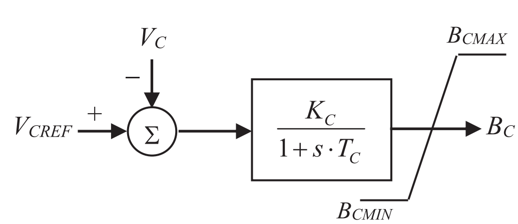

Fig. 3. SVC model.

A_{CLOSE} contains the differential equations coefficients that represent the dynamic performance of the main controllers, which were considered in the coordinated tuning algorithm, such as the AVR and PSS, and the group of SVC devices. The following equations describe the referred coefficients [12]:

$$\dot{E}_{FD} = (V_S + V_{REF} - V_{TR} - V_{TI})\cdot\frac{K_A}{T_A}\cdot\frac{E_{FD}}{T_A} \tag{5}$$

$$\dot{x}_1 = -\frac{1}{T_2}\cdot x_1 + \left(\frac{T_2 - T_1}{T_2^2}\right)\cdot\omega \tag{6}$$

$$\dot{x}_2 = -\frac{1}{T_2}\cdot x_2 + \left(\frac{T_2 - T_1}{T_2^2}\right)\cdot x_1 \tag{7}$$

$$\dot{x}_3 = -\frac{1}{T_W}\cdot x_3 - \frac{1}{T_2}\cdot x_2 + \left(\frac{T_2 - T_1}{T_2^2}\right)\cdot x_1 \tag{8}$$

$$x_4 = K_S\cdot x_3 \tag{9}$$

$$\dot{B}_C = -\frac{1}{T_C}\cdot B_C + \frac{K_C}{T_C}\cdot V_{CREF} \tag{10}$$

In Eq. (5), V_{TR} and V_{TI} represent the real and imaginary part, respectively, of each generator terminal voltage (V_T). The unknown entries x_1, x_2, x_3 and x_4 in the Eqs. (6) to (9) are referred to the state variables of the block diagram in Fig. 2. The proposed coordinated tuning algorithm modifies all coefficients of the Eqs. (5) to (10) directly in the closed-loop state matrix A_{CLOSE}.

3. Coordinated tuning procedure

3.1. AVR tuning

The AVR adjustment implemented in this work is based on the transient response of each generator terminal voltage; and, firstly, an independent equivalent network is created for each generator, based on [20], as shown in Fig. 4.

The reactance that connects the generator with the infinite bus is commonly made proportional to the generator transient reactance (X'_d), by some numerical factor K, such as graphically describe in Fig. 4, following the procedure described in [20]. Then, a step variation of V_{REF} was simulated on each generator of the corresponding PES. The tuning quality is evaluated by calculating the area between the time curve responses of the V_{REF} and the V_T, called the *Integration Area* (I_A), when it is simulated a 10% step variation of the V_{REF}, along the time simulation, such as described in Fig. 5.

In Fig. 5, ΔV_{REF} is the variation step of V_{REF} (ΔV_{REF} = 10% V_{REF}), t_Δ corresponds to the instant of V_{REF} variation, and t_{max} is the simulation time. Then, the objective is to minimize the shaded area shown in Fig. 5, by the proposed coordinated tuning algorithm implemented. The AVR tuning procedure has been implemented through the adaptation of **s_simu(·)** which is a function of the *Power System Toolbox* (PST) [21]. In this work, t_{max} = 5 s, and the time step (Δt) = 0.01 s.

3.2. PSS and svc tuning

$A_{CLOSE,j}$ is calculated in each operating condition, where $j \in \{1, 2, \ldots, N_{OP}\}$ | N_{OP} is the number of operating conditions considered for the PES, with the PSS and SVC parameters determined by the proposed coordinated adjusting. The dynamic stability of the PES is established when all real part of the all eigenvalues from $A_{CLOSE,j}$ are inside the left zone of the poles map [1], according to Modal Analysis Theory. The eigenvalues from the $A_{CLOSE,j}$ are calculated by the QR algorithm [22], in each *j-th* operating condition. Then, the minimum damped coefficient, ξ_{min}, is obtained considering all calculated eigenvalues, considering all operating scenarios.

