Coordinated Tuning of Power System Controllers Using Metaheuristic Techniques

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Abstract—This paper presents a new methodology for the coordinated tuning of power system stabilizers, automatic voltage regulators, and static Var compensators, considering various operating and loading conditions. The proposed method is based on the maximization of the damping ratio, which is calculated from the closed-loop state matrix. The optimization process is performed using different metaheuristic techniques, including Genetic Algorithm, Particle Swarm Optimization, and Differential Evolution. In order to obtain the closed-loop state matrix (containing all controllers) for each candidate solution, a new procedure is proposed, which is based on simple modifications of the closed-loop state matrices of each operating condition. This procedure is simple, but very efficient from the computational point of view. The proposed tuning methodology is tested using the standard IEEE 14-bus test system, the New England system, and the New England/New York interconnected system. Finally, time-domain simulation results are presented, which demonstrate the effectiveness of the proposed approach.

Keywords—power system stabilizers; automatic voltage regulators; static Var compensators; electromechanical stability; voltage control; damping ratio; metaheuristic techniques

I. INTRODUCTION

The constant increase in electrical energy demand has led power systems to operate highly interconnected. This dense interconnection reduces the electrical distance between substations in a way that any disturbance; such as equipment failures, circuit faults, etc., can affect neighboring areas with similar intensity [1]. Moreover, with the progressive increase in demand, most systems operate near their load limits. Thereby, any sudden change in the topology of the system, load variations or short circuits may cause significant electromechanical oscillations, as well as deviations from normal voltage levels.

Electromechanical oscillations associated to active power and rotor angle deviations are usually damped through Power System Stabilizers (PSS), while the voltage of stators is controlled by Automatic Voltage Regulators (AVR). Both PSS and AVR are located within the excitation system of each synchronous generator. The AVR, therefore, maintains the voltage module of the stator within permitted values, while the PSS gives an additional signal to the AVR’s reference in order to damp electromechanical oscillations. In addition, the Static Var Compensator (SVC) is a Flexible AC Transmission System (FACTS) device, which can control the voltage profile of the system by injecting the necessary reactive power [1]. In order to perform correctly, however, all of the above mentioned devices (i.e., the PSS, AVR, and SVC) have a set of parameters that need to be adequately adjusted. For instance, the PSS usually requires its gain and time constants to be optimized. Similarly, the AVR and SVC’s gains and the SVC’s time constant also require a tuning process.

Traditionally, the PSS and AVR are adjusted separately from the SVC [2]-[3]. Most of these methods, however, use open-loop state matrixes to represent the power system with the AVR and, therefore, it is necessary to calculate both the PSS’ state matrix and the closed-loop state matrix of the system; a procedure that may require significant computational time. Also, while these methods can result in a high degree of electromechanical stability, they usually lead to large deviations of bus voltages, even if the power system remains stable after a disturbance event. This happens because the AVR aims to maintain constant only the terminal voltage of generators, but not the nodal voltages. One way to solve this problem is to adjust the parameters of all controllers simultaneously, or in a coordinated way. An example of coordinated tuning methodology can be found in [4].

More recently, metaheuristic techniques were also applied to the coordinated tuning of PSS’ parameters [5]-[6]. A methodology for the coordinated tuning of AVR and PSS using Genetic Algorithms (GA) was proposed in [7]. In addition, a control strategy for the coordinated design of PSS, AVR, and SVC can be found in [4]. This control strategy combined switching technique and negative feedback to achieve a robust controller against load/generation disturbances. However, this reference only considered the tuning of the PSS, AVR, and SVC’s gains.

This paper presents a new methodology for the coordinated tuning of PSS, AVR, and SVC, to reduce electromechanical oscillations and to control bus voltages of multi-machine power systems under various operating and loading conditions. The proposed method is based on the maximization of the damping ratio, which is calculated from the closed-loop state matrix using modal analysis [1], [8]. The optimization process is performed using different metaheuristic techniques, including GA [9], Particle Swarm Optimization (PSO) [10], and Differential Evolution (DE) [11]. The tuning parameters are the PSS and AVR’s gains, the time constants from the PSS’ lead-
lag blocks, as well as the gains and time constants from the SVC’s voltage regulators. The number of SVC and their respective locations within the power system are chosen through the analysis of the Q-V curve of each load bus, considering a pre-specified set of different operating conditions, which were chosen based on analyses of load flow results. The SVC steady-state parameters, i.e., the voltage reference and the reactive power limits, are adjusted previously to the coordinated tuning of dynamic parameters [12]. In order to obtain the closed-loop state matrix (containing all controllers) for each candidate solution, a new procedure is proposed which is based on simple modifications of the closed-loop state matrixes, corresponding to the set of pre-specified operating conditions (the same set used to obtain the number and locations of the SVC). This procedure is simple, but very efficient from the computational point of view.

