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Optimal siting, sizing, and parameter tuning of STATCOM and SSSC using MPSO and remote coordination of the FACTS for oscillation damping of power systems

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Abstract: In electromechanical oscillation damping within power system, power system stabilizers (PSSs) are often deployed. However, a PSS is less effective in damping interarea oscillation and is limited by changes in network configuration due to weak tie-lines and load variations. Consequently, this paper presents a wide-area coordination approach that damps interarea oscillations using FACTS devices and phasor measurement units. We selected a static synchronous compensator (STATCOM) and static series synchronous compensator (SSSC) for realistic power system interarea oscillation damping. The performance of the coordinated FACTS installed in a power system depends on their suitable locations, sizes, tuned parameters, and remote input signal selection. Hence, we formulated a multiobjective problem to provide the STATCOM and SSSC's optimal solutions using multiobjective particle swarm optimization. In addition, we employed a participation factor to select suitable generator speed deviations as the wide area stabilizing signal. The proposed approach was tested on different configurations of the Kundur 2-area 4-machine test system within MATLAB and Psat environments. The outcome of the nonlinear simulation proved that the multimachine power system stability was enhanced.

Key words: FACTS devices, interarea oscillations, phasor measurement units, stability, wide-area, coordination

1. Introduction

Economic issues are continuously arising in modern power systems, triggered by deregulation and the emergence of market-driven operations, as well as weak tie-lines, load variations, and environmental factors resulting from renewables penetration as well as emission restriction. The highly loaded grids limit power transfer plans, thereby confining lines to operate at the edges of their stability limits. These operation states lead to interarea modes of oscillations [1].

To date, power system stabilizers (PSSs) have effectively damped local modes of electromechanical oscillations but are less effective in interarea mode [2–4]. The reason for the deficiencies of PSSs is that they can hardly observe interarea modes due to the nature of their input signals. The emergence of FACTS brought some relief in the enhancement of power system stability [5–7]. STATCOM and SSSC are voltage source converters and are used for systems stability improvement [8] in interconnected power systems that are usually large with many areas linked to others by distant transmission lines to improve reliability as well as reduce the requirements of the spinning reserve.

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The advent of wide-area measurement (WAMS), which uses global signals, brought a face lift to power systems monitoring and control using phasor measurement units (PMUs). WAMS offers increased observability and controllability in the power system, thereby improving the dynamic monitoring for stability enhancement [9]. Deployment of PMUs has brought about vast prospects for developing wide-area monitoring and control [10–12]. Many proposed methods apply wide-area signals for damping the interarea modes using PSSs and flexible AC transmission systems (FACTS) controllers [11–15].

Studies on the damping of electromechanical oscillations have been carried out with different controllers; for instance, the approach in [6] identified dominant algebraic sets associated with a critical mode and was used for placement of a SVC and STATCOM to damp the oscillations. In [16], an organized regulation of PSS/POD (power oscillation damper) and proportional integral (PI)-based STATCOM control enhancements of systems dynamic performance was proposed and realized, but the application was limited to a single-machine infinite-bus (SMIB) system. In [17] the authors suggested a joined fuzzy logic controller (FLC) voltage controller, bang-bang FLC-based controller, and STATCOM for improving power system damping performance. Optimal placement of the STATCOM was not a priority. The work in [18] demonstrated an approach that enhanced damping of interarea oscillations utilizing a consolidated optimal placement of a unified power flow controller (UPFC) and signal selection for the controller using a residue factor. The approach in [19] had a STATCOM optimally tuned for oscillation damping using honeybee mating optimization. In [20], the hybrid-fire algorithm and pattern search (h-FAPS) method was used to design a SSSC for damping oscillations. The work in [21] proposed the use of NSGA-II (nondominated sorting genetic algorithm-II) for adjustment of a lead-lag SSSC controller for damping oscillation, while [22] used a controllability and observability Gramian matrix for optimal placement, fine-tuning, and selection of signal location for a STATCOM-based POD in a large power network to eliminate oscillations. Despite the success, the computational effort of the placement procedure was tedious. However, the authors of [13] used an off-centered SVC and designed a WADC for interarea oscillations damping, but the optimal siting of the SVC was not considered. Also, [14] proposed a PI WADC (wide area damping controller) that was tuned using PSO with a controlled doubly-fed induction generator (DFIG)-based wind farm. The proposed strategy damped oscillation with continuous time-varying compensation. In [15], SVC installation was unilateral, and a WADC was designed for interarea oscillations damping. The idea shaped the electromechanical modes but the authors recommended the use of more than one FACTS device for better performance. The limitations of many of the mentioned applications, however, are their arbitrary placement of FACTS devices and the use of a single configuration of either shunt or series FACTS devices. This paper proposes wide-area coordination of a series and a shunt FACTS device optimally placed for damping interarea oscillations in power systems. The choice of FACTS devices for wide-area problems is suitable due to their swift response ability in handling chaotic systems with constraints in a unique way [15].

PSO is a promising evolutionary procedure that is stochastic and handles optimization problem excellently. Also, it is a population-based optimization method inspired by the social behavior of fish schooling or birds flocking [23, 24]. However, to solve some problems, different objective functions have to be considered at the same time. Therefore, the PSO algorithm is extended to a multiobjective optimization referred to as MPSO [24–26] in this paper. This paper shall investigate the application of MPSO in siting and sizing of the STATCOM and SSSC as well as their parameter tuning in a multimachine power system with WAMS to enhance power system stability by damping interarea oscillations.

