RESEARCH ARTICLE

INTERNATIONAL RESEARCH JOURNAL OF MULTIDISCIPLINARY TECHNOVATION

Asian Research Association

DOI: 10.54392/irjmt2568

Performance Analysis of Various FACTS Devices Incorporated in Power System Damping Controllers

Chandan Kumar Sah [a, *], A.S. Kannan [b]

[a] Department of Electrical Engineering, Annamalai University, Annamalainagar, Chidambaram-608002, India
[b] Department of Electrical Engineering, FEAT, Annamalai University, Annamalainagar, Chidambaram-608002, India
* Corresponding Author Email: chandanau6@protonmail.com
DOI: https://doi.org/10.54392/irjmt2568
Received: 22-04-2025; Revised: 11-10-2025; Accepted: 17-10-2025; Published: 04-11-2025

Abstract: Low-frequency oscillations (LFOs) present a considerable challenge to the long-term viability of contemporary interconnected electrical networks. These oscillations may cause instability in the system, increased equipment stress, and reduced reliability in power delivery. Traditional controllers, such as Power System Stabilizers (PSS), have limitations in efficiently reducing oscillations between areas, particularly in large, multi-machine networks. To address this, Flexible AC Transmission System (FACTS) devices present a promising alternative due to their ability to dynamically control transmission line parameters and enhance system stability. This research proposes an integrated damping strategy using four FACTS controllers ‘Static VAR Compensator (SVC), Unified Power Flow Controller (UPFC), Static Synchronous Compensator (STATCOM), and Static Synchronous Series Compensator (SSSC) for effective suppression of LFOs. The controllers settings are adjusted for maximum effectiveness utilizing the Ant Colony Optimization (ACO) algorithm to adapt to changing system conditions in real-time. The proposed control approach is tested within the IEEE 30-bus system under normal, light, and heavy loading conditions. The simulation outcomes demonstrate that ACO-optimized FACTS controllers significantly outperform both the base case and non-optimized configurations by reducing settling time, overshoot, and power losses, thereby enhancing overall system stability and damping performance. Performance is measured using indices like Integral of Squared Error (ISE), Integral of Time Squared Error (ITSE), Integral of Absolute Error (IAE), Integral of Time Absolute Error (ITAE), LMN (Line Stability Index), FVSI (Fast Voltage Stability Index) and VSF (Voltage Sensitivity Factor).

Keywords: Flexible AC Transmission System (FACTS), Static VAR Compensator (SVC), Unified Power Flow Controller (UPFC), Static Synchronous Compensator (STATCOM), Ant Colony Optimization (ACO), Low-Frequency Oscillations, Power System Stability

1. Introduction

The reliability of modern interconnected electrical network is essential to maintaining a steady, dependable, and safe supply of power. Among various disturbances affecting system performance, LFOs are considered especially critical due to their potential to induce inter-area power swings, voltage instabilities, and system-wide blackouts. Inter-area fluctuations typically arise in multiple machines where power is transmitted over long distances, making control and coordination more complex. These oscillations result in limited power transfer capability and pose challenges to operational reliability. Traditionally, PSS have been employed to mitigate LFOs by providing supplementary damping through generator excitation systems [1]. However, the efficacy of PSS is reduced in large-scale grids where dynamic behaviors vary across regions. In such networks, a localized controller like the PSS cannot respond effectively to inter-area interactions, especially under evolving load conditions and disturbances [2]. Furthermore, PSS tuning is often based on fixed parameters, which may not adapt well to nonlinear and time-varying dynamics of real-world systems. Hence, there is a growing demand for more flexible, responsive, and coordinated control mechanisms that can address these complex stability issues. As electric grids increasingly integrate renewable energy sources, decentralized loads, and distributed generators, the limitations of conventional control methods become more pronounced, emphasizing the need for advanced controller designs that can operate effectively across a wide range of scenarios [3].

To overcome these challenges, the power systems community has turned to FACTS devices, which are well-known for their ability to improve system reliability through the dynamic control of transmission characteristics in real-time. FACTS controllers such as SVC, STATCOM, SSSC, and UPFC provide fast-acting control over voltage, impedance, and phase angle, thereby contributing to both transient and steady-state stability [4]. These devices can be installed either individually or in coordination to target specific stability issues, such as voltage collapse, angle divergence, or frequency deviation. The SVC and STATCOM act as shunt compensators, injecting or absorbing reactive power to maintain voltage profiles, while the SSSC and UPFC act in series to control line power flow and improve oscillation damping [4, 5]. Although FACTS controllers have shown promising results, their damping effectiveness largely relies on the control settings being precisely adjusted. If done manually or heuristically, this may not yield optimal system responses. Furthermore, deploying multiple FACTS devices without coordinated tuning can lead to conflicting control actions and reduced system efficiency [6]. As the complexity of the power grid increases, coordinated optimization becomes essential to fully leverage the benefits of FACTS technology in stabilizing dynamic interactions across buses and lines.

In this study, we propose a coordinated damping controller design using a swarm intelligence based optimization algorithm, ACO to tune the settings of several FACTS controllers simultaneously. ACO, inspired by the foraging behaviour of ants, has proven effective in solving nonlinear, multidimensional optimization problems due to its adaptability and robustness against local optima [7, 8]. We apply this technique to coordinate the control actions of SVC, STATCOM, SSSC, and UPFC in an IEEE 30-bus test system modeled in MATLAB/Simulink. The arrangement is examined under a range of loading circumstances (normal, heavy, and light), with performance measured using established indices like ISE, ITSE, IAE and ITAE. The proposed approach is also compared with other optimization approaches, including Particle Swarm Optimization (PSO), Genetic Algorithm (GA), Grey Wolf Optimizer (GWO), and Whale Optimization Algorithm (WOA), to benchmark its efficiency. The results demonstrate that ACO-based coordination leads to significant improvements in damping oscillations, reducing overshoot, settling time, and power losses, thus affirming its potential for real-world deployment in smart grids and renewable-integrated power networks [9, 10]. The main findings of this study are listed below:

- The creation of a coordinated control scheme that integrates four types of FACTS controllers' SVC, UPFC, STATCOM, and to improve power systems ability to dampen low-frequency inter-area oscillations.
- Implementation of ACO to best modify the FACTS controllers, addressing the challenge of manual tuning and improving overall controller performance under varying operating conditions.
- Implementing of an IEEE 30-bus system using MATLAB/Simulink with nonlinear dynamic simulations to test and validate the proposed ACO-based FACTS control framework.
- Performance evaluation under diverse loading conditions (normal, heavy, and light) demonstrating the efficiency of the suggested strategy in improving damping ratio, reducing overshoot, minimizing settling time and power losses in contrast to base and FACTS-only systems.
- Comparison with existing optimization techniques like PSO, GA, GWO and WOA, showing that the proposed ACO-based method achieves superior results across key performance indices (ISE, ITSE, IAE, ITAE, Lmn, FVSI, and VSF).

The remainder of this paper is structured as follows: Section 2 describes the research methodology, including the modeling of the power system and the Ant Colony Optimization-based tuning strategy. Section 3 presents the simulation results and performance analysis under various loading conditions. Section 4 provides a detailed discussion of the outcomes in the context of existing literature. Finally, Section 5 concludes the study and highlights potential directions for future research.

2. Literature Review

The SCA is a stochastic metaheuristic optimisation technique described in [10]. The main goal of this algorithm was to fine-tune a PSS's settings to attenuate oscillations within a grid line connected to a large current supply. To find the ideal PSS parameter values, the SCA utilized the goal function to formulate the optimization issue in value minimization. In [11], the author presented a meta-heuristic optimization method that focuses on enhancing the stability of the power system through the SSSC and an additional dampening controller. The method utilizes two control channels, phase, and magnitude, to enhance stability and resistance under various operating conditions. For the optimization process, the author employed a multi-objective approach, using the approach of the total of weighted factors. In [12] the author introduces a hybrid control method for multi-machine power systems incorporating FACTS devices using nonlinear modelling. The method aims to minimize inter-area oscillations and maximize the utilization of the UPFC.

The authors of the [13] utilize PSO-ANFIS models for estimating the PSS parameters of SMIB systems, both with and without UPFC. They apply the ANFIS model, which combines fuzzy logic and neural networks, to model the complexities of these systems. Additionally, they employ the PSO algorithm, a metaheuristic optimization method to determine the best way to solve the issue. In [14], a hybrid optimization-based SSSC controller was developed to address power oscillations in power transmission systems. The introduced controller was designed to tune the values of the SSSC damping controller's parameters through a hybrid DE-PSO optimization algorithm. In [15] the author developed a hybrid optimization technique called hCSC-PS; CSCA and PS were used in conjunction to develop PSSs and SVC-based devices. In that technique, decision factors were the controllers' settings, but the design challenge was seen as a problem for optimization. The PSS-UPFC approach was developed to enhance the dynamic stability of power systems, as introduced in [16]. In reference [17], an optimization technique is proposed for the simultaneous coordinated design of a PSS and SVC as a damping controller in a multi-machine power system. An extensive analysis of research and improvements in power system stability development using FACTS controllers, along with utility experience, real-world installations, and semiconductor technology development, has been outlined in [18]. Furthermore, [23] presented a state-of-the-art review on concurrent voltage and frequency regulation problems in renewable integrated power networks, offering a holistic view of recent advancements in control coordination and system response challenges in hybrid energy systems. This work emphasises the need for robust controllers, such as FACTS and coordinated optimization algorithms, in renewable-dominated grids. Additionally, Sharma and Singh [24] introduced a hybrid Lyrebird–Pattern Search optimized PI-(1+DD) controller that significantly improves multi-area microgrid stability through virtual damping and energy storage inertia. Their approach, published in Journal of Energy Storage, showcases how novel hybrid metaheuristics can enhance system resilience supporting the relevance of Ant Colony Optimization used in our study. Table 1 shows the description of the related works.