In order to test the performance of the proposed approach, three power systems are used: the standard IEEE 14-bus test system [8], [13], the New England (39-bus 10-machine) system [14], and the New England/New York (68-bus 16-machine) interconnected system [15]. In each case, the optimal tuning parameters are obtained using GA, PSO, and DE, making it possible to compare their respective performances when applied to this particular problem. Finally, time-domain simulation results are presented, which demonstrate the effectiveness of the proposed coordinated tuning methodology.

II. MATHEMATICAL MODELS

A. Automatic Voltage Regulator Model

A first order model with a feedback block is used to represent the AVR. This model, which is illustrated in Fig. 1, is a variant derived from the IEEE ST1A model [2]. The gain $K_{A}$ is automatically adjusted by the proposed tuning procedure. The time constant $T_{A}$ is considered to be known and its value is set to 0.05 s. The gain $K_{F}$ is chosen within the interval 0.02–0.06 pu, and the time constant $T_{F}$ is normally considered fixed and near to 1 s [2].

B. Power System Stabilizer Model

The PSS model used in this work is shown in Fig. 2. It has one gain, named $K_{S}$, and two identical lead-lag blocks. The input signal of the PSS is the angular speed of the generator’s rotor ($\omega$). The time constants $T_{1}$ and $T_{2}$ of the lead-lag blocks are given by (1) and (2) [2], respectively, where $\alpha = T_{1} / T_{2}$.

$$T_{1} = \frac{\alpha}{\omega}$$  
(1)

$$T_{2} = \frac{1}{(\omega - \sqrt{\alpha})}$$  
(2)

The time constant $T_{F}$ (from the washout block) is usually chosen within 1 to 20 s [1]. In this paper, $T_{F}$ is set to 3 s. The PSS’ parameters that will be included in the tuning process are $K_{S}$, $\alpha$, and $\omega$. Also, notice that the output signal $V_{S}$ corresponds to one of the AVR’s input signals, as illustrated in Fig. 1.

C. Static Var Compensator Model

Fig. 3 shows the SVC dynamic model that will be used during the coordinated tuning procedure. Basically, it is a first order lag block, composed by the gain $K_{C}$ and the time constant $T_{C}$. These parameters will be automatically adjusted by the proposed approach. The input signal $V_{C}$ represents the substation voltage, which is monitored and compared to the voltage reference $V_{RSVC}$. Similarly, the output signal $B_{C}$ represents the compensator’s variable susceptance, which is compared to the minimum ($B_{CMIN}$) and maximum ($B_{CMAX}$) susceptance values. $B_{CMIN}$, $B_{CMAX}$ and $V_{RSVC}$ represent steady-state parameters that are adjusted previously to the proposed tuning approach (which considers only dynamic parameters). The procedure used to obtain the values of $B_{CMIN}$, $B_{CMAX}$, and $V_{RSVC}$ is detailed described in [12].

D. Power System Model

The power system mathematical model used for electromechanical transient studies is represented by a set of nonlinear differential and algebraic equations [1]. For small signal stability studies, these equations are usually linearized around a specific operating condition, as shown in (3).

$$\begin{bmatrix}
\frac{dx}{dt} \\
\theta
\end{bmatrix} =
\begin{bmatrix}
J_{1} & J_{2} & J_{3} & J_{4}
\end{bmatrix}
\begin{bmatrix}
\Delta x \\
\Delta V
\end{bmatrix}$$  
(3)

The Jacobian matrix in (3) is then used to obtain the closed-loop state matrix of the system, by eliminating the algebraic variables. This procedure is represented by (4).

$$\Delta x = (J_{1} - J_{2} \cdot J_{4} \cdot J_{3}) \cdot \Delta x = A \cdot \Delta x$$  
(4)

The matrix $A$ contains the coefficients of the differential equations corresponding to the PSS, AVR, and SVC models. These coefficients will be modified by the proposed coordinated tuning methodology in order to maximize the damping ratio of the system, considering a set of pre-specified operating conditions.
III. PROPOSED COORDINATED TUNING METHODOLOGY

The coordinated tuning problem consists in finding the best possible parameter values for each PSS, AVR, and SVC, simultaneously, while meeting a set of performance criteria, as described in [1]. A simplified flowchart of the proposed approach is shown in Fig. 4, where GA [9], PSO [10], and DE [11] are used to maximize the damping ratio of the system. The main blocks are detailed discussed in the following sections.