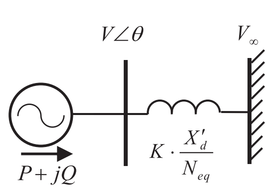

Fig. 4. Equivalent system implemented for *AVR* tuning on each synchronous generator.

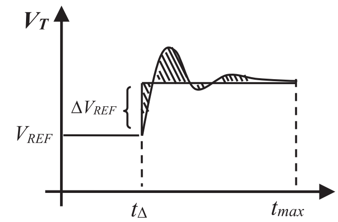

Fig. 5. Area between V_{REF} and V_T time response curves.

3.3. Coordinated tuning

In this work, the coordinated tuning procedure was posted as a multi-objective optimization problem, and the main goal is to minimize the I_A, from the AVR tuning scheme, and simultaneously, to maximize the global minimum damped coefficient, from the PSS and SVC adjustment approach, considering a list of several critical operating conditions of PES, following these steps:

(a) AVR parameters are included into Eq. (5), after the time domain adjusting scheme;
(b) Then, the PSS and SVC parameters are chosen by the GA procedure, and they are included into the Eqs. (6) to (10) to define the corresponding coefficients into the $A_{CLOSE,i}$. So, there are N_{OP} closed-loop state matrices that represent the main critical dynamic performance of the PES, making the proposed coordinated tuning technique a robust computational method;
(c) From those N_{OP} closed-loop state matrices is calculated the global minimum damped coefficient, ξ_{min}:

$$\xi_{MIN} = \min\left\{\left[\xi_{min,1} \quad \xi_{min,2} \quad \cdots \quad \xi_{min,N_{OP}}\right]\right\} \tag{11}$$

The coordinated tuning procedure is based on GA. Nevertheless, the GA described in [14] was adapted for multi-objective optimization based on the weighted sum technique.

4. MOGA for coordinated tuning

In this work, the coordinated tuning procedure was posted as a multi-objective optimization problem, and the main goals is to maximize the inverse value of I_A, from the AVR tuning scheme, and simultaneously, to maximize the ξ_{MIN}, from the PSS and SVC adjustment approach, considering a list of several critical operating conditions of PES.

4.1. Objective functions

The objective function associated with the AVR adjusted is given by:

$$F_1 = \max\left\{\left|\frac{1}{I_A}\right|_1 \quad \left|\frac{1}{I_A}\right|_2 \quad \cdots \quad \left|\frac{1}{I_A}\right|_{N_g}\right\} \tag{12}$$

where N_g is the number of generators belong to multi-machine PES, considered for the AVR tuning procedure. The objective function associated to the PSS and SVC coordinated tuning scheme is given by:

$$F_2 = \xi_{MIN} \quad (13)$$

4.2. Encoding

Eqs. (14) to (16) represent the adjusting solutions of AVR, PSS and SVC parameters of each generator and each group of static compensators, respectively, and Eq. (17) joins all potential solutions, and represents an individual in the Multi-Objective GA.

$$x_{AVR} = [K_{A1} \quad T_{A1} \quad \cdots \quad K_{ANg} \quad T_{ANg}] \quad (14)$$

$$x_{PSS} = [K_{S1} \quad \alpha_1 \quad \omega_1 \quad \cdots \quad K_{SNg} \quad \alpha_{Ng} \quad \omega_{Ng}] \quad (15)$$

$$x_{SVC} = [K_{C1} \quad T_{C1} \quad \cdots \quad K_{ANb} \quad T_{ANb}] \quad (16)$$

$$X = [x_{AVR} \quad x_{PSS} \quad x_{SVC}] \quad (17)$$

where N_b is the number of buses where were located the SVC devices.

The coordinated locating and MVAr sizing method for SVC devices were described in [23], and those techniques were applied in this work, in order to locate N_b group of static compensators at N_b substations, considering several critical operating scenarios for the PES.