Optimal placement of FACTS devices in the power system brought much relief to unstable or overstretched power systems. However, the introduction of WAMS has brought more insight into the options for improving stability in power systems using remote signals and WADCs. This paper proposes coordination of series and shunt FACTS devices optimally placed and tuned using MPSO with a remote supplementary control signal for damping of interarea oscillations in power systems. The main contributions of this paper are to achieve two objectives: (1) to optimally place, size, and tune the STATCOM and SSSC in a multimachine power system using MPSO; and (2) to introduce a supplementary remote signal to the FACTS devices to further improve the system damping ability without the use of a supplementary controller.The rest of the paper is organized as follows: Section 2 provides the formulation of the problem. Section 3 gives the implemented methodology. Section 4 describes the results, followed by conclusions in Section 5.

2. Formulation of problem

A nonlinear electrical system can be represented by the set of nonlinear equations described by Eq. (1).

$$\begin{aligned} \dot{x} &= f(x,u), \\ y &= g(x,u), \end{aligned} \tag{1}$$

where $x = [x_1, x_2, ..., x_k]^T$ is the system state; $u = [u_1, u_2, ..., u_l]^T$ is the input vector with its dimension and $y = [y_1, y_2, ..., y_m]^T$ is the output vector. Small signal stability analysis is achievable by linearizing Eq. (1) around an operating point [2], which will be established in Section 3. This paper desires to achieve enhanced power system oscillation damping using only FACTS devices and their wide-area coordination.

2.1. Problem

The optimal placement, sizing, and tuning of FACTS devices, which improve the damping of electromechanical oscillation modes, is required, but obtaining optimality is always problematic. Placement and tuning techniques are available in the literature in different forms [1, 6–16]. The problem formation in [24–26] showed some scientific rigor in the formulation of the problem. This paper modifies and expands the multiobjective ideology in [25] from two to four normalized objectives. Our objectives are to address, among many, the optimal installation of the STATCOM and SSSC [18], sizing, tuning, and their coordination in the power system to enhance power system stability. The location of these FACTS controllers in the configuration of large power systems is addressed by formulating an objective function that is optimized using MPSO for the placement, sizing, and tuning of the STATCOM and SSSC. The two FACTS devices are coordinated using remote signals to damp interarea oscillation (by using additional signals coupled with the reference voltage). These remote signals' observability must be adequate for the interarea modes.

2.2. Fitness function

To fully formulate the problem, a fitness function with different objectives for this minimization problem of optimal placement, sizing, and tuning of the STATCOM and SSSC is fused to minimize the objective function having four parts. The objectives are: (i) to determine the placement of the STATCOM by minimizing the system voltage deviations, (ii) to obtain a minimum size of the STATCOM by tuning the PV, (iii) to place the SSSC by minimizing the total active power loss of the system, and (iv) to obtain the percentage compensation of the SSSC. Hence, four metrics, J_a, J_b, J_c, and J_d, emerged. The multiobjective optimization problem is defined utilizing the weighted sum of the four metrics to create a befitting fitness function J in Eq. (2):

$$Min\ J = \alpha J_a + \beta J_b + \eta J_c + \rho J_d, \tag{2}$$

where: J is the fitness function and α, β, η, ρ are the weights of the fitness function. Also, $J_a = \frac{\Delta V}{\Delta V_{base}}$, $J_b = \frac{P_{loss}}{P_{loss,base}}$, $J_c = \frac{Q_{STATCOM}}{Q_{STATCOM\,\max}}$, and $J_d = \frac{C_{SSSC}}{C_{SSSC\,\max}}$.

The sum of voltage deviation in J_a is:

$$\Delta V = \sqrt{\sum_{j=1}^{c} (V_j - 1)^2}, \tag{3}$$

where c is the number of buses and V_j is the voltage at bus j.

The STATCOM size is determined by:

$$Q_{STATCOM} = V * i_{SH}. \tag{4}$$

$Q_{STATCOM}$ is the network STATCOM size influenced by V_{PV}. $Q_{STATCOM\,\max}$ is the maximum allowable size of the STATCOM for the system for V, $0.95 \leq V_j \leq 1.05$, and i_{SH} is the STATCOM injected shunt current.

The total active power loss in a power system is:

$$P_{loss} = \sum_{m=1}^{c_r} I_m^2 R_m = \sum_{j=1}^{c} \sum_{\substack{k=1 \\ j \neq k}}^{c} \left[V_j^2 + V_k^2 - 2V_j V_k \cos(\delta_j - \delta_k) Y_{jj} \cos\varphi_{jk} \right], \tag{5}$$

where c_r and c are the number of lines and buses, respectively; R_m is the resistance of line m; I_m is the current through line m; V_j and δ_j are the magnitude and angle of the voltage at the bus j; and Y_{jk} and φ_{jk} are the magnitude and angle of the line admittance between the jth and kth buses, respectively.

The active power loss is used to satisfy the power balance equations in Eqs. (6) and (7):

$$P_{Gi} - P_{Di} - V_i \sum_{j=1}^{N_b} V_j [G_{ij} cos(\delta_i - \delta_j) + B_{ij} sin(\delta_i - \delta_j)] = 0, \tag{6}$$

$$Q_{Gi} - Q_{Di} - V_i \sum_{j=1}^{N_b} V_j [G_{ij} sin(\delta_i - \delta_j) + B_{ij} (\delta_i - \delta_j)] = 0. \tag{7}$$

The percentage compensation is define within Eq. (8) as:

$$25\% \preceq \mathbb{C}_{SSSC} \preceq 75\%. \tag{8}$$

C_{SSSC} is the percentage compensation of the SSSC. $C_{SSSCmax}$ is the maximum percentage compensation of the SSSC.