A. Initial Solutions

For every metaheuristic technique, \( N - 1 \) initial solutions are randomly generated, such that: \( 1 \leq K_p \leq 20 \) pu; \( 0.1 \leq \alpha \leq 10 \); \( 0.4 \pi \leq \omega_o \leq 16 \pi \) rad/s; \( 50 \leq K_d \leq 300 \) pu; \( 5 \leq K_c \leq 200 \) pu; and \( 0.01 \leq T_c \leq 1 \) s. The upper and lower limits for these parameters were set considering both equipment restrictions and user experience. The remaining \( N \)-th solution is calculated by applying the Nyquist criterion for PSS tuning [2], where the AVR’s gain is fixed in 100 pu. Then, considering the whole system, the SVC’s dynamic parameters take standard values (e.g., \( K_c = 50 \) pu and \( T_c = 0.05 \) s), and the \( N \)-th solution is verified in order to obtain a stable system for every pre-established operating condition.

B. Solution Vector

Each feasible solution is represented by a vector containing the PSS, AVR, and SVC’s dynamic parameters, as shown in (5), (6), and (7), respectively.

\[
X_{PSS} = [K_{S1} \ \alpha_1 \ \omega_1 \ \omega_2 \ \ldots \ \omega_q \ \omega_p]
\]
(5)

\[
X_{AVR} = [K_{A1} \ \omega_2 \ \ldots \ \omega_q]
\]
(6)

\[
X_{SVC} = [K_{C1} \ T_{C1} \ K_{C2} \ T_{C2} \ \ldots \ K_{CB} \ T_{CB}]
\]
(7)

The vector \( X_{PSS} \) contains the parameters \( K_{S} \), \( \alpha \), and \( \omega \) of every PSS, where \( q \) indicates the number of stabilizers to be adjusted. The vector \( X_{AVR} \) contains the AVR’s gains \( K_{A} \), where \( q \) is the number of regulators. Finally, \( X_{SVC} \) contains the SVC’s dynamic parameters \( K_{C} \) and \( T_{C} \), where \( b \) is the number of compensators installed in the system. Together, these vectors represent the solution vector \( X = [X_{PSS} \ X_{AVR} \ X_{SVC}] \), which will be handled by every metaheuristic technique.

C. Modifications of the Closed-loop State Matrixes

In order to obtain the overall system closed-loop matrices, most methodologies require several operations [1]-[2], [17]. These operations, however, can be very computational demanding, especially when dealing with large power system. In order to improve the computational efficiency, this paper proposes a new procedure to calculate the closed-loop state matrices for each candidate solution, which can avoid many of the above mentioned operations. This procedure can be summarized as follows: For a given operating condition, consider \( A \) as the closed-loop state matrix (containing all controllers) obtained for the \( N \)-th initial solution (which used the Nyquist criterion for the PSS tuning); and \( A' \) as the desired closed-loop state matrix, corresponding to the \( j \)-th candidate solution. Also, consider that \( A_{i,j} \), represents an element of \( A \).

\[
A_{i,j} = T_{ij} - T_{ii} / T_o^2
\]
(8)

\[
A'_{i,j} = A_{i,j} + K_{D} / K_{D0}
\]
(13)

\[
A'_{i,j} = A_{i,j} + K_{F} / T_{F}^2
\]
(14)

\[
A'_{i,j} = A_{i,j} + K_{D} / T_{D}
\]
(15)

\[
A'_{i,j} = A_{i,j} + K_{F} / T_{F}
\]
(16)

\[
A'_{i,j} = A_{i,j} + K_{D} / T_{D}
\]
(17)

Adjust the SVC’s steady state parameters, as described in [12].

Calculate the initial solutions, as described in Section III.A. Also, set the generation counter \( k = 0 \).

Obtain the closed-loop state matrices corresponding to each operating condition, containing all controllers, and considering the initial solution obtained by the Nyquist criterion.

Modify the closed-loop state matrices based on the calculated initial solutions, as described in Section III.C. Also, calculate the initial fitness vector \( Z_0 \), as shown in Section III.D.

Generate new solutions (i.e., the next generation), based on the GA, PSO and DE’s operators.

Modify the closed-loop state matrices based on the current generation solutions, as described in Section III.C. Also, calculate the fitness vector \( Z_n \), as shown in Section III.D.

If \( Max[Z_k] \) represents the best damping ratio for the system obtained so far, save its value as well as the solution vector \( x_k \), corresponding to \( Max[Z_k] \).

Fig. 4. Flowchart of the proposed coordinated tuning methodology.

whose position is indicated by the row \( x \) and the column \( y \). Thus, in order to obtain \( \hat{A} \) for each candidate solution, set \( A' := \hat{A} \), and then modify \( \hat{A} \) according to (8)-(19):

- **PSS:**
  
  \[
  A'_{i,j} = A_{i,j} + \frac{T_{ij} - T_{ii}}{T_o^2}
  \]
  (8)

  \[
  A'_{i,j} = A_{i,j} + \frac{K_{D}}{K_{D0}}
  \]
  (13)

- **AVR:**
  
  \[
  A'_{i,j} = A_{i,j} + \frac{K_{F}}{T_{F}^2}
  \]
  (14)

  \[
  A'_{i,j} = A_{i,j} + \frac{K_{D}}{T_{D}}
  \]
  (15)

- **SVC:**
  
  \[
  A'_{i,j} = A_{i,j} + \frac{K_{F}}{T_{F}}
  \]
  (16)

  \[
  A'_{i,j} = A_{i,j} + \frac{K_{D}}{T_{D}}
  \]
  (17)

\( k := k + 1 \)

\( k < k_{MAX} \)

Obtain the PSS, AVR, and SVC’s parameters.