Table 1. Summary of Related Work on Damping Controllers and Optimization Techniques

Reference	Technique Used	Application & Key Contribution
[10]	Sine Cosine Algorithm (SCA)	Tuned PSS parameters to suppress oscillations in high-current power lines.
[11]	Multi-objective Optimization	Improved SSSC controller with dual-phase control for robust stability across conditions.
[12]	Hybrid Control Method	Nonlinear FACTS-based control for mitigating oscillations between areas in multi-machine systems.
[13]	PSO-ANFIS	Estimated PSS parameters in SMIB systems, combining fuzzy logic with swarm intelligence.
[14]	DE-PSO Hybrid	Designed SSSC controller to reduce transmission system oscillations.
[15	HCSC-PS (Cuckoo + PSO)	Coordinated SVC and PSS parameter optimization for stability enhancement.
[16]	PSS-UPFC Integration	Developed coordinated damping strategy using UPFC to improve dynamic system response.
[17]	PSS & SVC Co-design	Proposed simultaneous tuning of SVC and PSS for damping in multi-machine environments.
[19]	Improved PSO with Chaos	Optimized PSS location and settings for superior global damping in power networks.
[20]	Gravitational Search Algorithm (GSA)	Organized development of PSS and TCSC under diverse load profiles.
[21]	Chaotic PSO	Enhanced global search and avoided local optima in reducing controller design.
[22]	Improved Salp Swarm Algorithm (ISSA)	Provided robust damping control via modified leader-follower update mechanisms.
[23]	Literature Review	Reviewed voltage/frequency regulation challenges in hybrid renewable systems with focus on FACTS-based control.
[24]	Lyrebird–Pattern Search Hybrid	Introduced advanced PI-(1+DD) controller for microgrid damping using hybrid metaheuristics.

A novel method for the optimal location of the PSS by integrating the improved particle swarm optimization (IPSO) with the chaotic, which can find the best locations and the optimum PSS parameters simultaneously with an excellent global damping performance, is proposed in [19]. An author [20] developed a heuristic global optimization algorithm, called the gravitational search algorithm, which is applied for the simultaneous coordinated designing of the power system stabilizer and thyristor-controlled series capacitor as a damping controller in the multi-machine power system. A multi-objective optimization problem is used to express the coordinated design problem of controllers under a variety of loading situations. In reference [21], a chaotic particle swarm optimization (CPSO) technique was used to combine the population-based evolutionary searching ability of PSO and chaotic searching behaviour to improve the global searching capability and premature convergence to local minima. The author [22] presented the enhanced ISSA algorithm has higher convergence accuracy and stability than the original SSA and other researched algorithms. It improved the salp swarm algorithm for reducing power system oscillations. Author introduces new equations for leader and follower location updates.

3. Research Method

This research applies the proposed four FACTS controllers on AC power system networks. To increase the electricity system's stability and damp oscillations adopted an Ant colony optimization algorithm for high performance.

3.1 Facts Controller

"FACTS" is the name given to a collection of power systems devices that can boost the strength and steadiness of power systems as well as their capacity for transmitting electricity. The purpose of using FACTS tools is to improve the initial swing, effectively dampen oscillation, and aid in system stabilization in the case of a major failure [25].

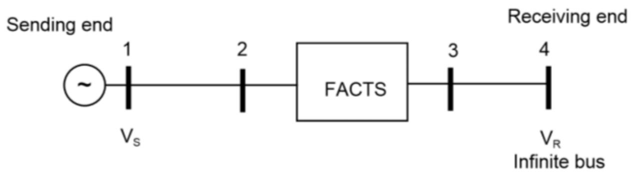

Figure 1. General block diagram of the transmission FACTS device. *(Source: Authors)*

FACTS controllers quickly adjust the network status and change the relative phase angle between control areas, facilitating active power exchange and stabilizing frequency variations. It reduces system oscillations and enhances transient stability and overall system reliability.

This basic design of FACTS on a transmission line is shown in Figure 1. The network status may be quickly controlled by the FACTs controllers. For effective management of transmission line power, FACTS controllers can be utilized to precisely alter the relative phase angle among the two control areas. This makes it easier to exchange active electricity over the transmission line and the frequency variations to be stabilized. By reducing the oscillations in the disrupted system with carefully regulated controller damping, transient stability may be attained. The key benefit of incorporating FACTS into a power system is boosting system stability and dependability by regulating the system's power flow and so providing enough power oscillation damping. Therefore, in the part following, we describe the model of the aforementioned FACTS controllers.

3.1.1 SVC model

One of the shunt devices in the FACTS series is the SVC. It comprises an FC-TCR type in which a permanent capacitor and a reactor with thyristor control are linked in parallel. SVC may also be used to reduce LFO by controlling the voltage point of reference with an additional signal. SVC is largely utilized to increase the stability of the voltage in electrical systems [26, 27]. Figure. 2 depicts the fundamental schematic circuit of the SVC.

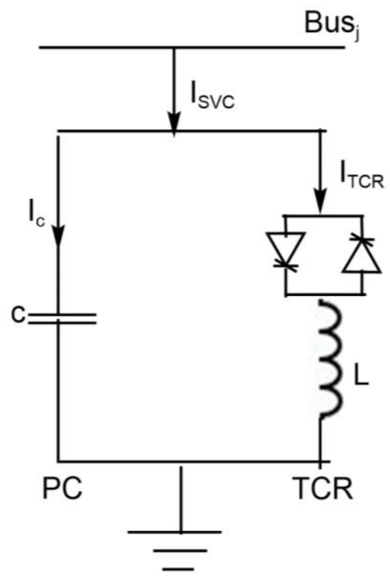

Figure 2. SVC model (Source: Authors)

3.1.2 UPFC model

The most widely used and adaptable FACT device is the UPFC, which uses electrical components to regulate power flow on power networks. UPFC can concurrently or selectively manage the voltage, impedance, and phase angle, and mitigate power system oscillations [28]. As shown in Figure 3, The

UPFC uses both series controller and shunt controller that are connected via a shared DC bus.

As seen in Figure. 3, UPFC has two converters that are each linked to the system through an insertion transformer and arranged in series. To accommodate the shared DC voltage, a DC connection, and capacitor bank connect the two converters. UPFC may regulate the line phase angle, voltage and impedance simultaneously or independently. A VSC is used by the series and shunt converters, and it is attached to the secondary side of the linked transformer. The reactive power of the conversion device may beutilized to regulate the current value of the bus in which the shunt converter is linked. The complicated power flow may be managed with a transmission line by controlling the series converter.

3.1.3 STATCOM model

A STATCOM is a shunt-coupled FACTS component and utilized as a source of variable voltage. By adjusting the injected voltage source's magnitude and phase angle in a steady state, it can either absorb reactive power or inject it. It typically consists of a pairing transformer, a capacitor, and a voltage source converter [29]. Although they may be used to control other system variables, the shunt-linked FACTS devices are mostly employed to adjust the bus voltage magnitude. The basic STATCOM model circuit is depicted in Figure 4.

The required reactive power in either direction will be provided by installing STATCOM at the proper position. The direction of the voltage supplied by the STATCOM's VSC determines whether reactive power is absorbed or delivered at the utility bus.

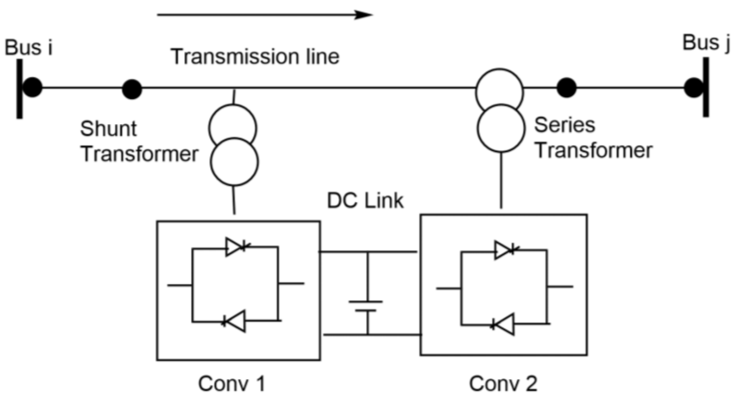

Figure 3. Basic schematic of UPFC (Source: Authors)

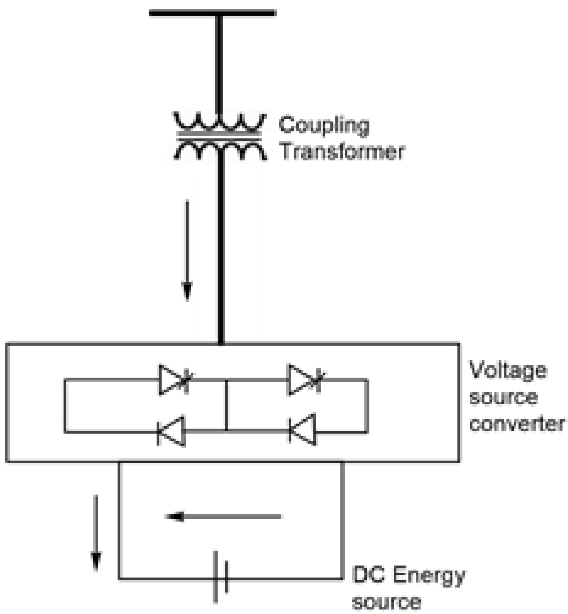

Figure 4. Circuit for STATCOM (Source: Authors)

Additionally, how much voltage is there between the utility bus and the converter terminal is a factor. Therefore, it is mostly utilized for changing compensation to maintain voltage, improve transient stability, and increase damping.

3.1.4 SSSC model

A series converter called the SSSC injects a voltage into the line in parallel to the line flow. The power system's power flow may be managed using it. As seen in Figure 5, an SSSC is a series-connected capacitor that is linked to the transmission line via an additional transformer and made up of a VSC, diode, and DC link capacitor. This device may provide several compensations by providing a controllable voltage into the line, which changes the transmission line impedance [30]. The SSSC enables both active and reactive power exchange with the power system, which makes it possible to regulate the flow of both types of power.