Additionally, the fitness function members of J as described in Eq. (2) are utilized within the optimization procedure. The objectives in Eq. (2), if treated independently, could lead to conflict. To avoid any conflict, the fitness functions of J are defined in the same mathematical function, Eq. (2), by being normalized comparatively with the base case of the test network and are connected with weights that are evaluated using a rank exponent model equation [27]. The fitness function objectives are arranged in a prioritized manner from $J1$ to $J4$ and their weights are set by a direct weight elicitation technique called rank exponent, described by Eq. (9) [27]:

$$w_i = \frac{(K - r_i + 1)^z}{\sum_{j=1}^{K} (K - r_j + 1)^z}, \tag{9}$$

where the ith objective rank is r_i and $i = 1, 2, ...K$, r_j ranges within $j - K$, and K is the total number of objectives. The normalized approximation ratio scale weight of the ith objective is w_i; z is an approximate quantity of the distribution in the weights. The bigger z is, the bigger the fraction of the most ranked objective to the smallest ranked objective will be [27]. There are four independent objectives in J with four weights and the weights' sum is unity.

Among our goals is inhibiting excessive power swings across the power system by achieving convergence of the generator's rotor speed and angle. This improvement is attributed to the introduction of both the MPSO design and the coordination signal to the FACTS devices to be utilized.

2.3. Wide-area damping concept

In power systems, optimally placed, sized, and tuned FACTS devices improve the damping of electromechanical oscillation modes. However, they have limitations in handling some oscillations since most areas are unobservable to the FACTS device. Consequently, for the damping of unobservable oscillation modes to be effective, a wide-area signal is introduced to the FACTS devices as a supplement using WAMS. Figure 1 shows the proposed wide-area coordination concept of this paper, called wide-area feedback signal coordination concept (WAFSCC) architecture.

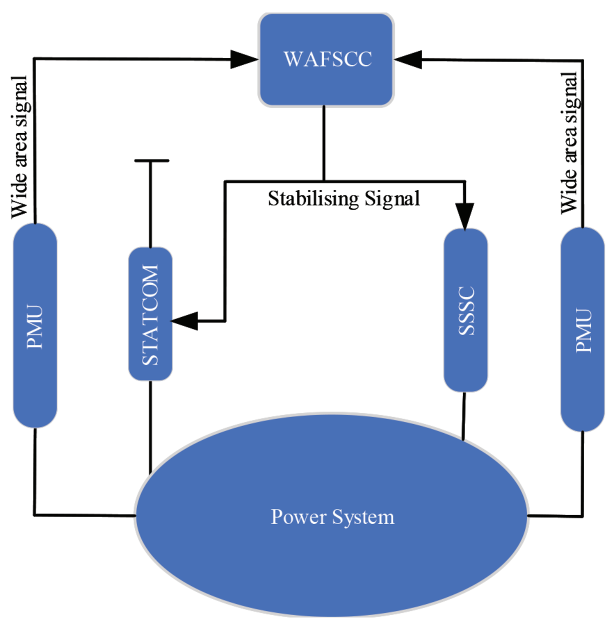

Figure 1. Wide-area system architecture.

The WAFSCC concept includes WAMS and PDC [16], in which the PMUs, measuring voltage phasors of generator buses, send data to the PDC, which is linked to the optimally placed FACTS devices. The PMUs used are placed at all generator buses to make the generators observable. The stabilizing signal is the generator's speed deviation, which is obtained by estimation [28, 29]. The speed deviation estimation obtained from the PDC data sends the appropriate stabilizing signal to the FACTS.

In real time, PMUs measure the critical signals of the system, which gives its actual state, and communicate with the SSSC and STATCOM controller via the WAMS assuming zero time delay. The stabilizing signal selected must be useful to both the STATCOM and SSSC or any other FACTS device in use [16]. In the operations of WAFSCC, at every swing of the generators, data are measured, processed, and transmitted from the generators to the FACTS controllers through the WAFSCC. The PMUs sense at every instance the phasor measurement data. If any generator is unavailable at any instance, the reaction of the generators sets oscillations into the network. The rotor speeds are intended to be the source of the remote signal to the FACTS devices that will provide corrective measures by either injecting or absorbing reactive power within the power system.

3. Methodology

3.1. Modal analysis

Small signal analysis is achievable by linearizing Eq. (1) around an operating point [2, 30] as follows:

$$\begin{aligned} \dot{x}(t) &= Ax(t) + BU(t), \\ y(t) &= Cx(t) + DU(t), \end{aligned} \tag{10}$$

where $x \in \Re^{n\times n}$ are the state variables, $u \in \Re^{n\times m}$ are the input variables, and $y \in \Re^{p\times n}$ the output variables. A, B, C, and D are the state matrix, input matrix, output matrix, and feed forward matrix that connects input with output directly. Supposing we take any complex conjugate eigenvalues $\lambda_{1,2} = \sigma \pm j\omega$ of matrix A, they provide details of the critical modes (oscillatory traits) in Eq. [2]. The real part, σ, relates to damping, and the imaginary part, ω, relates to the frequency of oscillation. In power system small signal stability the damping ratio ζ and linear frequency f (Hz) are used as stability criteria and are related to λ [2–4, 31–33]:

$$\lambda_i = \sigma_i \pm j\omega_i;\ \zeta_i = -\sigma_i/\sqrt{\sigma_i^2+\omega_i^2} \text{ and } f_i \ = \ \omega_i/2\pi. \tag{11}$$

The modes having a damping ratio below 3% are said to be delicate; 5% is adequate [34, 35]. This paper aims to have the system better damped and compensated by improving the damping ratio to be higher than adequate.

3.2. STATCOM and SSSC

The STATCOM size is to be determined by MPSO using Eq. (4). Reactive power absorption or injection by the STATCOM through reactive shunt compensation controls transmission voltage. The injected current through a coupling transformer connected to a bus sends a voltage into the grid system [30]. The simplified model of the STATCOM control block diagram used is presented in Figure 2.