While \( k < k_{MAX} \)

Knowingly
• SVC:

\[ A_{ij}^j = \frac{K_{C}}{K_{C0}} \frac{T_{CO}}{T_C} A_{ij}^{j-1} \] (18)

\[ A_{ij}^j = \left( A_{ij} - x_j \right)^j + \frac{1}{T_{CO}} \left( \frac{K_{C}}{K_{C0}} \frac{T_{CO}}{T_C} - \frac{1}{T_C} \right) \] (19)

where \( K_{CO} \), \( K_{C0} \), and \( T_{CO} \) are respectively the AVR gain, the SVC gain, and the SVC time constant, corresponding to the \( N \)-th initial solution, which were used to calculate the closed-loop state matrix \( A ; s_{ij} \) indicates the row and/or column of the field voltage \( E_{FD} \) within the matrix \( A \) (see, Fig. 1); \( x_j \) indicates the positions of the respective variables inside \( A \), such that \( l \in \{ \alpha, 1, 2, 3 \} \) (see, Fig. 2); \( x_k \) indicates the row and column of the reactive susceptance \( B_{C} \) of the SVC within \( A \) (see, Fig. 3). Also, in (13) and (18), the colon mark “:” means that the corresponding expression is performed in all columns of the indicated row. The remaining values \( K_{s}, T_{s}, T_{a}, K_{A}, K_{C}, T_{A}, K_{C}, T_{C} \) were defined in Section II.

The same procedure described above is repeated for each pre-specified operating condition. As previously mentioned, this procedure can be very useful to improve the computational performance of the proposed coordinated tuning methodology, since many matrix operations are avoided. This is especially true when dealing with large power systems containing many controllers to be adjusted.

D. Objective Function

Consider \( \zeta \) as the damping ratio calculated from the \( i \)-th eigenvalue, such that \( i \in \{ 1, 2, \ldots, m \times n \} \); where \( m \) is the closed-loop matrix order and \( n \) is the number of pre-specified operating conditions. The eigenvalues are calculated using the QR factorization approach. The fitness function for the \( j \)-th candidate solution is evaluated as the minimum value of \( \zeta = \left[ \zeta_1, \zeta_2, \ldots, \zeta_{m \times n} \right] \), which is represented by \( \min \{ \zeta \} \). The fitness vector for a given generation is then defined as \( \mathbf{z}_g = \left[ \min \{ \zeta_1 \}, \min \{ \zeta_2 \}, \ldots, \min \{ \zeta_{m \times n} \} \right] \); where \( N \) is the number of candidate solutions and \( g \) is the generation counter. The objective function of the proposed coordinated tuning method is then given by

\[ \text{Max} \{ \mathbf{z}_g \} \] (20)

GA, PSO, and DE are then used to find the best combination of parameters for all controllers, such that \( \mathbf{z} \) is maximized. In this work, the objective function in (20) is evaluated by every metaheuristic technique using \( N = 50 \) candidate solutions, for a maximum number of generations \( k_{\text{MAX}} = 400 \). These values are set based on authors’ experience.

E. Metaheuristic Techniques’ Parameters and Operators

GA is a well-known search heuristic and optimization tool that is designed to mimic the process of natural selection. In this work, the GA algorithm uses a roulette-wheel Selection operator [9], on which individuals with better fitness values are more likely to be selected. Crossover and Mutation operators are then applied to the selected individuals in order to obtain a new population of candidate solutions. A uniform arithmetic Crossover is carried-out using a constant probability \( p_{\text{cras}} \).

Similarly, Mutation operations are performed considering a fixed probability \( p_{\text{mut}} \).

PSO [10] is a powerful metaheuristic technique which is inspired on the synchronized movement of flocks of birds without collision [16]. In this paper, the particles are manipulated according to (21) and (22)

\[ \mathbf{v}_{j,k+1} = \mathbf{w} \cdot \mathbf{v}_{j,k} + c_1 \cdot r_{j,k} \cdot (\mathbf{p}_{j,k} - \mathbf{x}_{j,k}) + c_2 \cdot r_{j,k} \cdot (\mathbf{p}_{g,k} - \mathbf{x}_{j,k}) \] (21)

\[ \mathbf{x}_{j,k+1} = \mathbf{x}_{j,k} + \mathbf{v}_{j,k+1} \] (22)

where \( k \) is the iteration counter; \( \mathbf{x}_j \) and \( \mathbf{v}_j \) are the position and velocity of the particle \( j \), respectively; \( g \) is the index which indicates the best particle of the swarm; \( r_1 \) and \( r_2 \) are uniformly distributed random numbers within the interval [0, 1]; and \( \mathbf{p}_j \) is the best position obtained so far for \( j \)-th particle. Finally, \( c_1 \) and \( c_2 \) are constant positive numbers, which represent the cognitive and social parameters, respectively; and \( \mathbf{w} \) is the inertia weight.