4.3. MOGA implementation

The proposed coordinated tuning algorithm based on MOGA is better described by the following pseudocode:

MOGA Pseudocode

1. Initial Population
   - $N - 1$ individuals are randomly generated, but satisfying their lower and upper limits, where $N = 48$;
   - *Remaining individual.* The PSS parameters are adjusted applying the *Nyquist* criterion for each generator, with AVR and SVC parameters kept constants [24]: $K_A = 100$ pu, $T_A = 0.05$ s, $K_C = 100$ pu, and $T_C = 0.5$ s.
2. Fitness Evaluation

F₁: from AVR tuning, described in section A, Section III, and Figs. 4 and 5;
F₂: PSS and SVC tuning, through ξ_{MIN} and Eq. (11).
$F_i = a_1 \cdot F_{1,i} + a_2 \cdot F_{2,i}$ (18)
$a_1 = 1/F_{1,\max}$ $a_2 = 1/F_{2,\max}$
Where $i \in \{1, 2, \ldots, N\}$ | N is the population size of the GA, and F_{1max} and F_{2max} correspond to the maximum values of F_1 and F_2, respectively.

3. Elitism

Individual with maximum *Fitness* is preserved for the next generation, in the current generation.

4. Genetic Operators [14]
   - *Selection operator.* Stochastic Tournament with four individuals and is performed in each generation;
   - *Crossover operator. One-point* crossover with crossover percentage of 0.7 ($p_c = 0.7$), i.e. with $N = 48$, the crossover is applied 34 times, approximately, in order to obtain new individuals for next generation;
   - *Mutation operator.* Simple mutation was used altering each component of the individual according to a probability 0.01 ($p_m = 0.01$), that is, for every 100 components will be altered randomly one component in the current solution vector (individual).
5. Stop Criterion.

Check if the stop criterion is satisfied (maximum number of generations – *maxGen*), otherwise return to step 2, and repeat all calculations. In this work *maxGen* = 40 generations.

The coefficients a_1 and a_2 are calculated in each iteration (generation) of the MOGA algorithm in order to normalize the objective functions $F_1(x)$ and $F_2(x)$ to avoid that disproportionately numerical values for $F_2(x)$, with respect to $F_1(x)$, or vice versa, lead the search and reach local optimum. The maximum values for $F_1(x)$ and $F_2(x)$, $F_{1,\max}$ and $F_{2,\max}$, are found in each generation for Fitness calculation from (18).

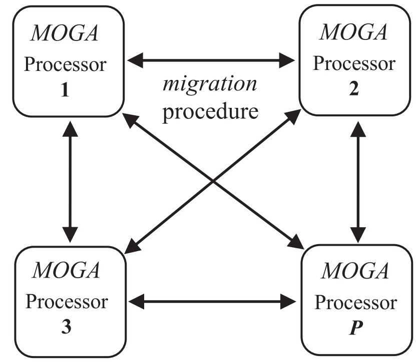

Fig. 6. Communication topology of parallel MOGA.

4.4. Parallel MOGA

The sequential version of MOGA, such as described in MOGA Pseudocode above, requires higher computational efforts in order to get good solutions when it is applied on stability studies and coordinated tuning controllers on PES and considering, simultaneously, several operating conditions for operation and expansion planning. Then, an alternative solution for that inconvenience is to adapt the MOGA for parallel computing.

In this work, a population, with N_P individuals, was located on each computer belongs to an available *Local Area Network* (LAN), and N_P is calculated through the following equation:

$$N_P = N/P \quad (19)$$

where P is the number of available processors into the LAN, and N is the global population size of MOGA; and, Fig. 6 shows the scheme and topology of the parallel MOGA implemented.

Then, such as indicated in Fig. 6, the MOGA algorithm operates on N_P individuals located into each processors of the LAN; and, in order to get different populations, the initial values of the random numbers generator [22], called seed number ($seed_{Pk}$), is modified for each available processor on the LAN, through the following mathematical expression:

$$seed_{Pk} = seed/P_k \quad (20)$$

where $P_k \in \{1, 2, \ldots, P\}$, and *seed* represents the original initial value of the random numbers generator, and $seed_{Pk}$ is the initial value of random numbers sequence in each active processor of the LAN.

As described in Fig. 6, some data solutions are transmitted between processors, available in the LAN, and that operation is called *migration*. Therefore, the *migration* introduces new variables in order to define the transmission mechanism between processors into the Parallel MOGA [25].