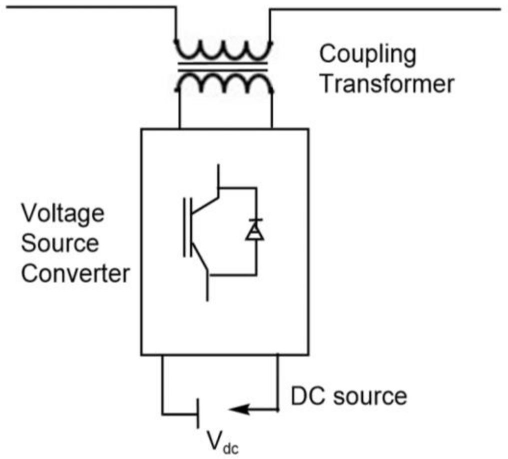

Figure 5. SSSC model (Source: Authors)

The SSSC has the benefit of eliminating the capacitance and inductance of reactors and capacitors as compared to the TCSC. Additionally, it is symmetrically proficient in both capacitive and inductive modes.

The SVC controls voltage points with an additional signal to reduce LFO and enhance voltage stability. The SVC model's control system uses a first-order dynamic simulation. The UPFC manages voltage, impedance and to reduce power system oscillations, as well as phase angle. A voltage is injected in series with the line by the series controller, and the shunt controller controls the terminal voltage and supplies or absorbs real power from the line. The ability to regulate multiple parameters either selectively or concurrently helps in mitigating oscillations by ensuring optimal power flow conditions. A STATCOM adjusts voltage magnitude and phase angle to absorb or reject reactive power. It improves voltage stability, transient stability and damping by providing required reactive power in either direction. This capability improves stability of voltage by providing the necessary reactive electrical power in response to system demands. The SSSC provides a controllable voltage applied in series to the transmission line, managing power flow and enhancing stability. It functions in both capacitive and inductive modes symmetrically, eliminate the need for reactors and capacitors.

Each of these FACTS devices has its control. In any case, innovative methods and strategies have been successful in controlling power systems, increasing the capacity and dependability of electrical power transmission, and maintaining system stability. The controllers are expanding the available power transmission capacity to deliver more practical and silent electricity coefficients to strengthen the system. The parameter settings of the abovementioned controllers must be changed because these controllers face several optimization difficulties.

FACTs controllers are highly effective, but they have a few small shortcomings. For example, they have trouble managing complicated system dynamics. To address these problems, we need the help of an optimization method by fine-tuning the control parameters to solve these issues. For dampening oscillations in power systems, FACTS controller performance is greatly improved by optimization methods. To successfully minimize oscillation problems and preserve the stability of the grid, they enable fine adjustment of control settings, take into account complicated system dynamics, react to changing conditions, and optimize the general response in FACTS devices. For the best tuning in the FACTS devices in our proposed system, the swarm-based optimization approach ACO is utilized.

3.2 Optimization Technique

This section will describe the ACO algorithm's specific that was utilized in the STATCOM, SSSC, UPFC, and SVC controllers coordinated parameter-tuning architecture. ACO, a probabilistic approach to addressing computing issues, could be used for speeding up the process of locating an appropriate path through a network. Macro Doriso made the initial suggestion for this method in his 1992 doctoral thesis. The initial algorithm was created using the concept of the ant colony's search for food concerning a food supply. Ants begin the process of hunting for food by wandering randomly throughout the nest [31, 32]. Once they locate a food source, they transport small quantities of food to their nest. When traveling back, it deposits a chemical pheromone based on its characteristics and those of its food source.

The pheromone that ants leave behind when they migrate from one location to another is followed by the ants that come after them. Ants go in the direction where there is the greatest concentration of pheromones. By doing this, they may mark the trail so that it can be recognized and followed by other ants. Subsequent ants can then choose the shortest way out of multiple options. The parametric random decision rules control the sequential decision process that creates the solution. The successive learning of the parameters that the decision policy depends on forms the foundation of the ACO algorithm. To successfully combat oscillation behaviour and ensure stable grid operation, the ACO algorithm can dynamically adjust and optimize control settings in real-time. Shown in below in Table.2

Table 2. ACO's parameters and their values

Parameters of ACO	Value
Iteration nn	150
No of ants	50
α	0.7
β	0.3
Rate of evaporation	0.9
No of parameters	4
No of nodes	200

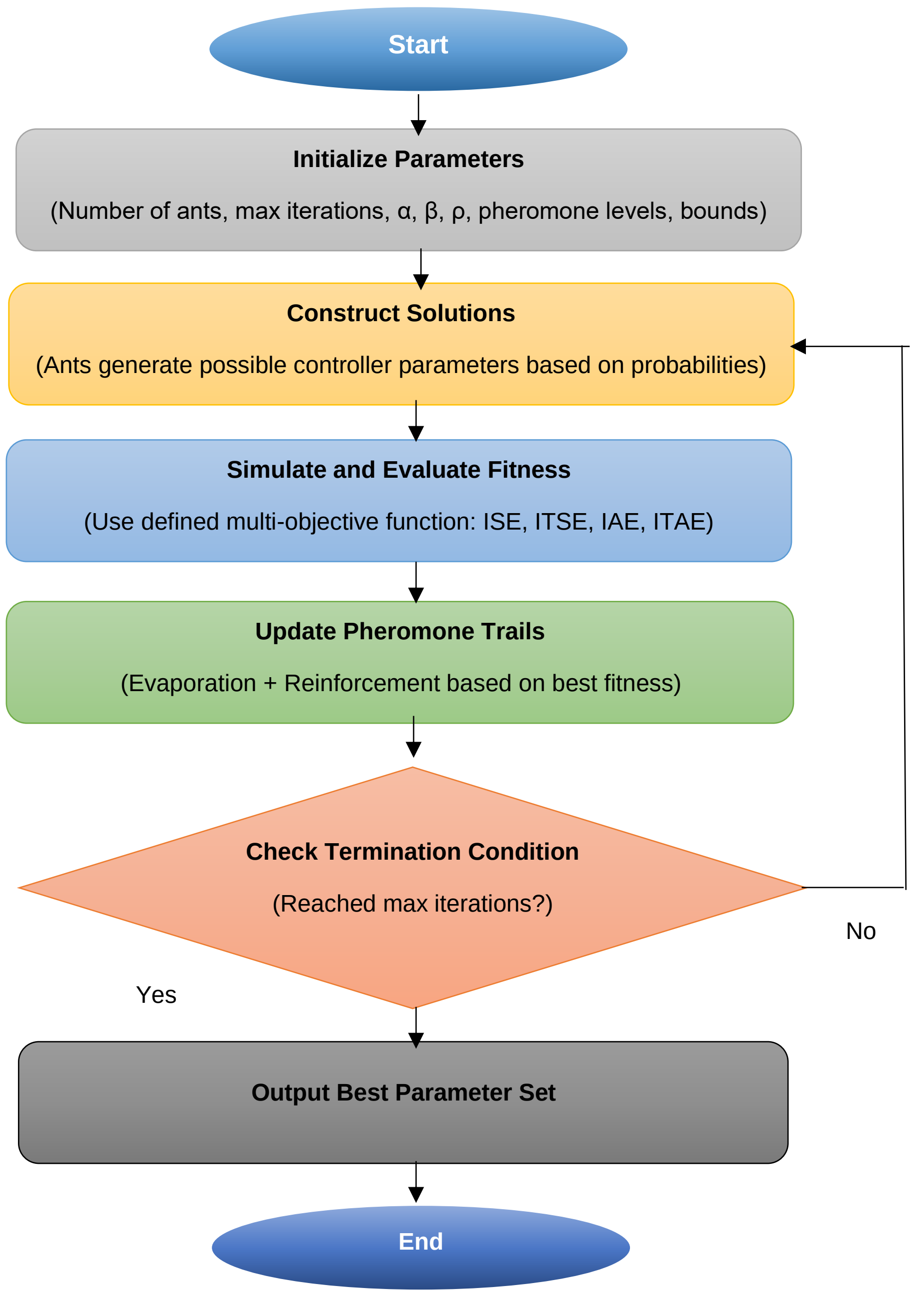

Figure 6. Flowchart of the ACO Algorithm for Tuning FACTS Controller Parameters (Source: Authors)

The ACO parameters and their values are shown in Table 2. Through these parameters, the FACTS controllers' settings are modified. ACO's fundamental process has been represented into four essential phases. The flowchart of the ACO Algorithm for Tuning FACTS Controller Parameters is shown in figure 6.

3.2.1 Problem Representation

I. ***Search Space:*** The search space includes all possible configurations of the four controllers (SVC, UPFC, STATCOM, and SSSC). Each dimension corresponds to a control parameter that needs optimization.

II. ***Decision Variables:*** This phase encompasses the physical limits of each controller, including maximum and minimum reactive power levels for SVC and STATCOM, voltage and impedance limits for UPFC, and series voltage limits for SSSC. Additionally, it includes the overall system stability requirements, thermal limits of transmission lines, and regulatory compliance.

3.2.2 Construct Solutions

Every ant finds a solution through motion the search space, making decisions based on pheromone trails (τ) and heuristic information (n). The probability P_{ij}which an ant will travel between node i andnode$j$ is given by:

$$P_{ij} = \frac{[\tau_{ij}]^{\alpha}[\eta_{ij}]^{\beta}}{\sum_{k\in \text{allowed}} [\tau_{ik}]^{\alpha}[\eta_{ik}]^{\beta}} \quad (1)$$

Where, τ_{ij} is the pheromone level on the path between node i and node j . η_{ij} is the heuristic value associated with the path between node i andnode j. α andβ are factors that regulate how much heuristic and pheromone information is used. Each ant explores different settings for the controllers, constructing potential solutions.

I. ***Fitness Function:*** To evaluate and guide the optimization process using ACO, a composite fitness function is defined. This function combines multiple performance indices that are critical to damping control performance in power systems. The fitness function is formulated as,

$$\text{Fitness} = w_1 \times ISE + w_2 \times ITSE + w_3 \times IAE + w_4 \times ITAE \quad (2)$$

Where, ISE denotes Integral of Squared Error that punishes major deviations more heavily, ITSE denotes Integral of Time Squared Error which penalizes errors that persist longer, IAE denotes Integral of Absolute Error which measures total accumulated deviation, ITAE denotes Integral of Time Absolute Error which improves long-term stability by focusing on time-weighted error, w_1, w_2, w_3, w_4 are weighting factors assigned to each objective, depending on system design priorities. These performance indices collectively assess both transient and steady-state responses. The weights w_1 to w_4 are set based on the desired balance between rapid damping, minimal overshoot, and long-term stability. In our case, all weights are set equally to 0.25 for balanced performance across criteria, though this can be adapted for specific control objectives.