DE [11], [16] is a GA like numerical algorithm, but differs from it in the way Selection, Crossover, and Mutation are performed. In this work, DE performs Mutation using

\[ \mathbf{u}_{j,k+1} = \mathbf{x}_{j,k} + F \cdot (\mathbf{x}_{r1,k} - \mathbf{x}_{r2,k} + \mathbf{x}_{r3,k} - \mathbf{x}_{r4,k}) \] (23)

where \( \mathbf{x}_j \) represents the \( j \)-th candidate solution corresponding to the \( k \)-th generation; \( \mathbf{u}_{j,k+1} \) is the mutated \( j \)-th solution for the next generation; \( F \) is a constant within the interval [0, 2]; and \( r_1, r_2, r_3, r_4, \) and \( r_5 \) are random integer numbers within the interval [1, \( N \)]. Next, \( i \)-th crossover is applied on each candidate solution as shown in (24)

\[ \mathbf{v}_{j,k+1} = \mathbf{x}_{j,k} \cdot (1 - P) + \mathbf{u}_{j,k+1} \cdot P \] (24)

where \( P \) is the crossover constant and \( \mathbf{v}_{j,k+1} \) is the trial vector of the \( j \)-th candidate solution for the next generation. The parents for the next generation are then selected as

\[ \mathbf{x}_{j,k+1} = \left\{ \begin{array}{ll}
\mathbf{v}_{j,k+1} & \text{if } f(\mathbf{v}_{j,k+1}) > f(\mathbf{x}_{j,k+1}) \\
\mathbf{x}_{j,k+1} & \text{if } f(\mathbf{x}_{j,k+1}) > f(\mathbf{v}_{j,k+1})
\end{array} \right. \] (25)

where \( f(\mathbf{v}_{j,k+1}) \) is the fitness value of the \( j \)-th candidate solution on which Mutation and Crossover were applied; and \( f(\mathbf{x}_{j,k+1}) \) is the fitness value of the \( j \)-th solution in the original population.

An additional Mutation operator was implemented for the DE algorithm, which consists in altering the value of one (randomly chosen) element within each \( \mathbf{x}_{j,k} \) when the value of \( \text{Max} \{ \mathbf{z}_g \} \) remains the same for \( k_{\text{MAX}} \) generations.

IV. APPLICATION RESULTS

The proposed methodology will be tested using three different power systems: the IEEE 14-bus [8], [13], the New England [14], and the New England/New York [15]. In each case, the optimal PSS, AVR, and SVC parameters were obtained using GA, PSO, and DE. All computations were performed in a MATLAB platform using an Intel Core i5 2.27 GHz processor. Finally, the systems’ dynamic performance, before and after the tuning of their respective controllers, is simulated using ANATEM; an electromechanical transient analysis software widely used in the Brazilian electric sector.
TABLE I. PSS AND AVR’S PARAMETERS OBTAINED FOR THE IEEE 14-BUS SYSTEM

<table>
<thead>
<tr>
<th>Bus</th>
<th>GA</th>
<th>PSO</th>
<th>DE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$k_\alpha$</td>
<td>$k_\omega$</td>
<td>$k_\alpha$</td>
</tr>
<tr>
<td>1</td>
<td>196.44</td>
<td>16.18</td>
<td>10.00</td>
</tr>
<tr>
<td>2</td>
<td>199.49</td>
<td>20.00</td>
<td>6.653</td>
</tr>
<tr>
<td>3</td>
<td>300.00</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>6</td>
<td>299.90</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>8</td>
<td>187.07</td>
<td>---</td>
<td>---</td>
</tr>
</tbody>
</table>

TABLE II. SVC’S PARAMETERS FOR THE IEEE 14-BUS SYSTEM

<table>
<thead>
<tr>
<th>Bus</th>
<th>GA</th>
<th>PSO</th>
<th>DE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$k_c$</td>
<td>$T_c$</td>
<td>$k_c$</td>
</tr>
<tr>
<td>13</td>
<td>83.852</td>
<td>0.8064</td>
<td>89.092</td>
</tr>
<tr>
<td>14</td>
<td>64.268</td>
<td>0.5263</td>
<td>194.20</td>
</tr>
</tbody>
</table>