- *Migration interval*. Number of generations between each *migration*. In this work, the *Migration interval* was fixed in 10 generations;
- *Migration rate*. Number of individuals to be transmitted from a processor to others. In this work, the *Migration rate* = 1 individual;
- *Individuals' Selection Strategy*. Selection rule of the individual to be transmitted. In this work, the individual with maximum Fitness was transmitted;
- *Reception Strategy*. It refers to the rule for incorporating the received individuals into the current population. In this work, each processor receives P–1 individuals, and then a *Tournament selection*, with P–1 individuals, is applied in order to get one individual for incorporating into the current population;

In addition, the communication between each computer in the LAN is made with the blocking transmission toolbox of the Pelican HPC platform [26], i.e. when the *Migration interval* is reached, during the optimization process in each processor; all computers stop their current execution in order to prepare and transmit the individual from one processor to the rest of computers, and perform the receiving procedure to incorporate the arriving individuals into the current population.

5. Results

5.1. LAN and parallel computing platform

The LAN is composed by 8 Intel dual core 2.30 GHz computers with 2 GBytes RAM, and each of one is connected through switched 100Mbits Fast-Ethernet network. Each computer runs on Linux. The Pelican HPC platform [26] is used for parallel computing, which contains MPI commands for data transmission between processors. The Pelican HPC allows implementation of parallel algorithm using the MatLab and GNU Octave [27].

5.2. Initial values for MOGA

In order to initialize the population was considered the following upper and lower limits for controller parameters:

(a) *AVR parameters*. 100 pu $\le K_A \le$ 400 pu, and 0.02 $s \le T_A \le$ 0.5 s;
(b) *PSS parameters*. 1 pu $\le K_S \le$ 20 pu, 0.1 $\le \alpha \le$ 10, and 0.4π *rad/s* $\le \omega \le 16\pi$ *rad/s*;
(c) *SVC parameters*. 5 pu $\le K_C \le$ 200 pu, and 0.01 $s \le T_C \le$ 1 s.

5.3. Test system data

The PES used as a test system was the New England electric system, originally described in [28], which contains 39 buses and 10 generators. In this system, there are nine excitation controllers (AVR and PSS) and three SVC devices to be tuned using the proposed coordinated tuning algorithm, considering six operating conditions, such as described on Table 1, with initial values for all AVR parameters fixed in K_A = 200 pu and T_A = 0.05 s (Base Case). The SVC devices are located on buses 6, 7, and 20 calculated by the algorithm described in [23]. Fig. 7 shows the New England system topology.

In Table 1, the column with the symbol $\xi_{\min}$(%) indicates the minimum coefficient damping regarded to the dominant electromechanical mode associated to each operating point. Then, according to the list of minimum damping coefficient in Table 1, the 4th operating condition is considered the most critical compared to the rest scenarios.

Instead the New England is a small scale electric system, the resulting optimization problem, in order to adjust parameters of distinct controllers, taking into account several performance criteria, and, simultaneously, consider many contingences and critical operating conditions, may become a large scale numerical optimization problem and implies huge computational resources to be used (digital memory and large computing time).

5.4. Numerical results

Table 2 shows the experimental results for the MOGA sequential version and Parallel MOGA, considering all operating condition described in Table 1.

Table 1
Operating conditions.

#	Descriptions	$\xi_{\min}$ (%)
1	Base Case.	−1.02
2	TL 4–14 and TL 16–17 out of service.	−0.91
3	TL 3–18 and TL 25–26 out of service.	−0.97
4	TL 6–11 out of service.	−1.03
5	Total load incremented in 10%.	−1.02
6	Total load decremented in 10%.	−0.90

The high computation time, t_{MEAN} (s), observed in Table 2, for the sequential MOGA, are principally due to the time simulation required for the time domain adjustment of the AVR in each generator, taking into account all operating conditions described in Table 1. For that reason, the MOGA was adapted for parallel computation. There are two metrics indicate the performance of the parallel algorithm compared to the sequential version of the same algorithm: The computational Speedup (S_P) and Percentage Efficiency (E%), such as shown in Table 2