The injected current i_{SH} in Figure 2 as obtained by [30]:

$$\dot{i}_{SH} = (K_r(V_{ref} + v_{remote} - V) - i_{SH})/T_r, \tag{12}$$

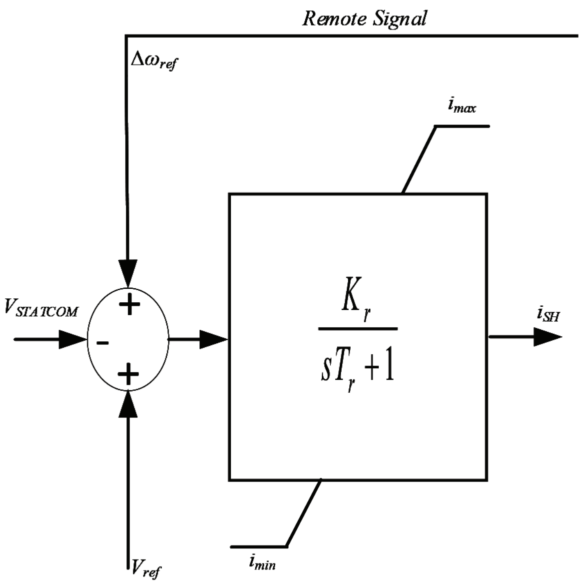

Figure 2. Control block diagram of STATCOM.

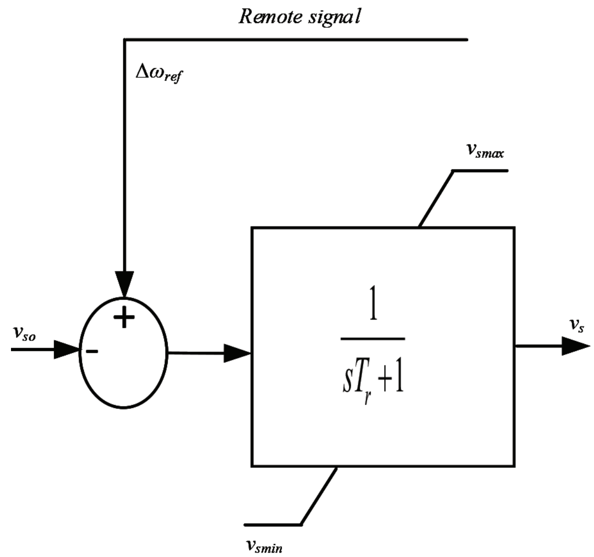

Figure 3. Control block diagram of SSSC.

where K_r is the regulator gain, V_{ref} is the reference voltage, v_{remote} is the stabilizing signal $\Delta\omega_{ref}$, V is the STATCOM voltage, and T_r is the regulator time constant. The sizing of the STATCOM is achieved as defined by Eq. (4).

The SSSC offers series compensation in constant reactance mode, in which the magnitude of the voltage is proportional to the current of the line while the sum of the reactance of the line having the SSSC remains constant [27]. The simplified model of the SSSC with its control block diagram is presented in Figure 3.
The input mode to the SSSC is:

$$\dot{v}_s = (v_{so} + v_{remote} - v_s)/T_r, \tag{13}$$

$$\begin{gathered} v_S = kx_{km}I_{km}, \\ k_{\min} \leq k < k_{\max}, \end{gathered} \tag{14}$$

in which v_{so} is the initial compensation voltage, v_s is series voltage, k is the percentage compensation, x_{km} is the transmission line reactance, and I_{km} is the line current magnitude. The size of the SSSC required for similar power enhancement when compared with the STATCOM at the midpoint relates to the STATCOM size in Eq. (4). The sizing relationship of the STATCOM and SSSC is given by [31] as:

$$Q_{SSSC} = Q_{STATCOM} \cdot tan^2(\delta_{max}/2), \tag{15}$$

where $0 < \delta_{max} < 90°$
and δ is the operating angle. Meanwhile, the remote signal selection is done by participation factor (the selected signals are added to the STATCOM and SSSC controller for stabilization), as described next.

3.3. Selection of remote stabilizing signal

For the selection of the remote signal, a participation factor (PF) is adopted, which is a degree of the relative participation. By selecting the most participating mode, the best stabilizing signal for the STATCOM and SSSC coordination is established. From the eigenvalues computation, if V and W are the right and the left system eigenvector matrices, then the participation factor p_{ij} of the ith state variable to the jth eigenvalue is computed by [27, 36]:

$$p_{ij} = w_{ij}v_{ij}/w_i^t vj. \tag{16}$$

For complex eigenvalues, the amplitude of each element of the eigenvectors without normalization is:

$$p_{ij} = |w_{ij}|\,|v_{ji}|/\sum\nolimits_{k=1}^{n} |w_{jk}|\,|v_{kj}|. \tag{17}$$

Participation factors for each generator, which are useful in large power systems, should be evaluated. Using eigenvector normalization, the sum of the participation factors associated with any mode ($\sum\limits_{j=1}^{n} p_{ji}$) or with any state variable ($\sum\limits_{k=1}^{n} p_{ki}$) is equal to one. The state variable with the largest magnitude is categorised as the remote stabilising signal.