TABLE III. OPERATING CONDITIONS FOR THE IEEE 14-BUS SYSTEM

<table>
<thead>
<tr>
<th>#</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Base case</td>
</tr>
<tr>
<td>2</td>
<td>TL 6–13, out of service.</td>
</tr>
<tr>
<td>3</td>
<td>TL 6–13 and TL 9–10, out of service.</td>
</tr>
<tr>
<td>4</td>
<td>TL 6–13 and TL 9–14, out of service.</td>
</tr>
<tr>
<td>5</td>
<td>Total load incremented in 10%.</td>
</tr>
<tr>
<td>6</td>
<td>Total load decreased in 10%.</td>
</tr>
</tbody>
</table>

TABLE IV. IEEE 14-BUS SYSTEM METAHEURISTIC PERFORMANCES

<table>
<thead>
<tr>
<th>Metaheuristic Technique</th>
<th>$\text{Max}(\alpha)$ [%]</th>
<th>Time [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>GA</td>
<td>14.016</td>
<td>136.84</td>
</tr>
<tr>
<td>PSO</td>
<td>14.029</td>
<td>135.88</td>
</tr>
<tr>
<td>DE</td>
<td>14.029</td>
<td>133.89</td>
</tr>
</tbody>
</table>

A. IEEE 14-bus System

The standard IEEE 14-bus system [8], [13] has two generators, three synchronous condensers, and 20 circuits. There are two PSS, five AVR, and two SVC, totaling 15 parameters that need to be adjusted by the proposed approach (which is the size of the solution vector). The optimal tuning parameters for the PSS and AVR are shown in Table I. Similarly, the obtained parameters for the SVC are presented in Table II. For this case, six operating conditions were considered during the tuning process (including circuit outages and load variations), as defined in Table III. The controllers were adjusted by GA, PSO, and DE considering the following set of parameters: $p_{\text{cross}} = p_{\text{mut}} = 0.2$; $c_1 = c_2 = 2$; $w = 0.8$; $F = 0.3$; $P_c = 0.2$; and $k_{\text{fit}} = 20$.

From the results presented in Table IV it is possible to conclude that all metaheuristic techniques had a similar performance for the IEEE 14-bus system, both in terms of CPU time and objective function value. In this case, all methods reached a $\text{Max}(\alpha)$ around 14% and spent approximately 135 s to converge. Dynamic simulations were carried-out to test the performance of the obtained controller parameters. Fig. 5, for example, shows the electromechanical oscillations of the generator at Bus 1 resulting from a short circuit in transmission line (TL) 2-5, which lasted 100 milliseconds. It is possible to observe that the system remains stable after this event, even without the actions of the PSS (the AVR is maintained active). However, the PSS and AVR tuned with the metaheuristic techniques significantly damped the rotor angle oscillations.

Fig. 5 shows the voltage profile in Bus 14 before and after the outages of TL 6-13 and TL 9-14. Without the action of the SVC, the voltage levels are near 1.04 pu and 0.90 pu before and after the outage event, respectively. With the voltage control provided by the SVC (whose parameter were tuned by the metaheuristic techniques), the voltages before and after the event remained basically the same, and near 1.01 pu.

It is important to stress that the reported computational performance (CPU time near 135 s) was obtained by using the matrix modification procedure discussed in Section III.C. In order to verify the efficiency of this approach, an additional test was performed with the IEEE 14-bus system, where the parameters of the controllers were adjusted using a standard procedure to obtain the closed-loop state matrices [17]. The CPU time in this case was around 869 s. Thus, by using the matrix modification procedure presented in Section III.C, the tuning process was approximately 6.44 times faster (speed-up), and exactly the same parameters were obtained for all controllers. It is expected that this speed-up would increase with the size of the system and the number of controllers, since the number of closed-loop matrices that need to be evaluated are given by: $N \times N_{OC} \times K_{MAX}$, where $N_{OC}$ is the number of pre-specified operating conditions.
B. New England System

The New England system [14] has 39 buses, 10 generating units, and 46 circuits. There are nine PSS, nine AVR, and three SVC, which results in 42 parameters that need to be adjusted simultaneously by the proposed approach. The optimal parameters obtained for the PSS and AVR are shown in Table V, and the SVC parameters are presented in Table VI. For this system, the coordinated tuning process is performed considering six pre-specified operating conditions, which are enumerated in Table VII. The metaheuristic parameters used for this case were: $p_{cross} = p_{mut} = 0.2; c_1 = c_2 = 2; w = 0.8; F = 0.2; P_c = 0.7;$ and $k_{fit} = 15.$