S_P is the ratio of the serial runtime of the best sequential algorithm for solving a problem to the time taken by the parallel algorithm to solve the same problem on P processors:

$$S_P = \frac{T_S}{T_P} \tag{21}$$

The *Efficiency* is defined as the ratio of *speedup* to the number of processors. *Efficiency* measures the fraction of time for which a processor is usefully utilized:

$$E\% = \frac{S_P}{P} \times 100 = \frac{T_S}{P \cdot T_P} \times 100 \tag{22}$$

Fig. 8 shows the S_P curve of the Parallel MOGA when it is compared with the ideal parallelism behavior (linear curve), and it is observed a sub-linear behavior. The Eq. (22) describes the percentage *Efficiency*. In both equations, (21) and (22), T_S is the computation time of the sequential version of MOGA, and T_P is referred to the parallel runtime of Parallel MOGA on P available processors in the LAN.

Tables 3 and 4 show the numerical results for controller parameters, obtained by the best parallel algorithm of MOGA, associated to the higher Fitness (the parallel solution with four computers in the cluster, from Table 2). However, any set of parameters optimized associated to the solutions from parallel algorithms, in Table 2, is valid to be used.

Where ***#G*** and ***#B***, in columns on Tables 3 and 4, represent the bus where is connected the corresponding generator and the SVC device, respectively. Fig. 9 shows the open-loop and closed-loop eigenvalues for the PES operating without controllers and the operation with the adjusted controllers' parameters by the proposed coordinated tuning algorithm, respectively, considering the 4th operating condition.

In Fig. 9, poles marked with the symbol 'o' and '◆' correspond to the open-loop and closed-loop eigenvalues (poles), respectively.

Figs. 10 and 11 show the rotor angle response of the generators located in buses 33, 35 and 38 and the voltage response at buses 5, 6, 7, 10, 11 and 12, respectively, in the 4th operating scenario.

Figs. 12 and 13 show the rotor angle response of the generators located in buses 33, 34, 35, 36 and 38 and the voltage response at buses 4, 8, 16 and 20, respectively, in the 5th operating scenario. In this case, the total load was incremented suddenly in 10%.

In Figs. 10–13, the dashed lines correspond to the undamped time response of the rotor angle, and solid and thick lines are associated to the damped time response of the rotor angle and bus voltage of the neighboring substations by the transmission lines outages.

The overshoot in voltage response, in Figs. 10 and 11, in each generator with AVR, whose parameters were adjusted by the proposed coordinated tuning, is reduced, compared to the response curves of generators with AVR parameters fixed in standard values (K_A=200pu and T_A=0.05 s). The response curves, in Figs. 12 and 13, correspond to the load incremented keeping power factor.

6. Conclusions

This paper described a computational methodology for coordinated tuning of power controllers, such as AVR and PSS located into excitation system of each generator, and a group of SVC devices, belong to a multi-machine PES under study, considering, simultaneously, several critical operating conditions, in order to apply on stability studies and operation and expansion planning.

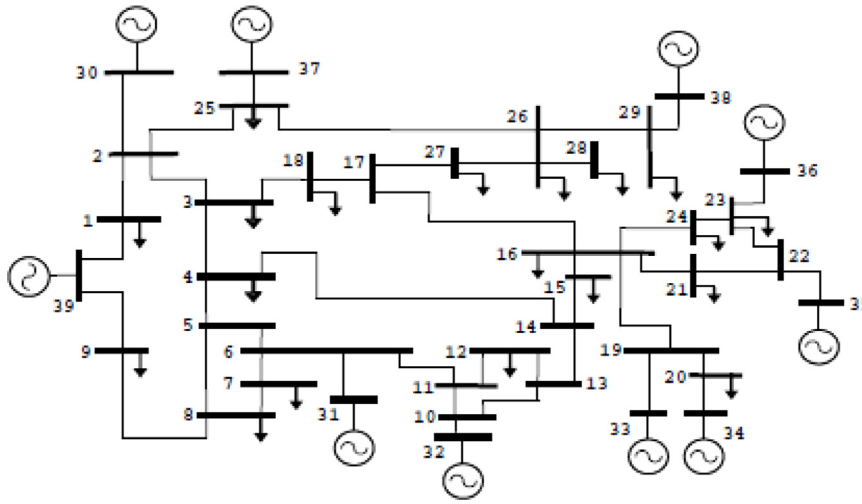

Fig. 7. New England electric system (39 buses).