3.4. Particle swarm optimization (PSO)

The PSO technique utilizes individuals' populations, referred to as particles. With some initial velocities, they fly through their problem space [37] in search of an optimal solution. Also, in every iteration, the particle velocities are adjusted stochastically bearing in mind the personal best particle's position and the global best position. The determination of these positions within some predefined fitness function [38] is governed by Eq. (18):

$$x_i(It) = x_i(It-1) + v_i(It). \tag{18}$$

Also, at each iteration It, a particle's velocity is determined by individual and group skills as in Eq. (19):

$$v_i(It) = w \cdot v_i((It-1)) + c_1 \cdot rand_1 \cdot (p_i - x_i(It-1)) + c_2 \cdot rand_2 \cdot (p_g - x_i(It-1)). \tag{19}$$

The weight is defined by:

$$w = w - 0.8\frac{It-1}{MaxIt-1}, \tag{20}$$

where inertia weight is w, which is in the range of $0-1$; c_1 is a cognitive constant, whereas c_2 is a social acceleration constant. c_1 and c_2 are related by $c_1 = 4 - c_2$, and we adopted $c_1 = 1.5$ [26]. $rand_1$ & $rand_2$ are of the interval [0,1]; they are uniformly distributed and randomly generated. p_i is the best position found by particle i; p_g is the best global position that any particle in the swarm could see and $MaxIt$ is the maximum iteration. In this study, we are applying the MPSO algorithm.

3.5. MPSO implementation

To correctly apply the MPSO algorithm, quite a few parts have to be well thought out. We have defined a suitable fitness function that presents a good performance of individuals in the population. Also, we have defined a potential solution to the optimization problem in Eq. (2). Characterization of the search space based on feasible solutions and some MPSO parameters were defined in Section 3.4 to have less computational effort with more accuracy.

Definition of particle: A particle in this paper is a vector that contains four columns. The first column (bus number) is for the STATCOM site. The second column is the voltage magnitude of PV (V_{PV}), influencing STATCOM sizing. The third column is line number for SSSC siting, and the fourth column is the percentage compensation of the SSSC as shown in Eq. (21):

$$x_i = [\kappa_1, \lambda_1, \kappa_2, \lambda_2], \tag{21}$$

where κ_1 = candidate site (bus) for STATCOM placement; λ_1 = for STATCOM sizing; κ_2 = candidate line for SSSC placement, and λ_2 = percentage compensation of SSSC. The constituents of the particle vector x_i (bus number, V_{PV}, line number and SSSC compensation) are all real numbers, $x_i \in \Re$ and $i = 1, 2, ..., nparticles$.

Search space definition: The features of the power system, its stability, and the anticipated voltage profile call for restrictions in the minimization problem addressed. Individual restriction characterizes a boundary in the search space; hence, the MPSO procedure has to be planned so that the particles move over their search region only. In the procedure, every time a particle's new position includes either a bus with a generator or a line with a transformer, the site changes to the geographically neighboring load bus or a transmission line, respectively. If any of κ_1 or κ_2 is out of the range, their values are shuffled, i.e. the particle moves to a randomly chosen bus or line as the case may be. Also, the size of the STATCOM unit and the percentage compensation of SSSC are restricted by Eq. (22) applied to the particles. If the maximum limits are exceeded, then the particles get reshuffled.

$$\begin{gathered} 0 \preceq Q_{STATCOM} \preceq 250Mvar, \\ 25\% \preceq \kappa_2 \preceq 75\%. \end{gathered} \tag{22}$$

In STATCOM placement and sizing, an individual result that does not satisfy the constraint in Eq. (23) is infeasible. Consequently, its fitness function value is set to pick a randomized value within the specified range. Also, the anticipated voltage profile is restricted as:

$$0.95 \leq V_j \leq 1.05. \tag{23}$$

The particles in Eq. (21) are therefore bound by Eq. (24):

$$\begin{gathered} \kappa_1^{\min} \leq \kappa_1 \leq \kappa_1^{\max}, \\ \lambda_1^{\min} \leq \lambda_1 \leq \lambda_1^{\max}, \\ \kappa_2^{\min} \leq \kappa_2 \leq \kappa_2^{\max}, \\ \lambda_2^{\min} \leq \lambda_2 \leq \lambda_2^{\max}. \end{gathered} \tag{24}$$

4. Results and discussion

4.1. Test system

We tested our WAFSCC concept on a Kundur two-area four-machine systems as shown in Figure 4, which is an IEEE benchmark model for small signal analysis [39]. The model consists of 4 machines, 11 buses, 12 lines, and two load centers at buses 7 and 9. The system is heavily loaded with a flow from area 1 (with generators at buses 01 and 02) to area 2 (with generators at buses 03 and 04) of about 400 MW interconnected by buses 7, 8, and 9 with a three-phase fault at bus 8. The parameters of the network are available in [28]. The loads considered here are constant ZIP loads and the proposed method is expected to handle dynamic loads with little or no variation. All optimization and simulations are done using PSAT, a MATLAB-based software, and MATLAB.

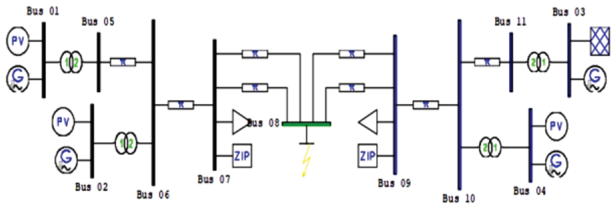

Figure 4. Two-area 4-machine power system.

4.2. Modal analysis of the test system

The entire generator states are 40; the active and reactive load modulation states are 12 each, bringing the total number of states for the test system to 64. The small signal investigation carried out shows the presence of two local modes and one interarea oscillation mode with the interarea mode having a damping ratio a little bit above 5% at a frequency of 0.61 Hz. Table 1 shows the system's modes. The local modes appear due to the absence of a PSS in the system. The large frequencies even with insufficient damping quickly decay, as their effect is of negligible consequence.

Table 1. Results of modal analysis of the default test system.