The respective performances of the metaheuristic techniques are shown in Table VIII. For the New England system, all techniques presented similar CPU times (around 34 minutes). In terms of objective function value, PSO obtained the best performance with 18.2%. GA and DE converged with 16.2% and 14.4%, respectively. Fig. 7 shows the electromechanical oscillations of the generator at Bus 32, after a short circuit event in TL 6-11 (which lasted 100 milliseconds). The PSS and AVR adjusted with all metaheuristic techniques presented similar dynamic performances, and were able to maintain the system stability. Without the action of the PSS, however, the system loses its stability after this short circuit event. Fig. 8 shows the voltage oscillations at Bus 3, after the outages of TL 3-18 and 25-26. Once more, the SVC parameters adjusted by all metaheuristics performed similarly, and were able to maintain the voltage profile at Bus 3 close to its pre-fault value. Without the action control of the SVC, the bus voltage also stabilizes near its pre-fault value, but the oscillations are significantly larger and need more time to be damped.

### Table V. PSS and AVR’s Parameters Obtained for the New England System

<table>
<thead>
<tr>
<th>Bus</th>
<th>GA</th>
<th>PSO</th>
<th>DE</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_s$</td>
<td>$k_s$</td>
<td>$\omega$</td>
<td>$k_s$</td>
</tr>
<tr>
<td>30</td>
<td>128.44</td>
<td>7.089</td>
<td>8.2217</td>
</tr>
<tr>
<td>32</td>
<td>164.73</td>
<td>14.40</td>
<td>8.398</td>
</tr>
<tr>
<td>33</td>
<td>246.29</td>
<td>9.368</td>
<td>8.948</td>
</tr>
<tr>
<td>34</td>
<td>202.01</td>
<td>12.62</td>
<td>6.167</td>
</tr>
<tr>
<td>35</td>
<td>222.54</td>
<td>8.872</td>
<td>3.852</td>
</tr>
<tr>
<td>36</td>
<td>127.73</td>
<td>17.76</td>
<td>7.395</td>
</tr>
<tr>
<td>38</td>
<td>163.34</td>
<td>18.72</td>
<td>6.627</td>
</tr>
</tbody>
</table>

### Table VI. SVC’s Parameters for the New England System

<table>
<thead>
<tr>
<th>Bus</th>
<th>GA</th>
<th>PSO</th>
<th>DE</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_C$</td>
<td>$\tau_C$</td>
<td>$K_C$</td>
<td>$\tau_C$</td>
</tr>
<tr>
<td>6</td>
<td>88.505</td>
<td>0.2978</td>
<td>160.69</td>
</tr>
<tr>
<td>7</td>
<td>128.82</td>
<td>0.2795</td>
<td>150.39</td>
</tr>
<tr>
<td>20</td>
<td>143.63</td>
<td>0.1487</td>
<td>142.63</td>
</tr>
</tbody>
</table>

### Table VII. New England System Operating Conditions

<table>
<thead>
<tr>
<th>#</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Base case.</td>
</tr>
<tr>
<td>2</td>
<td>TL 4–14 and TL 16–17, out of service.</td>
</tr>
<tr>
<td>3</td>
<td>TL 3–18 and TL 25–26, out of service.</td>
</tr>
<tr>
<td>4</td>
<td>TL 6–11, out of service.</td>
</tr>
<tr>
<td>5</td>
<td>Total load incremented in 10%.</td>
</tr>
<tr>
<td>6</td>
<td>Total load decreased in 10%.</td>
</tr>
</tbody>
</table>

### Table VIII. New England System Metaheuristic Performances

<table>
<thead>
<tr>
<th>Metaheuristic Technique</th>
<th>$\text{Max} { Z } %$</th>
<th>Time [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>GA</td>
<td>16.201</td>
<td>2086.20</td>
</tr>
<tr>
<td>PSO</td>
<td>18.234</td>
<td>2055.19</td>
</tr>
<tr>
<td>DE</td>
<td>16.406</td>
<td>2079.34</td>
</tr>
</tbody>
</table>

---

B. New England System

The New England system [14] has 39 buses, 10 generating units, and 46 circuits. There are nine PSS, nine AVR, and three SVC, which results in 42 parameters that need to be adjusted simultaneously by the proposed approach. The optimal parameters obtained for the PSS and AVR are shown in Table V, and the SVC parameters are presented in Table VI. For this system, the coordinated tuning process is performed considering six pre-specified operating conditions, which are enumerated in Table VII. The metaheuristic parameters used for this case were: $p_{cross} = p_{mut} = 0.2; c_1 = c_2 = 2; w = 0.8; F = 0.2; P_c = 0.7; \text{ and } k_{fit} = 15.$

The respective performances of the metaheuristic techniques are shown in Table VIII. For the New England system, all techniques presented similar CPU times (around 34 minutes). In terms of objective function value, PSO obtained the best performance with 18.2%. GA and DE converged with 16.2% and 14.4%, respectively. Fig. 7 shows the electromechanical oscillations of the generator at Bus 32, after a short circuit event in TL 6-11 (which lasted 100 milliseconds). The PSS and AVR adjusted with all metaheuristic techniques presented similar dynamic performances, and were able to maintain the system stability. Without the action of the PSS, however, the system loses its stability after this short circuit event. Fig. 8 shows the voltage oscillations at Bus 3, after the outages of TL 3-18 and 25-26. Once more, the SVC parameters adjusted by all metaheuristics performed similarly, and were able to maintain the voltage profile at Bus 3 close to its pre-fault value. Without the action control of the SVC, the bus voltage also stabilizes near its pre-fault value, but the oscillations are significantly larger and need more time to be damped.