Table 2
Results for sequential and parallel MOGA.

Sequential MOGA					
P	F_1 (Area)	F_2 (ξ%)	t_{MEAN} (s)		
1	1.2976	8.7978	138,873.2685		
Parallel MOGA					
P	F_1 (Area)	F_2 (ξ%)	t_{MEAN} (s)	S_P	E(%)
2	1.2915	9.4791	70,536.6342	1.9688	98.44
4	1.3539	9.6991	35,489.3171	3.9131	97.83
6	1.2910	9.6431	24,098.5447	5.7627	96.05
8	1.2937	9.5756	18,759.1586	7.4030	92.60

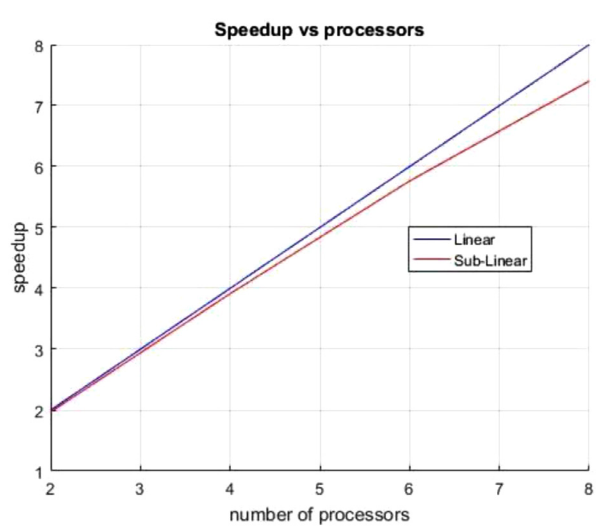

Fig. 8. Speedup curve of parallel MOGA.

Table 3
Parameters values for AVR and PSS.

#G	K_A	T_A	K_S	T_1	T_2
30	200.0	0.08	15	0.10	0.011
31	147.9	0.07	20	0.09	0.001
32	173.4	0.02	19	0.07	0.019
33	157.6	0.04	15	0.09	0.001
34	118.6	0.09	15	0.10	0.005
35	200.0	0.09	19	0.08	0.001
36	133.9	0.04	17	0.10	0.006
37	170.3	0.09	17	0.10	0.001
38	129.4	0.06	15	0.07	0.001

Table 4
Parameters values for SVC.

#B	K_C	T_C
6	100.0	0.04
7	258.1	0.50
20	100.0	0.49

The proposed coordinated tuning method was posted as a multi-objective optimization algorithm based on the MOGA, with two objectives to optimize: the AVR tuning in time domain, and the PSS and group of static compensators using the frequency domain technique. However, the sequential version of MOGA adapted for coordinated tuning spends large time and efforts to reach optimal solutions.

The PSS adjusted by the proposed algorithm quickly damped the electromechanical oscillations and the group of static compensators keep an optimum voltage profile in the critical operating conditions considered. In addition, the time-domain AVR tuning procedure combined to the frequency-domain PSS and SVC adjusting technique, using the Parallel MOGA, reduce the voltage overshoot and speed up the time response of the stator voltage of generators to close with the V_{REF} of its corresponding AVR.

The Parallel MOGA, adapted for coordinated tuning of power system controllers, reduces the computing time and increments virtually the size of the research space, due the several computers used in the LAN, obtaining optimal parameters, with better values than sequential version, improving the dynamic response, damping electromechanical oscillations quickly and enhance substantially the voltage profile of the PES, became as an interesting alternative tool for operation and expansion planning, and coordinated tuning of controllers.

Further work regarding to unblocking communication technique in Parallel MOGA, another multi-objetive optimization method such as Pareto GA approaches, tests with larger PES and applies in large-scale and real electric system, such as stability studies of the interconnected operation of Yacyreta and Itaipu hydroelectric plants, are planned for the continuity of this work.