Type of mode	Most associated states	Damping ratio (%)	Freq. (Hz)
Local	ω_2 & δ_2	12.85	1.12
Local	$\omega 4$ & $\delta 4$	13.74	1.16
Interarea	$\omega 3$ & $\delta 4$ against $\omega 1$ & $\delta 2$	5.80	0.61

Participation factor: After evaluating the participation factor of the test system, Figure 5 shows that rotor speed (omega) contributed most in the interarea mode. To achieve the purpose of this study all generators' rotor speeds are made observable as well as additional input signals to the STATCOM and SSSC. The stabilizing signal is the speed deviation.

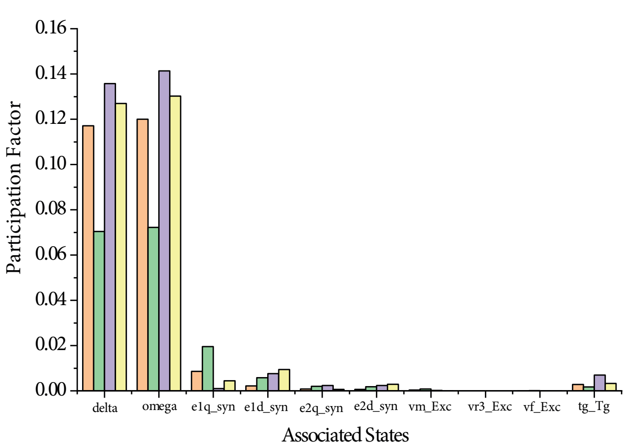

Figure 5. Participation factor of the interarea mode.

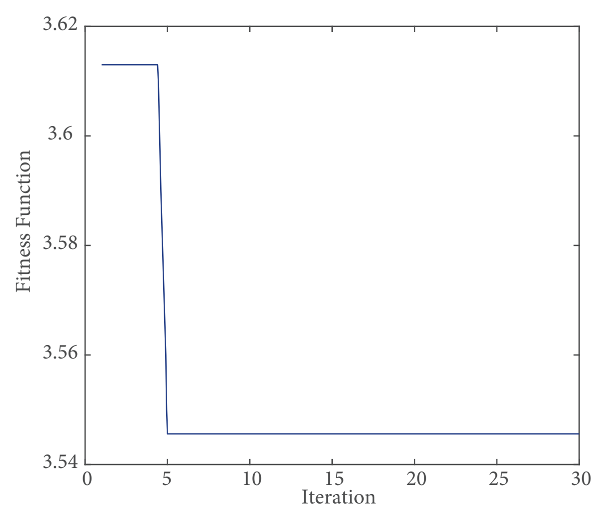

Figure 6. MPSO minimization fitness function J.

4.3. Design of the controllers

The nonlinear model used in STATCOM and SSSC design using MPSO-based optimization was effective. Fifteen particles were used, and a total of 30 iterations were set with $K = 4$, $z = 0.3$, $w_1 = \alpha$, $w_2 = \beta$, $w_3 = \eta$, $w_4 = \rho$, to achieve optimal results using a linearly decreasing inertia weight. The desired goal was achieved as shown in Table 2. Figure 6 shows the convergence of the global best fitness function at 3.5456.

Table 2. PSO parameters and results.

Design parameters	Status & values
STATCOM and SSSC location	Bus and line 7
SSSC Compensation in %	50.61
V_{pv} voltage	0.9803 p.u.
i_{SH}	0.966 p.u.
Size of STATCOM	0.947 p.u.
Size of SSSC	0.9296 p.u.
α & $beta$	0.3
η & ρ	0.2

4.4. Simulation results

The performances of the STATCOM, SSSC, and WAFSCC designed were tested, evaluated, and compared in three configurations: (i) the test system without any controller; (ii) the test system with STATCOM and SSSC controllers optimally placed, sized, and tuned by MPSO; and (iii) the test system with WAFSCC. Validation of time domain simulation was carried out for each configuration with a three-phase short-circuit fault, which occurred at bus 8 at time t= 5 s, which lasted for 100 ms. Modal analysis of configuration (i) has been discussed in Section 4.2. In configuration (ii) the modal analysis results presented in Table 3 show an improvement compared to the test system without any FACTS. Despite the results obtained, we achieved 10% damping ratio.

Table 3. Results of modal analysis of the test system with controllers.

Type of mode	Most associated states	Damping ratio (%)	Freq. (Hz)
Local	ω_2 & δ_2	12.201	1.1259
Local	$\omega 4$ & $\delta 4$	13.937	1.1634
Interarea	$\omega 3$ & $\delta 4$ against $\omega 1$ & $\delta 2$	7.858	0.6410

Configuration (iii)'s modal analysis results in Table 4 show the best performance of the test system among the three configurations. The designed goal of damping ratio targeted at 10% was met.

Table 4. Results of modal analysis of the WAFSCC concept.

Type of mode	Most associated states	Damping ratio (%)	Freq. (Hz)
Local	ω_1 & δ_1	12.172	1.187
Local	$\omega 2$ & $\delta 2$	11.498	1.196
Interarea	$\omega 3$ & $\delta 3$	14.383	1.227

Table 5 demonstrates the effects of the FACTS and WAFSCC in the improvement of the voltage profile, which settles between 0.95 and 1.05 as proposed in the design. Buses mostly affected are 6, 7, 8, 9, and 10 with the fault bus (bus 8) responding swiftly in all three configurations.

Table 5. Voltage profile magnitude.