3.2.3 Update Pheromones

Once every ant has built a solution, update the pheromone trails to reflect the standard of the solutions discovered. Pheromone evaporation ensures that older paths are less likely to be chosen:

$$\tau_{ij} = (1-\rho)\tau_{ij} + \sum \Delta\tau_{ij} \quad (3)$$

Where ρ is the evaporation rate. $\Delta\tau_{ij}$ is the amount of pheromone placed by ants that used the path ij. Good solutions deposit more pheromones:

$$\Delta\tau_{ij} = \frac{Q}{L} \quad (4)$$

Where Q is constant. $L$is the length (or cost) of the solution found by the ant.

It updates the pheromone trails according to the solutions' quality, favouring paths that lead to better system stability. The initial parameter settings for the FACTS controllers were obtained through a hit-and-trial approach based on literature guidelines and system response observations, and were subsequently refined using an in-house developed MATLAB-based ACO toolbox to achieve optimal performance.

3.2.4 Iteration

Repeat the process, gradually converging on an ideal or almost ideal controller setting solution.

The gain settings of the AC FACTS controllers are initialised using the hit-trial method, and the optimal values are then selected using ACO. The gain values of the four FACTS controllers in ACO are based on the ants' locations. The related output values of the FACTS controllers are modified in response to changes in the ant's location. SVC dynamically injects or absorbs reactive power to stabilize voltage at critical points. By modulating the reactive power, the SVC helps support damping of voltage fluctuations and reduces oscillations. UPFC can adjust voltage levels, line impedance, and phase angles. This flexibility allows it to manage power flow effectively and mitigate oscillations. The STATCOM adjusts the voltage magnitude and phase angle on its connection point, reactive power can be injected or absorbed as neededto stabilize the voltage. The SSSC injects a controllable series voltage into the transmission line, directly influencing power flow and enhancing stability. The pseudocode for ACO-Based Tuning of FACTS Controller Parameters is shown in algorithm 1.

Algorithm 1. Pseudocode for ACO-Based Tuning of FACTS Controller Parameters

ACO for FACTS Controller Parameter Tuning	
1.	**Initialize parameters:**
	No of ants (N_ants)
	No of iterations (Max_iter)
	Evaporation rate (ρ)
	Pheromone importance factor (α)
	Heuristic importance factor (β)
	Initial pheromone levels (τ)
	Define parameter bounds for each FACTS controller
2.	**Define the fitness function:**
	$\text{Fitness} = w_1 \times ISE + w_2 \times ITSE + w_3 \times IAE + w_4 \times ITAE$
3.	**For each iteration (t = 1 to Max_iter):**
	a) For each ant (k = 1 to N_ants):
	i) Construct a solution by selecting controller parameters based on probability: $P_{ij} = \frac{[\tau_{ij}]^{\alpha}[\eta_{ij}]^{\beta}}{\sum_{k\in \text{allowed}} [\tau_{ik}]^{\alpha}[\eta_{ik}]^{\beta}}$
	Simulate the power system using the selected parameters
	Analyze the fitness of the solution by utilize the defined fitness function
	b. Identify the best ant with minimum fitness value (best solution)
	c. Update pheromone levels:
	i) Evaporate pheromones: $\tau_{ij} = (1-\rho)\tau_{ij} + \sum \Delta\tau_{ij}$
	ii) Reinforce pheromone trails based on the best solution: where $\Delta\tau_{ij} = \frac{Q}{L}$
4.	**Repeat steps 3a–3c until Max_iter is reached**
5.	**Output**
	Optimal FACTS controller parameter set with best fitness value

3.3 Simulation Setup

The simulation studies for this research were conducted using MATLAB/Simulink with the Power System Toolbox. The IEEE 30-bus system was modeledto evaluate the damping capabilities of FACTS devices under various loading and disturbance scenarios. A simulation time step of 0.01 seconds and total simulation duration of 10 seconds were employed for all test cases. The solver was set to variable-step with a relative tolerance of 1e-4 to ensure numerical accuracy. To evaluate dynamic system response, disturbances were introduced as a result of an unexpected 10% increase in bus load 15 occurring at 2 seconds into the simulation. Additional load perturbations were applied at Bus 7 and Bus 21 during heavy and light load conditions. The system was tested under three loading scenarios, light (80% of nominal load), nominal (100%), and heavy (120%) to examine the robustness of the controller configurations. All simulations were performed on a 100 MVA system base. These parameters were chosen to ensure the replicability of the experiments and to reflect realistic power system disturbances and operating conditions.

3.4 Benchmark Justification

Although direct validation with a publicly available benchmark dataset is not feasible due to the unique configuration of the proposed ACO-optimized FACTS framework, the IEEE 30-bus test system was selected because of the widely accepted standard for evaluating power system stability and controller performance. This system is frequently used in the literature for studies involving damping control, FACTS device coordination, and metaheuristic optimization techniques. Its moderate complexity, multiple generations, and load buses, along with its ability to model diverse operational scenarios, make it suitable for the generalised testing of new methodologies. Consequently, the outcomes derived from the IEEE 30-bus system provide credible information about the efficacy and scalability of the suggested method in practical applications.

4. Results and Discussion

To verify the performance of FACTS controllers on the IEEE 30 bus system constructed in MATLAB/SIMULINK. This paper's primary goal is to examine these FACTS devices using the IEEE-30 bus and to evaluate the outcomes. The FACTS used to dampen the oscillation are STATCOM, SSSC, UPFC, and SVC. The effectiveness of FACTS controllers with and without using the ACO algorithm to dampen oscillations is covered in this section.

4.1 IEEE 30 bus system with multiple FACTS device

The evaluation of the active and reactive currents flowing in each line of the accepted IEEE 30-bus system is applied to identify candidate sites for installing FACTS devices [33, 34].

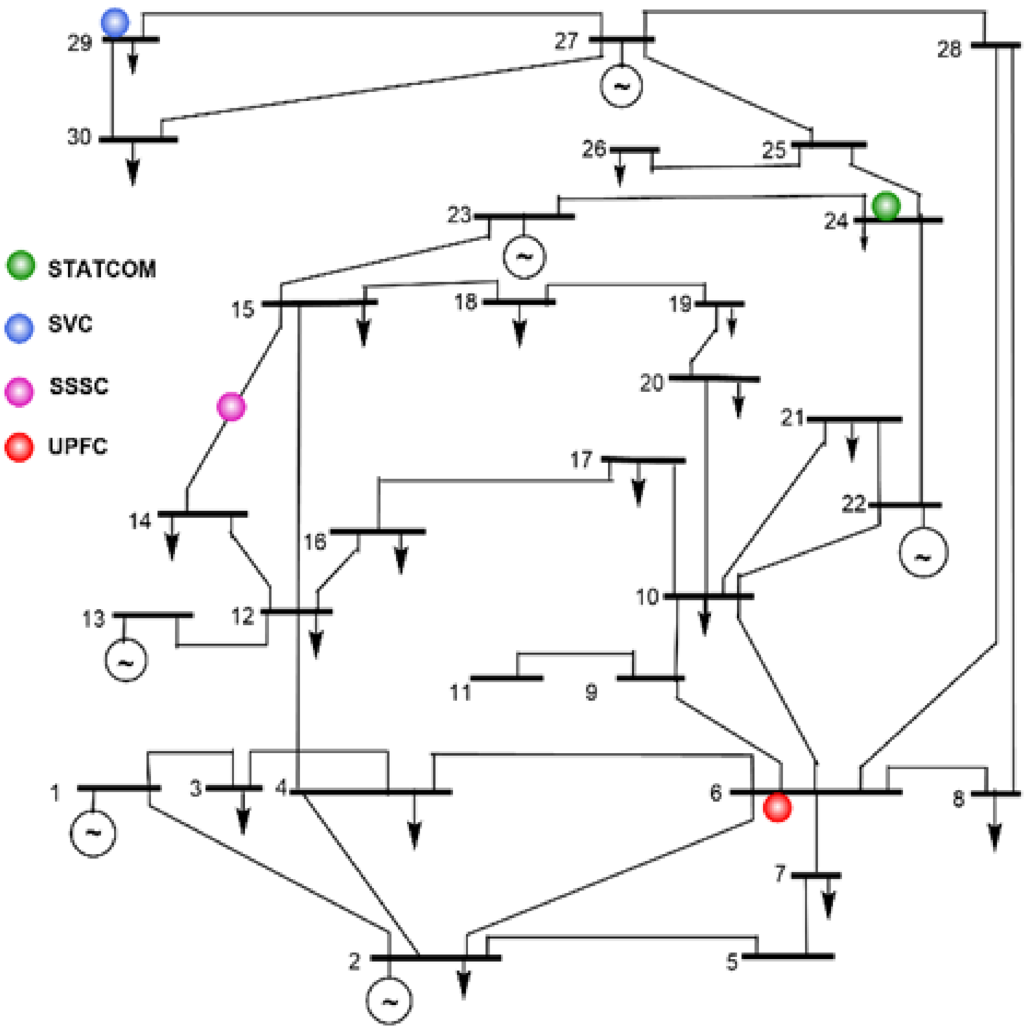

Figure 7a. General structure of the proposed model.