Declaration of Competing Interest

The authors whose names are listed immediately below certify that they have NO affiliations with or involvement in any organization or

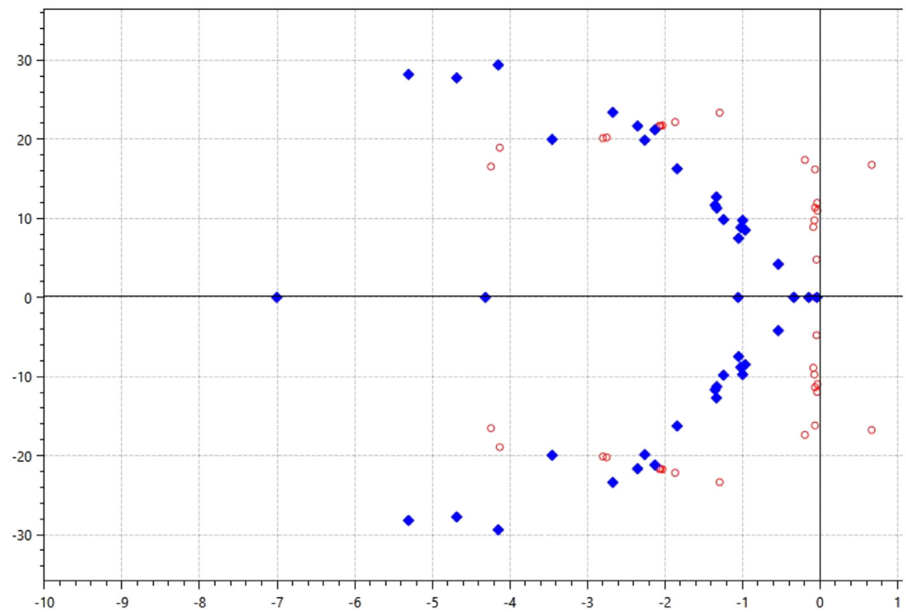

Fig. 9. Open-loop and closed-loop poles – 4th operating scenario.

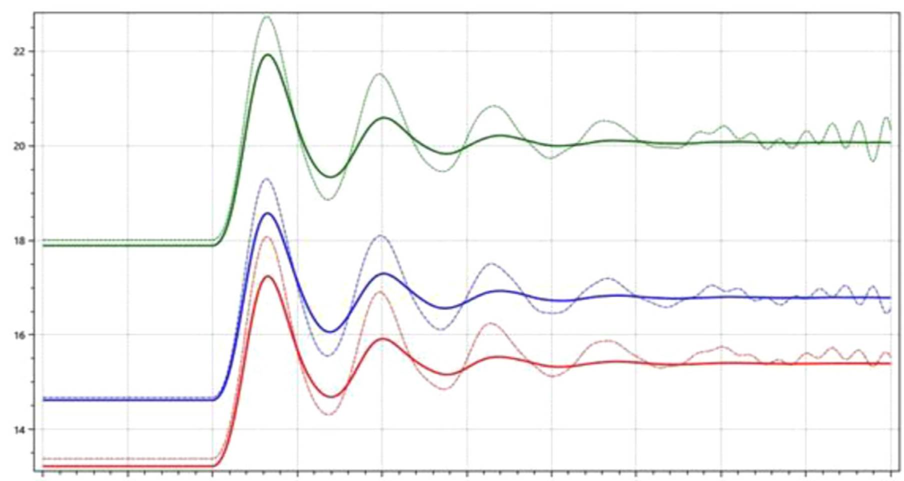

Fig. 10. Rotor angle response vs time - 4th Scenario (Table 1).