Bus no.	No controllers	With controllers	WAFSCC
5	1.0035	1.0097	1.0063
6	0.9726	0.9877	0.9962
7	0.9532	0.9803	0.9803
8	0.9301	0.9636	0.9884
9	0.9670	1.0005	0.9876
10	0.9798	0.9965	0.9948
11	1.006	1.0134	1.0066

The improvement of the system voltage gave rise to active power improvement. Table 6 demonstrates how the concept used improved the system by reducing the active power loss over the three different configurations, with the WAFSCC having the largest percentage power loss reduction.

Table 6. Active power loss reduction.

No controller	With controllers	WAFSCC
0.896	0.633	0.523
0%	29.30%	41.69%

The time domain simulation of the three configurations lasted for a period of 20 s. When the tests system without FACTS was simulated, the rotor angle acceleration was increasing throughout. When the STATCOM and SSSC were introduced, the acceleration reduced considerably. However, with the STATCOM, SSSC, and WAFSCC in place, the acceleration was curtailed within 6 s. All the responses are captured in Figure 7.

Also, the speed deviation of the configurations after the simulation is shown in Figure 8. The tests system without FACTS caused the deviation to oscillate, which spanned throughout the set time with an effort to damp out after $t = 17\ s$. With the introduction of the STATCOM and SSSC, the oscillation peak was reduced. However, with the STATCOM, SSSC and WAFSCC in place, the speed deviation among the generators damped out within $t = 3\ s$. The deviations recorded in Figure 8 were area 1 against 2 for Gen.1&3, Gen.1&4, Gen.2&3, and Gen.2&4.

The responses displayed in Figures 7 and 8 prove that the oscillatory modes of the first configuration were reduced by the STATCOM and SSSC when placed, sized, and tuned optimally. Moreover, with the introduction of the remote signal to the FACTS through WAFSCC, which is the third configuration, the oscillatory mode ended in a brief time. The results obtained proved that MPSO's proposed siting, sizing, and tuning were successful. The WAFSCC coordination concept of the STATCOM and SSSC was achieved and effective. The choice of controllers that resulted in enhanced voltage profiles, oscillatory modes damping, and better system stability is suitable. Also, with the large frequencies and damping ratios above our design threshold, as shown in Table 4, the system oscillation quickly disappeared as shown in Figures 7 and 8. The FACTS devices and the concept used in the test network have proven that with this design they can be robust despite their subjection to a severe fault.

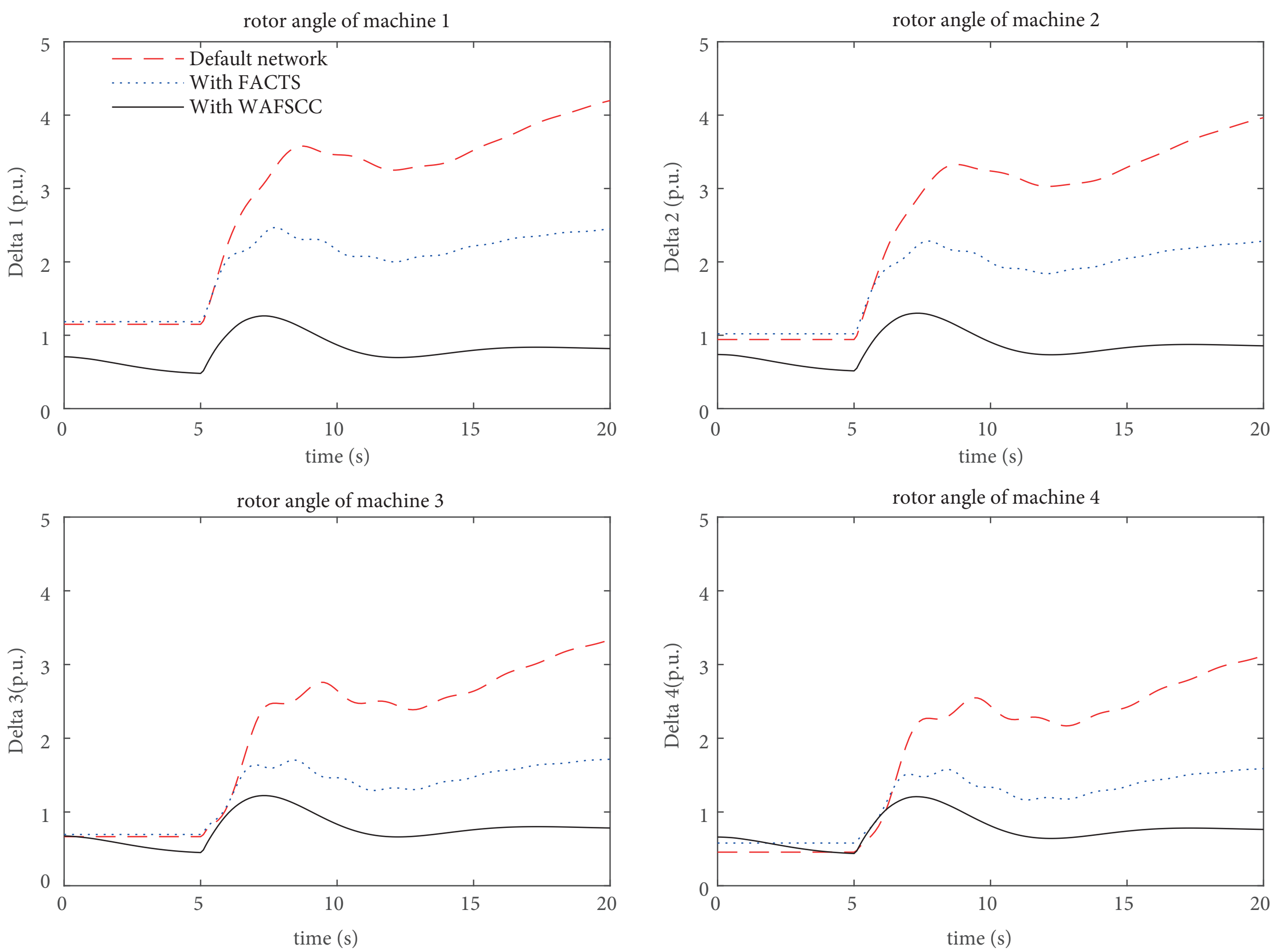

Figure 7. Rotor angle swing of the three configurations.