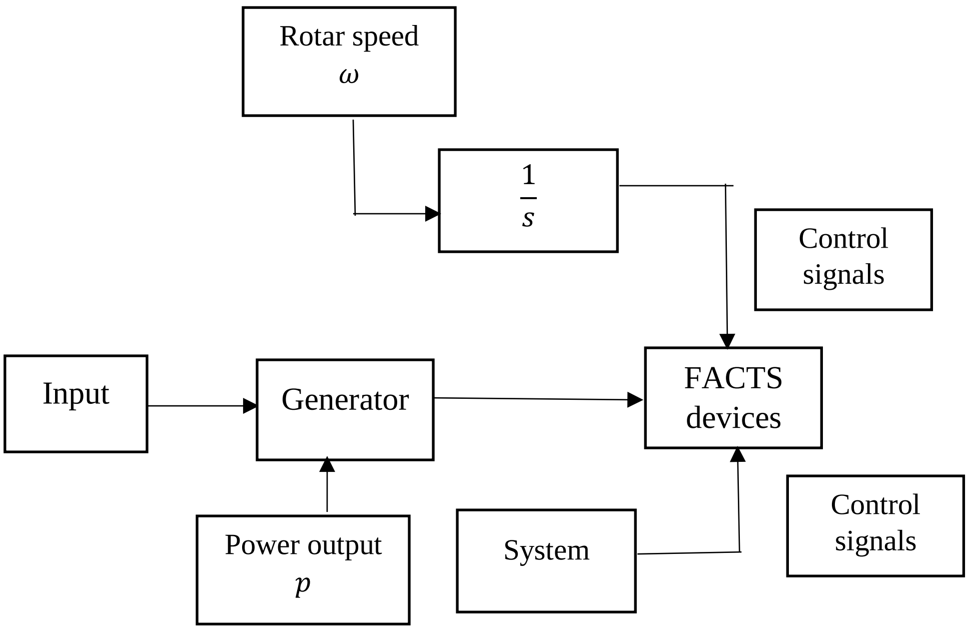

Figure 7b. Dynamic block diagram of the IEEE 30-bus system showing rotor speed (ω), rotor angle (δ), and FACTS control signals.

SVCs are placed in this operation to change the total reactive power supply through the buses. UPFCs are used to boost current and expand the capacity of transmission lines' power flow. STATCOM is used to tame oscillations and stabilize voltages. Here, SSSC are employed to alter the line's obstruction, which controls the actual power flow in the grid lines. To prevent transmission line overloading, FACTS installed poor buses and lines. This is primarily because they may change the total reactive current flow in these lines. The structure of the IEEE 30 bus with FACTS controllers is displayed in Figure 7a.

The proposed bus system has 41 transmission lines and 6 generators. The IEEE 30 bus branch 15 is an appropriate site for the SSSC placement based on the Lmn sensitivity index. Additionally, with the FVSI, buses 26 and 29 exhibit greater voltage changes with increasing loads, and bus 29 represents the location where the SVC is positioned. As a result, these buses are weak. The VSF detects changes in the voltage level in the IEEE-30 bus lines, and STATCOM is attached to bus 24 as a result. UPFCs are linked at bus 6 to manage the voltage magnitude and corresponding angles, as lines 4, 7, and 9 in the IEEE-30 bus carry more active power and are interconnected through buses 6-8, 4-5, and 6-7.

Figure 7b shows a simplified dynamic block representation of the studied IEEE 30-bus system, indicating the key system states monitored during simulation: rotor speed (ω), rotor angle (δ), power output (P), and control signals applied by various FACTS devices. These states are the basis for performance evaluation in Table 7 and are also reflected in Figure 7b, which plot variations in rotor speed and rotor angle under different operating conditions. Including this diagram provides a clearer visual link between the modelled system and the output performance variables analysed.

4.2 Performance Indices

ISE - Measures the cumulative squared deviation of the output from the desired value, giving more weight to larger errors.

$$\mathrm{ISE} = \int_0^{\infty} e^2(t)dt \tag{5}$$

It penalizes large errors more heavily, focusing on minimizing significant deviations.

ITSE -Similar to ISE but multiplies the error by time, penalizing errors that persist longer.

$$\mathrm{ITSE} = \int_0^{\infty} t \cdot e^2(t)dt \tag{6}$$

It emphasizes errors that persist over time, penalizing long-duration errors more heavily.

IAE - Calculates the total magnitude of the error over time, treating all deviations equally regardless of sign.

$$\mathrm{IAE} = \int_0^{\infty} |e(t)|dt \tag{7}$$

It provides a measure of total accumulated error, useful for assessing overall performance. **ITAE -** Similar to IAE but multiplies the error by time, penalizing sustained errors more heavily.

$$\mathrm{ITAE} = \int_0^{\infty} t \cdot |e(t)|dt \tag{8}$$

It focuses on reducing errors that persist over time, improving long-term stability. **LMN-** Represents the smallest number of system elements, samples, or nodes needed to meet a specified performance requirement.

$$Lmn = \frac{4\times(Q_r\times X)+(V_r\times V_s\times\sin(\delta_1-\delta_2))}{V_S^2} \tag{9}$$

It measures line stability, with values close to 1 indicating proximity to instability.

FVSI - A scalar metric used to assess the proximity of a power system to voltage collapse based on bus voltage and line parameters.

$$FVSI = \frac{4ZQ_r}{V_S^2\cos(\delta_1-\delta_2)} \tag{10}$$

It indicates voltage stability, with values near 1 showing the line is close to instability.

VSF - Indicates how close a power system is to its voltage stability limit, with lower values implying higher stability margins.

$$VSF = \frac{\partial V}{\partial Q} \tag{11}$$

It indicates the voltage control stability, with high values suggesting bus fragility and potential instability.

4.3 Facts Controller's Parameters

Selecting suitable parameter values is critical to improve the stability of the power system and minimizing fluctuations. In this context, the ACO algorithm plays a crucial part in fine-tuning the parameters of FACTS controllers to achieve optimal dynamic response. The initial parameter settings for the FACTS controllers were selected based on established modelling standards and previous studies [26–28, 30–32], and were subsequently optimized using the ACO algorithm to improve performance. The following tables present the original and ACO-tuned parameter values for each FACTS device. The UPFC controller parameter values are shown in table 3. The initial configuration of an SSSC controller is presented in Table 4, along with the parameters adjusted using the ACO method.

The initial parameters of the STATCOM controller and the parameters tuned using the Ant Colony Optimisation (ACO) technique are presented in Table 5.

Table 3. UPFC controller parameter values([28], [31])

Parameter Description	Original Value (Base)	FACTS Only	FACTS with ACO
Voltage Setpoint (Bus 6)	0.95 p.u.	0.96 p.u.	0.98 p.u.
Reactive Power Setpoint	0 MVAr	20 MVAr	30 MVAr
Voltage Control Gain	0.2	0.22	0.25
Reactive Power Control Gain	0.7	0.68	0.65
Voltage Deadband	0.02	0.018	0.015
Output Voltage Limit	±1.1	±1.08 p.u.	±1.05 p.u.
Damping Factor	0.05	0.055	0.06
Time Delay	0.1 sec	0.09 sec	0.08 sec

Table 4. SSSC controller parameter values([30], [32])

Parameter Description	Original Value (Base)	FACTS Only	FACTS with ACO
Series Compensation Factor	0.5	0.52	0.55
Series Reactance	0.1	0.09	0.08
Voltage Source Magnitude	0.8	0.82	0.85
Voltage Source Frequency	60 Hz	59.9 Hz	59.8 Hz
Phase Angle Compensation	0 degrees	0.5 degrees	1 degree
Damping Factor	0.1	0.11	0.12
Control Gain	0.6	0.58	0.55
Compensation Capacity (MVA)	50 MVA	52 MVA	55 MVA

Table 5. STATCOM controller parameter values([27], [31])

Parameter Description	Original Value (Base)	FACTS Only	FACTS with ACO
Voltage Setpoint (Bus 24)	0.95 p.u.	0.96 p.u.	0.98 p.u.
Reactive Power Setpoint	0 MVAr	5 MVAr	10 MVAr
Voltage Control Gain	0.2	0.22	0.25
Reactive Power Control Gain	0.8	0.75	0.7
Voltage Deadband	0.02	0.018	0.015
Output Voltage Limit	±1.2	±1.15 p.u.	±1.1 p.u.
Ramp Rate	5 MVAr/min	6.5 MVAr/min	8 MVAr/min
Damping Factor	0.05	0.06	0.07

Table 6. SVC controller parameter values([26], [31])

Parameter Description	Original Value (Base)	FACTS Only	FACTS with ACO
Voltage Setpoint (Bus 29)	0.95 p.u.	0.96 p.u.	0.98 p.u.
Reactive Power Setpoint	0 MVAr	15 MVAr	30 MVAr
Voltage Control Gain	0.2	0.22	0.25
Reactive Power Control Gain	0.7	0.68	0.65
Voltage Deadband	0.02	0.018	0.015
Output Voltage Limit	±1.1	±1.08	±1.05
Damping Factor	0.05	0.055	0.06
Time Delay	0.1 sec	0.09 sec	0.08 sec

The ACO method was employed to fine-tune the SVC controller's initial settings, as shown in Table 6.

These optimized parameter values, obtained via ACO, result in significantly improved damping performance, which is discussed in detail in the following results section.

4.4 Results in Various Loading Conditions

Examining the impact of the difference in loading situations on the system's efficiency is important, as the operational load is always changing. The various states of the power system, including variations in both speed and angle, as well as rotor angle, were employed with the default system, with FACTS devices, and with FACTS devices in conjunction with the ACO system. For comparison, three distinct situations were considered, including normal, lighter, and heavy loading conditions.

4.4.1 Results from Simulation under Normal Operating Conditions

To determine the efficacy of the ACO-based FACTS controllers in comparison to the base case system, a simulation was conducted under typical loading conditions.

According to the data displayed further down, the oscillations for the base system are unable to damper the oscillation. The power system states under typical operational conditions are shown in Table 7.

The speed variations exhibited with the basic case, FACTS only, and FACTS along with ACO are shown in Figure 8a above under typical operating conditions. For the FACTS-only and ACO-based FACTS, respectively, the high overshoot ranges from 0.09 to 7.25%, and the time of settling from 47.25 to 81.56% due to little generator oscillation. The system's rotor angle deviation under typical operating conditions is shown in Figure 8b.

The angle of the rotor variation in the initial situation oscillates and requires a lengthy period to improve the stability of the power system, but it dampens the LFO since the FACTS controllers are coordinated with the ACO. The system becomes unstable when a power change affects the power, or an angle change causes angle variations.