C. New England/New York Interconnected System

The New England/New York interconnected system [15] has 68 buses, 16 generating units, and 86 circuits. There are 16 PSS, 16 AVR, and six SVC, which totalizes 76 parameters that need to be adjusted by the proposed approach. Table IX shows the PSS and AVR parameters obtained with the metaheuristic techniques. Similarly, the obtained SVC parameters are shown.
in Table X. The operating conditions considered for this system are shown in Table XI. The proposed tuning approach considers the following set of parameters: $p_{cross} = 0.3$; $p_{mut} = 0.2$; $c_1 = c_2 = 2$; $w = 0.8$; $F = 0.1$; $P_c = 0.8$; and $k_{fit} = 5$.

The $\text{Max}[Z]$ values and CPU times for this system are presented in Table XII. PSO obtained the best objective function value with 23.8%, followed by DE and GA with 20.0% and 14.8%, respectively. In terms of CPU time, PSO, GA, and DE spent respectively 2.64 h, 2.78 h, and 2.83 h.

Fig. 9 shows the electromechanical oscillations of the generator at Bus 55, after a short circuit event in TL 6-11 (which also lasted 100 milliseconds). It is possible to observe that the PSS and AVR tuned with DE, GA, and PSO successfully maintained the system stability after the disturbance event. Conversely, without the action of the PSS, the system presents oscillatory instability after the short circuit. Fig. 10 shows the voltage profile of Bus 46 considering the outages of TL 33-34 and 38-46. The SVC parameters tuned with all metaheuristic techniques presented similar dynamic performances. The voltage levels before and after the contingency event were near 1.05 pu and 1.02 pu, respectively. Without the SVC, the bus voltages were approximately 1.03 pu and 0.94 pu, before and after the circuits outage.
Finally, Fig. 11 illustrates the convergence process of the metaheuristic techniques for the New England/New York interconnected system, considering $k_{\text{MAX}} = 400$ iterations. Clearly, PSO performed better, reaching a $\text{Max}\{Z\} = 20\%$ in approximately 13 iterations. GA improved its $\text{Max}\{Z\}$ value rather quickly during the first 50 iterations, but was not able to find a significantly better solution after $k = 69$ (approx. 14.5%). DE improved its objective function value more slowly, but with an almost constant rate, surpassing GA in $k = 220$ and achieving a $\text{Max}\{Z\} = 20\%$ in approximately 397 generations. If a $\text{Max}\{Z\} = 15\%$ (which is already a good damping ratio value) was used as an additional convergence criterion, the CPU times for PSO, DE and GA would be 1.18 min., 1.52 h, 2.78 h, respectively.

V. CONCLUSIONS

This paper presented a new methodology for the coordinated tuning of PSS, AVR, and SVC’s parameters, to reduce electromechanical oscillations and to control bus voltages of multi-machine power systems, considering different operating and loading conditions. The proposed method was based on the maximization of the damping ratio, which is calculated from the system closed-loop state matrix using modal analysis. The optimization process was performed using different metaheuristic techniques (GA, PSO, and DE), making it possible to compare their performances when applied to this particular problem.

The closed-loop state matrixes (containing all controllers) for each candidate solution and operating condition were obtained using a simple and efficient procedure, which is based on direct modifications of the initial closed-loop state matrixes. By avoiding the constant need to eliminate algebraic variables from the Jacobian matrixes (this elimination is performed only once per operating condition during the tuning procedure), the method’s performance becomes independent of the network size, depending only on the number of state variables (which, in the case of this paper, are 5 per generator, 4 per PSS, 2 per AVR, and 2 per SVC).

The proposed method was tested using the standard IEEE 14-bus system, the New England system, and the New England/New York interconnected system. For the IEEE 14-bus, which is the smallest power system used in this paper, GA, PSO, and DE showed similar performances. Conversely, for the two remaining systems, PSO showed the best computational performance, both in terms of CPU time and objective function value. Nevertheless, GA and DE also presented good results and obtained parameters that helped to improve the system stability. Nonlinear time-domain simulations were also presented and discussed. Finally, the proposed coordinated tuning methodology can be easily adapted to adjust other control devices, such as HVDC links and TSCS.

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REFERENCES