5. Conclusions

This paper implements a MPSO method to determine the optimal locations, sizes, and tuning of a STATCOM and SSSC in a multimachine power system. The coordination of the two FACTS controllers using the speed deviation as the feedback signal was introduced to enhance the system stability. The effectiveness of the proposed technique improved the voltage profiles and shaped the interarea modes, thereby improving the system stability. Also achieved was a significant reduction of active power loss from 29.3% using the STATCOM and SSSC to 41.7% with the WAFSCC concept. A Kundur test system having 2 areas, 4 machines, and 11 bus bars and 12 lines has been used to validate the technique's effectiveness. The nonlinear simulations have shown how the responses of the rotor angle and the speed deviations were damped swiftly. The optimization technique of MPSO used for the FACTS devices installations, operations, and their coordination (WAFSCC) thus seem promising despite the disturbance initiated. Optimal siting, sizing, and tuning with the influence of WAMS on FACTS as discussed in this paper was a success; however, time delay with WAMS involvement and the nature of the power system network remain essential issues to be resolved among many others in future work.

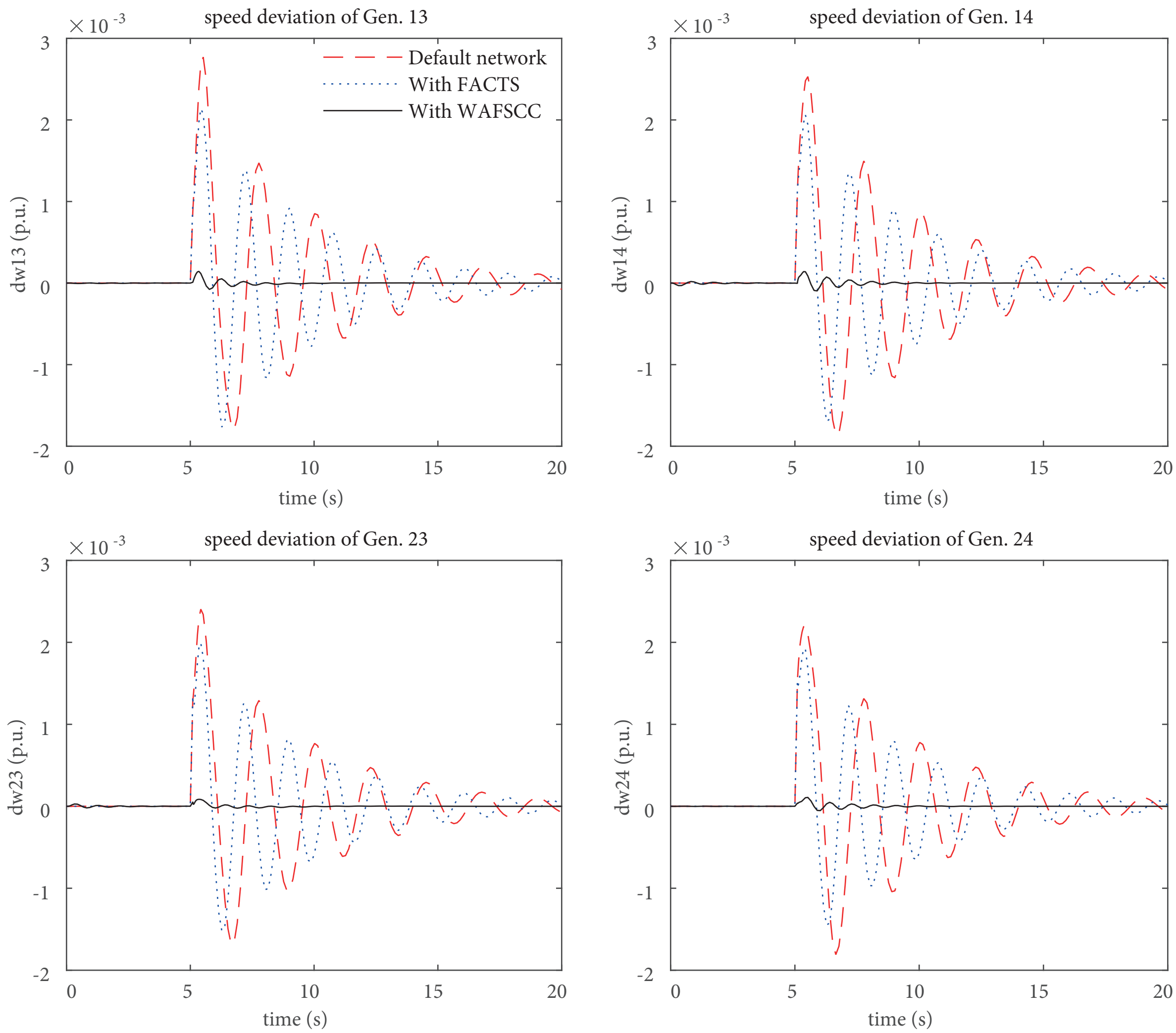

Figure 8. Speed deviation responses for the three configurations.

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Author contributions

Sunusi Sani Adamu and James Garba Ambafi came up with the idea; did the exploration, modeling, and simulations; interpreted the results; and wrote the paper.

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