Table 7. States of a system under normal functioning conditions

Power system states	Overshooting			Time of settling (s)		
	Base Case	FACTS only	FACTS with ACO	Base Case	FACTS only	FACTS with ACO
$\Delta\omega$	0.0185	0.0181	0.0155	25	9.2	3.12
$\Delta\delta$	-2.014	-2.016	-1.83	25	11.15	2.98
δ	2.32	2.11	1.97	14	4.27	2.45

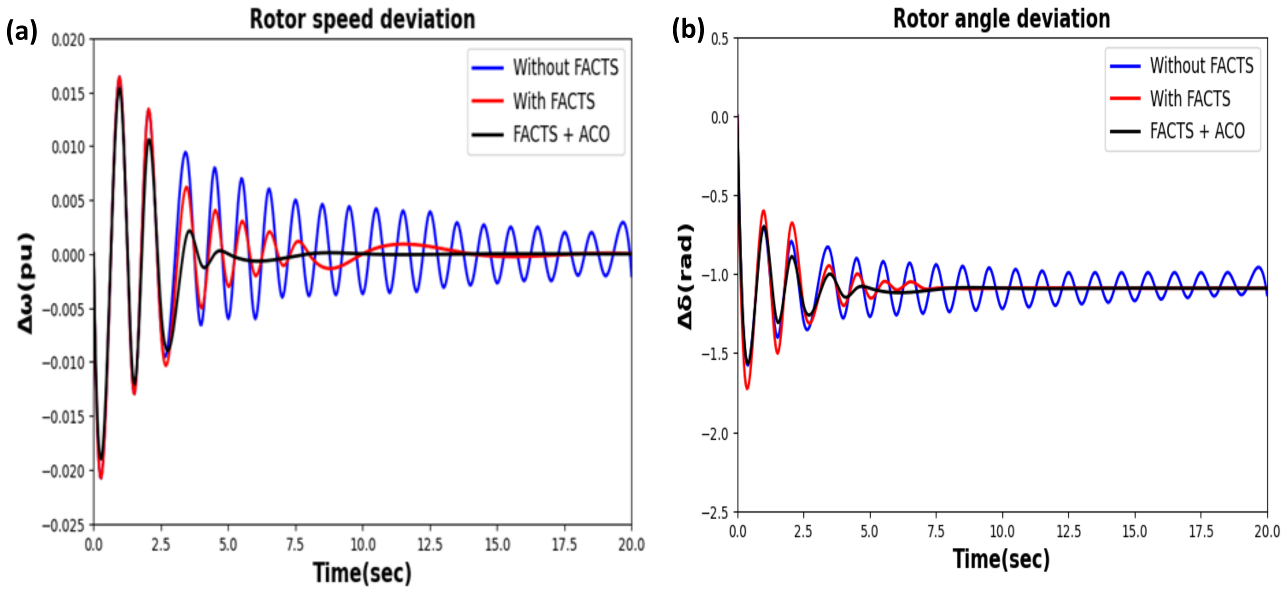

Figure 8. Comparative simulation results under normal loading. (a) Rotor speed variation (b) Rotor angle deviation (Source: Authors, MATLAB simulation output)

The angle of the rotor for the basic case and the ACO with the FACTS based on typical loads is shown in Figure 8. The greatest overshoot for the FACTS and the FACTS-ACO was 0.15 and 13.75%, respectively, while the settling times were 62.83 and 88.39%. In contrast to the default case, ACO-based FACTS controllers can successfully enhance the process when a disturbance occurs in the system.

4.4.2 Results from Simulation under Heavy Operating Conditions

To cause a disturbance in heavy operational circumstances, the planned ACO with FACTS controllers at an incremental, quick load was selected. Table 8 displays the state of the device under demanding operating conditions.

According to Figure 9a, the overshoot for the first case, FACTS, and ACO-based FACTS, respectively, is 0.0175, 0.0171, and 0.0153pu, and the time of settling is 25, 9.4, and 3.54 s due to minimal generator disturbance. Therefore, compared to the first case and without ACO in demanding loading conditions, the rotor speed variation of the ACO-based FACTS controllers substantially enhances power system stability. The system's angle deviation oscillates in the base case, but when ACO-based FACTS controllers are applied, the oscillations are reduced and a steady state is reached. As a result, adopting ACO-based FACTS damping controllers efficiently increases power system stability. The device achieves a steady state when a variation in the angle of the rotor is subjected to an Impair negatively. The rotor angle deviation for the basic case and the FACTS controllers when the ACO is heavily loaded is shown in Figure 9b.

The device obtains inter-area oscillation depending on the angle stability. After gaining a maximum value, then starts to decline as the machine returns to its usual value. The settling time for using FACTS is 65.3%, and the settling time for FACTS based on the ACO is 87.2%.

4.4.3 Results from Simulation under Lighter Operating Conditions

A disturbance is thought to occur when the load changes quickly. The overshoot and settling time under lighter operation conditions are illustrated in Table 9.

Table 8. Power system conditions under heavy loading

Power system states	Overshoot			Time of Settling (s)		
	Base Case	FACTS only	FACTS with ACO	Base Case	FACTS only	FACTS with ACO
$\Delta\omega$	0.0175	0.0171	0.0153	25	9.4	3.54
$\Delta\delta$	-2.06	-2.01	-1.76	25	10.7	2.86
δ	2.27	2.5	1.92	10.3	4.19	2.32

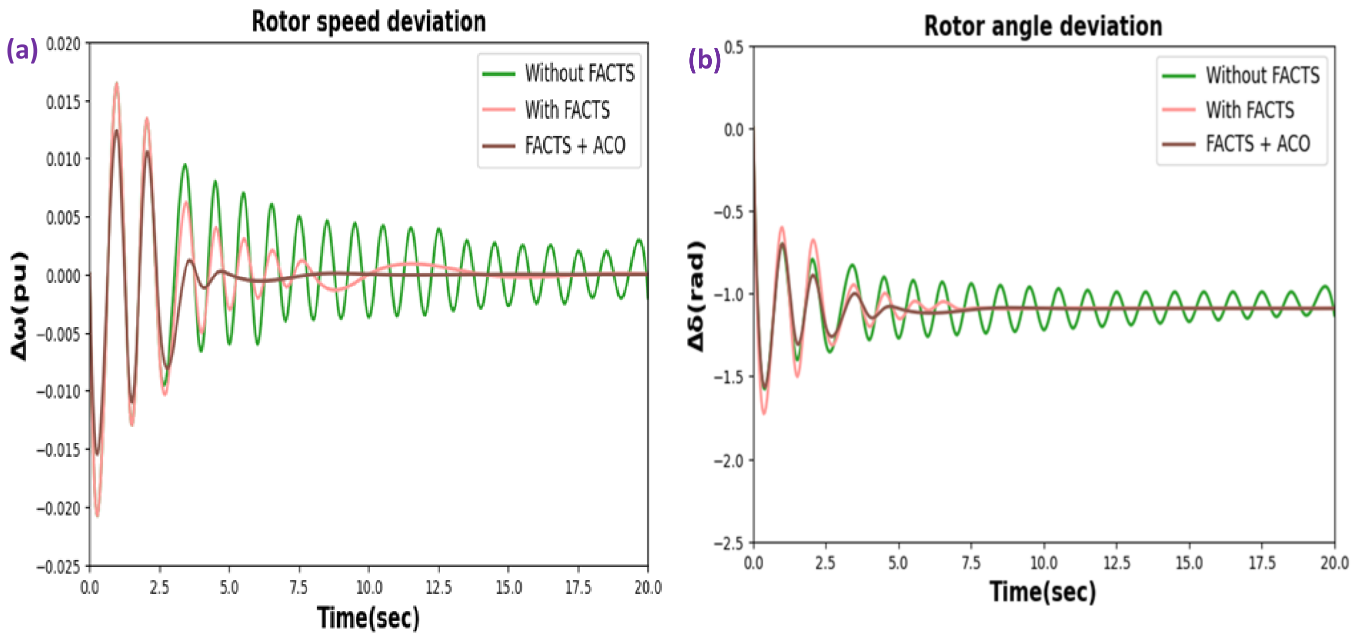

Figure 9. Comparative simulation results under heavy loading conditions. (a) Rotor speed variation (b) Rotor angle deviation (Source: Authors, MATLAB simulation output)

The numerical results presented in Tables 7 to 9 clearly demonstrate the efficiency of the proposed ACO-optimized FACTS controller strategy. As an instance, under normal loading conditions, the ITAE value was reduced from 1.215 (base case) to 0.473 with FACTS+ACO, reflecting a 61% improvement, which indicates significantly faster damping of oscillations over time. Similarly, ISE decreased from 0.765 to 0.301, representing a 60.65% reduction, which highlights improved control accuracy with minimized deviations.

Under heavy loading, ITSE dropped from 3.951 (base) to 1.501 (FACTS+ACO), representing an approximate 62% enhancement in dynamic stability. Meanwhile, the IAE improved by over 58%, indicating an overall smoother response curve with fewer prolonged errors. In light loading scenarios, the pattern remains consistent, with all four indices ISE, ITSE, IAE, and ITAE showing notable reductions of over 55–65% when comparing FACTS+ACO to the base case and FACTS-only configurations. These numerical improvements validate the superior damping performance and responsiveness of the proposed optimization approach over conventional methods.

The speed of high overshoot variations from 0.0169, 0.0166, and 0.0144 then a time of settling is 25, 9.45, and 3.16 s for the first case, FACTS only, and FACTS-ACO, respectively, in Figure 10a, which is caused by the generator's disturbance. Compared to the default situation and the FACTS-only system, the speed variation of the suggested system generally exhibits enhanced damping. The device is not stable when the deviation on the rotor angle is exposed to an angle change since performing so also exposes the current power supply to a variation in power, even when the angle the device obtains its typical value. The rotor angles for the basic case and the FACTS controllers with the ACO are shown in Figure 10b under mild loading circumstances.

The angle of the rotor is about 2.09, 2.01, and 1.87 with the default case, FACTS only, and FACTS plus ACO, accordingly. In general, the suggested system exhibits improved damping behaviour under mild loading situations to enhance the steadiness of the power system. In general, the gain in system stability is reduced by a longer settling period. As a consequence, the simulation results indicate the damping controllers may be fine-tuned to show their superiority over the base case system's insufficient sizing.