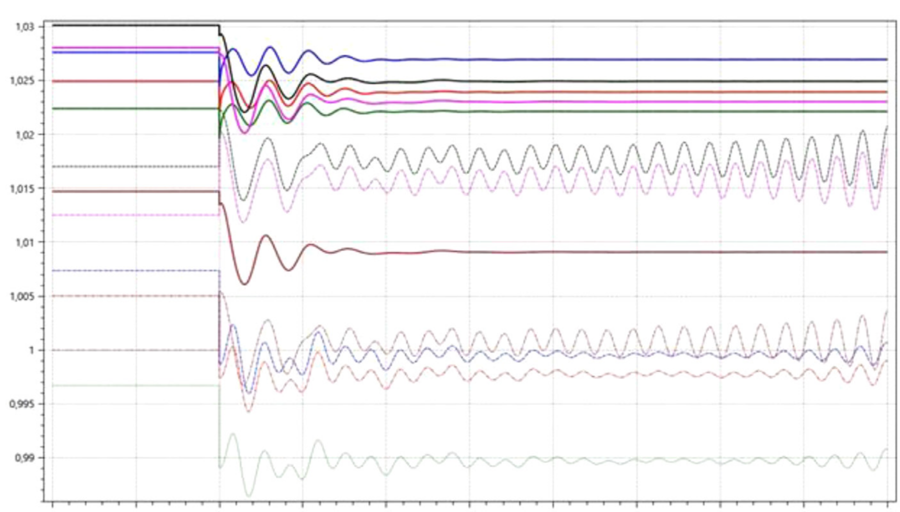

Fig. 11. Voltage response vs time - 4th Scenario (Table 1).

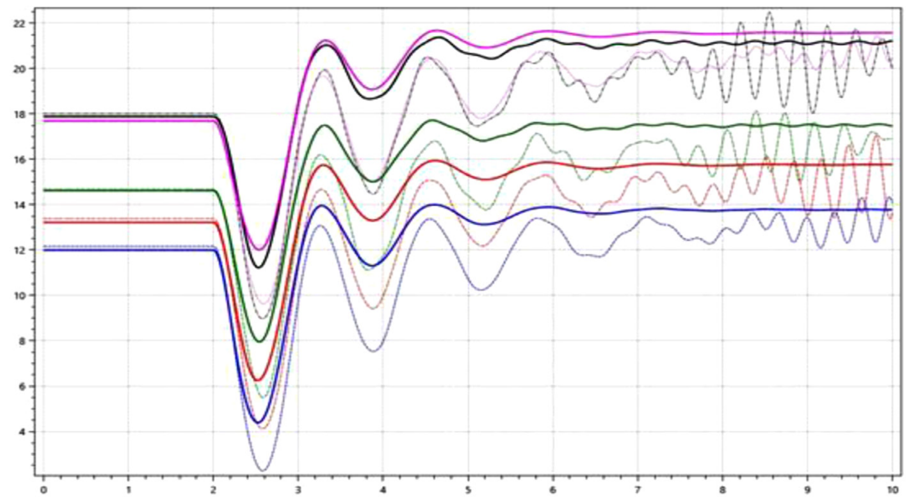

Fig. 12. Rotor angle response vs time - 5th Scenario (Table 1).

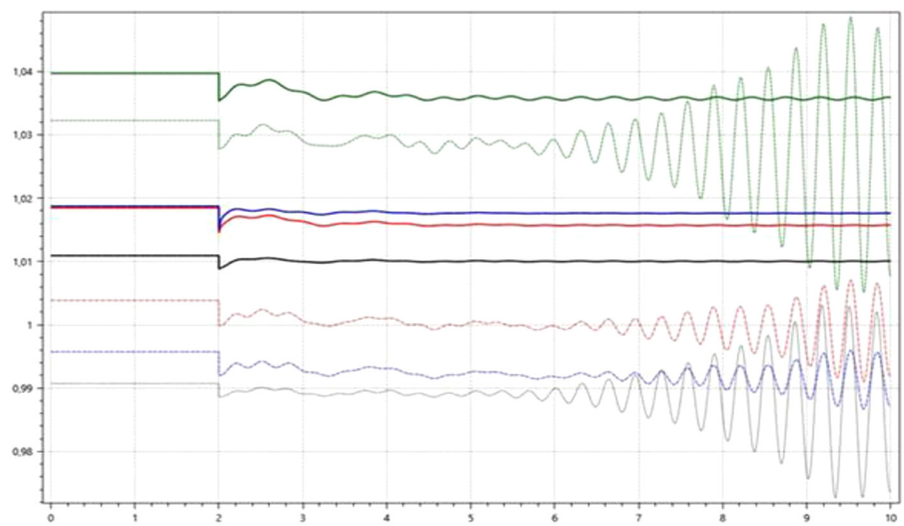

Fig. 13. Voltage response vs time - 5th Scenario (Table 1).

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.epsr.2020.106628.

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