Table 9. States of the system under lighter operation

Power system states	Overshoot			Time of settling (s)		
	Base Case	**FACTS only**	**FACTS with ACO**	**Base Case**	**FACTS only**	**FACTS with ACO**
$\Delta\omega$	0.0169	0.0166	0.0144	25	9.45	3.16
$\Delta\delta$	-2.01	-1.95	-1.62	25	7.07	3.02
δ	2.09	2.01	1.87	9.36	3.59	2.16

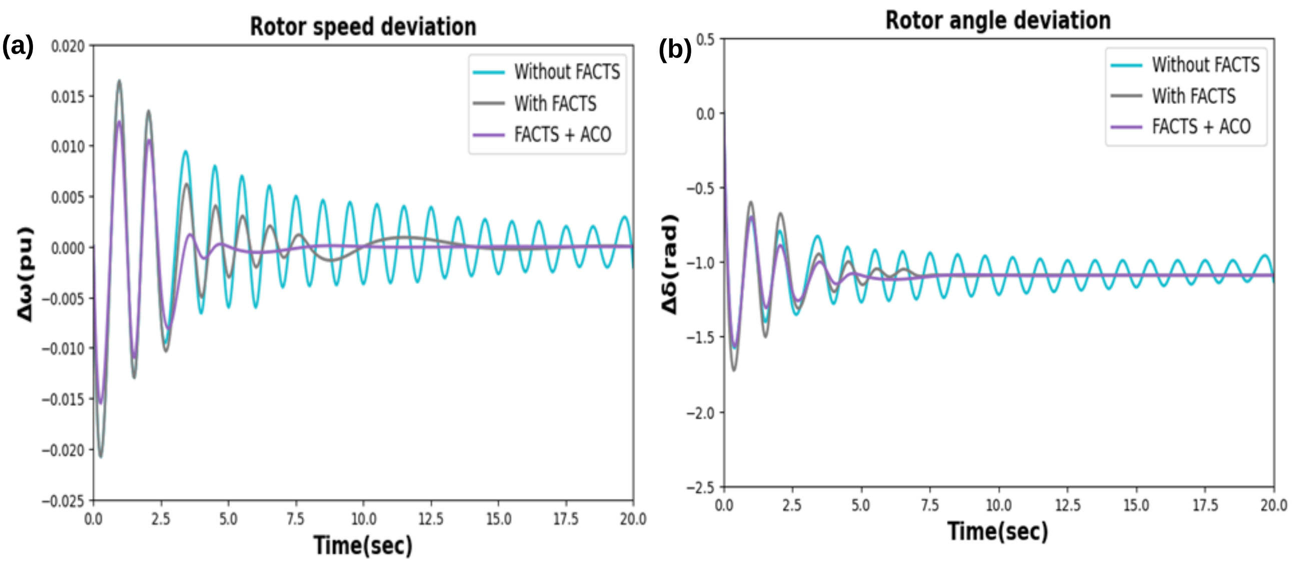

Figure 10. Comparative simulation results under light loading conditions. (a) Rotor speed variation (b) Rotor angle deviation (Source: Authors, MATLAB simulation output)

Table 10. Total losses for 30 bus system

Power type	Without FACTS controllers	With FACTS controllers	FACTS with ACO
Total Real Power Loss (p.u)	0.1457	0.1195	0.0624
Total Reactive Power Loss (p.u)	0.2578	0.2356	0.1132

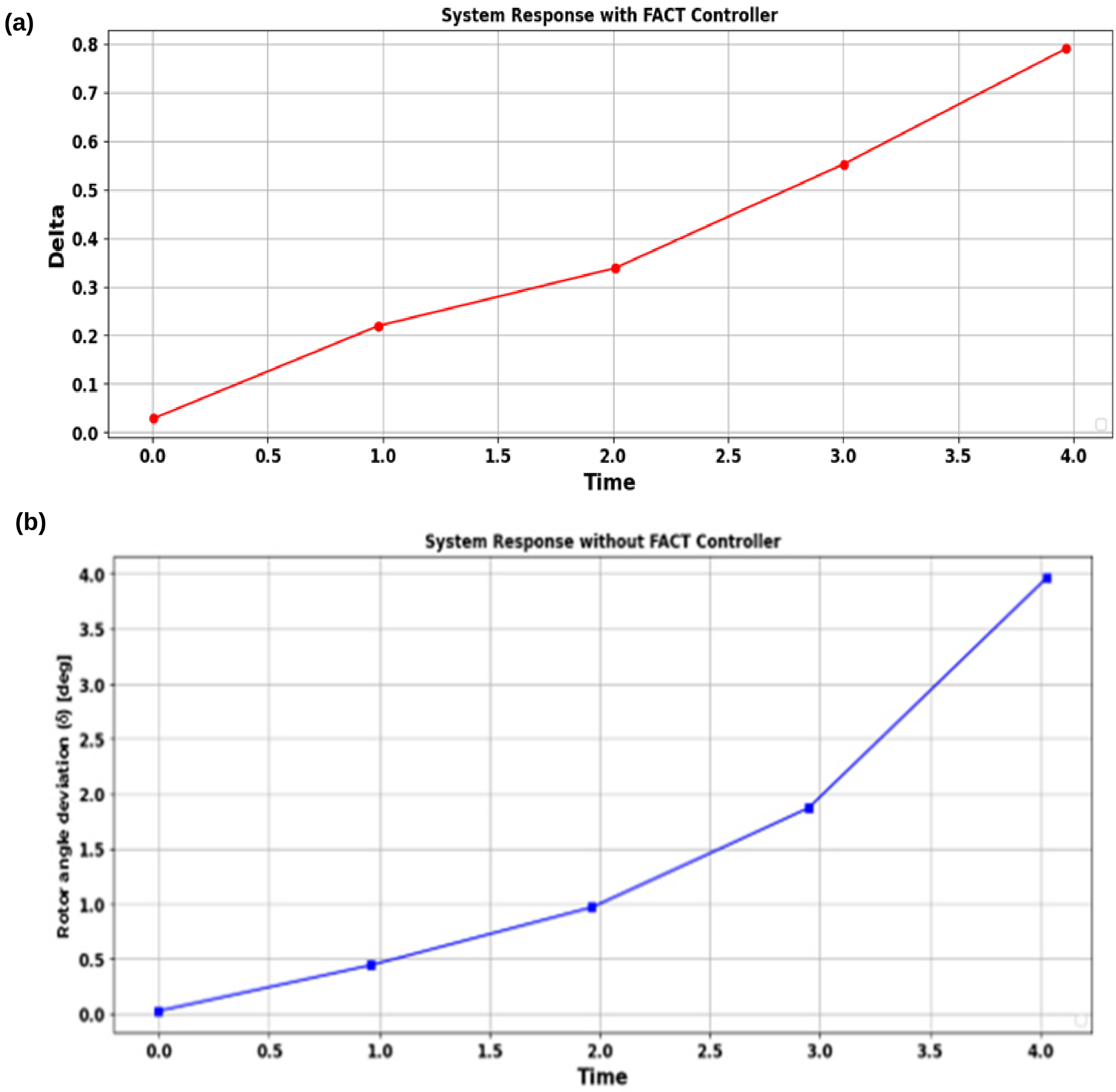

Figure 11. Performance comparison with and without FACTS controllers **(a)** Without FACTS controller **(b)** With FACTS controller (Source: Authors, MATLAB simulation output)

Table 10 illustrates the overall actual and reactive power loss with and without FACTS controllers for ACO-based systems. Less power loss is achieved using the proposed approach. With and without FACTS controllers are compared in Figure 11a, where the FACTS controllers deliver the best outcomes and the most effective system responses. Rotor speed variation can significantly affect damping oscillations, as shown in Figure 11b, where the rotor speed deviation is compared with and without FACTS controllers. Rotor speed is highly managed by the FACTS controllers, which also reduces deviations.

Figure 12 displays the significance of the proposed approach. When a disturbance occurs, the system experiences sudden fluctuations in load and generator. To prevent instability caused by these oscillations, the suggested system combines an effective ACO algorithm with FACTS controllers before regulating the rotor speed, as shown in Figures 12a and 12b.

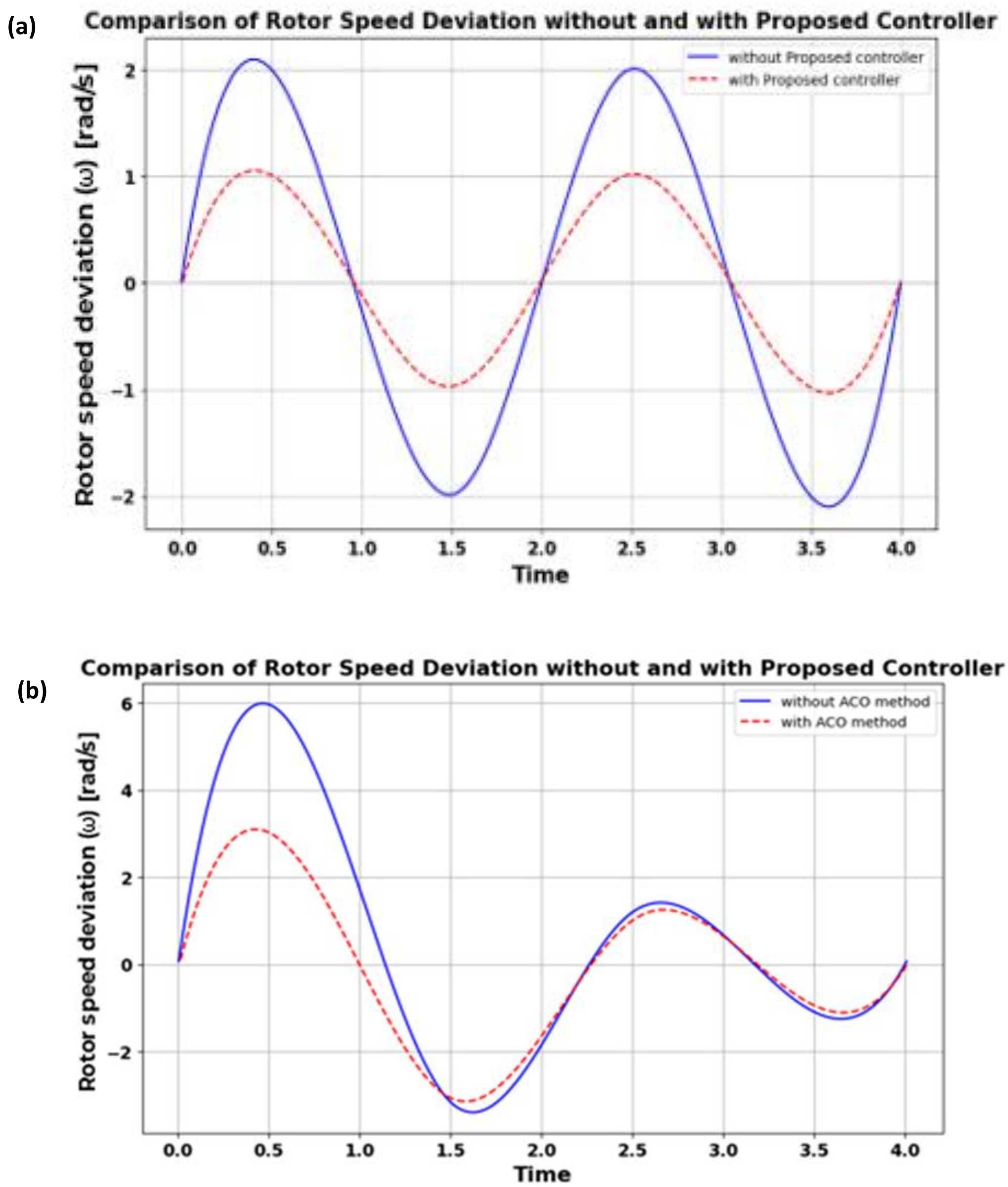

Figure 12. System response comparison with FACTS-only vs. ACO-optimized FACTS controllers **(a)** With FACTS controller **(b)** With ACO-optimized FACTS controller (Source: Authors, MATLAB simulation output)

The system's reaction to an external disturbance will differ depending on the kind, dynamics, and nature of the disturbance. In general, when an external disturbance occurs, a system may exhibit transient behaviour before entering a new steady state or exhibiting oscillatory activity. Application of the system's reaction to an external perturbation at 0.5 s;

The dynamic power system stability is enhanced by the optimum synchronization of four FACTS controllers, like SVC, STATCOM, SSSC, and UPFC, utilizing the ACO method. By comparing the damping ratio, rotor angle, and time of settling outcomes of the recommended ACO technique with a default case system and ACO-based FACTS controllers under various loading scenarios (as shown in Figure 13), this section assesses the efficacy of the methodology. This result illustrates that the proposed approach is successful in decreasing and improving the dynamic steadiness of power networks.

4.5 Discussion

The simulation results presented in Section 4 demonstrate the effectiveness of ACO-optimized coordination of FACTS devices, such as SVC, STATCOM, SSSC, and UPFC, in damping LFOs under various loading conditions. In the “FACTS only” configuration, these devices enhance system stability by injecting or absorbing reactive power, adjusting voltage levels and impedance, and providing voltage support during disturbances. The modification for reactive power mitigates the LFOs and enhances the voltage regulation. Nevertheless, in the “FACTS with ACO” configuration, the ACO algorithm is used to fine-tune control parameters adaptively.

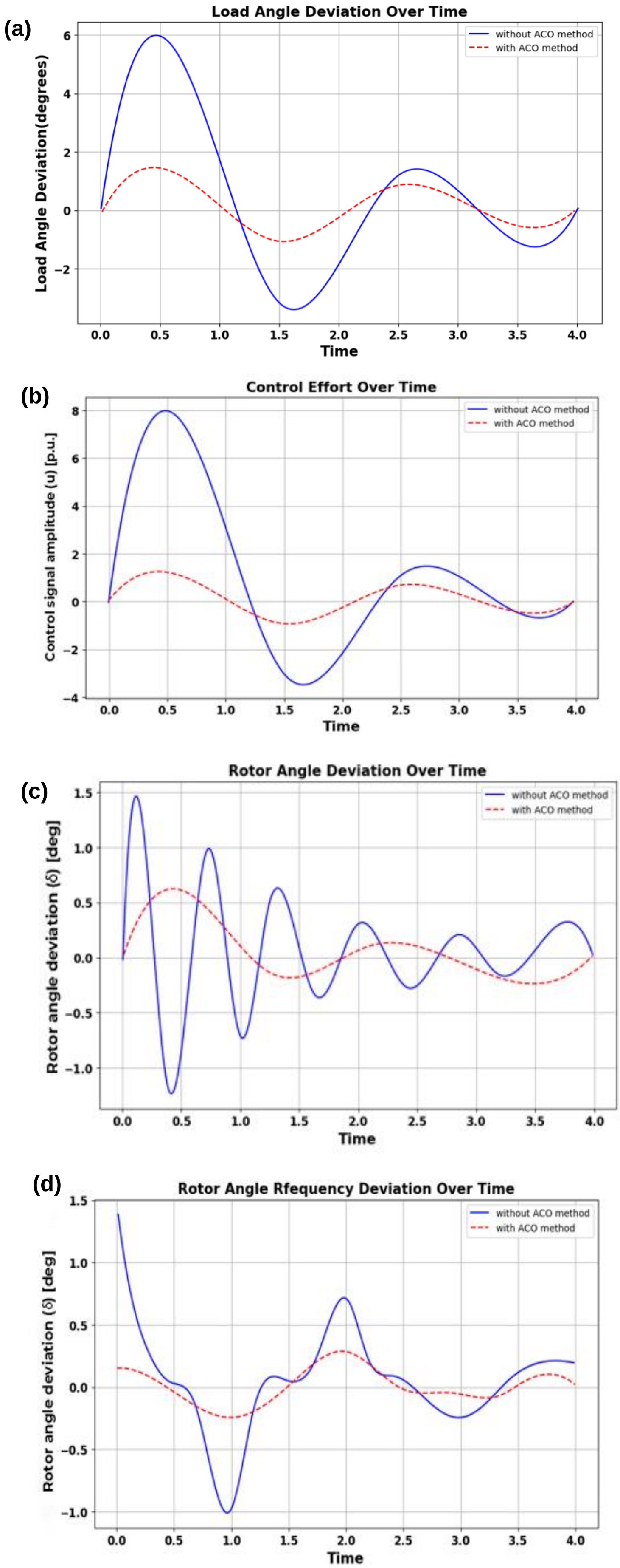

Figure 13. Comparative system responses with ACO-optimized FACTS controllers (a) Rotor angle change (b) Control effort over time (c) Rotor angle deviation (d) Rotor angular frequency variation (Source: Authors, MATLAB simulation output)

Table 11. Comparative analysis of the proposed model

Index	PSO	GA	GOA	WOA	Proposed ACO
ISE	12.5	13.75	11.9	12.1	**10.25**
ITSE	6.4	7.3	5.8	6	**4.53**
IAE	10.85	11.6	9.95	10.2	**8.95**
ITAE	5.7	6.5	4.9	5.1	**3.87**
Lmn	0.62	0.68	0.57	0.6	**0.45**
FVSI	0.67	0.72	0.62	0.65	**0.5**
VSF	0.5	0.55	0.45	0.48	**0.3**

ACO dynamically adjusts controller gains in response to system feedback, allowing real-time adaptation to varying load and disturbance conditions. This results in faster settling times, reduced overshoot, and significantly lower real/reactive power losses. To validate the proposed strategy, a detailed comparative analysis was performed using established optimization techniques like PSO, GA, WOA, and GOA. As shown in Table 11, the ACO-based approach consistently outperformed all others across performance indices, ISE, ITSE, IAE, ITAE, Lmn, FVSI, and VSF.

For instance, the ITAE was reduced by 22% compared to PSO [13] and 18% compared to a hybrid DE-PSO model for SSSC [14]. Compared to the hybrid UPFC model in [13], the proposed model exhibited faster damping and improved stability. Unlike [15] and [21], which applied hybrid metaheuristics like CPSO and HCSC-PS, our approach balances optimization accuracy with computational simplicity. While [16] focused on UPFC-based damping alone, our multi-controller configuration proved more robust under diverse scenarios. Moreover, ACO demonstrated competitive or superior performance to recent techniques such as ISSA [22] and chaotic PSO [21], showing faster convergence and improved system stability even under severe disturbances. The overall improvement across all loading conditions ranged between 20% and 35%, highlighting the robustness and efficiency of the proposed method. In summary, the coordinated ACO-FACTS framework provides a powerful, adaptive damping solution with clear advantages in dynamic performance, convergence efficiency, and practical feasibility. These results underscore its potential for integration into smart grids and renewable-rich power systems requiring rapid real-time control under varying operating conditions.

5. Conclusion

This study proposed a coordinated damping strategy incorporating four key FACTS devices like SVC, STATCOM, SSSC, and UPFC, whose control parameters were optimized using the ACO algorithm. The goal was to improve the damping of LFOs in interconnected AC power systems. Simulation results for the IEEE 30-bus system under various loading conditions demonstrated that the ACO-optimized controllers significantly improved system stability, reducing oscillations, overshoot, and settling time compared to base and non-optimized models. These results validate the effectiveness of coordinated FACTS controllers in enhancing dynamic performance and robustness under disturbances. Despite these promising outcomes, the study has some limitations. Only the IEEE 30-bus system was analyzed, and MATLAB/Simulink simulation-based modeling was used. Real-time validations, including Hardware-in-the-Loop (HIL) implementations, were not performed, which limits practical applicability. Additionally, the convergence behavior of the ACO algorithm is sensitive to control parameters (e.g., α, β, and ρ), which may need dynamic tuning based on system scale and topology.

In future work, the proposed approach will be expanded to elaborate and massive networks, including IEEE 57-bus or 118-bus systems, to assess scalability. Hybrid optimization techniques (e.g., ACO-PSO, ACO-GA) will also be explored to improve convergence speed and solution accuracy. Furthermore, real-time validation using digital simulators like OPAL-RT will be considered. This approach can be integrated into real-world smart grids and renewable-rich systems to improve dynamic response and resilience during operational disturbances.

Abbreviations

Symbol / Abbreviation	Description
ACO	Ant Colony Optimization
DD	Derivative Delay
FACTS	Flexible AC Transmission System
FVSI	Fast Voltage Stability Index
GA	Genetic Algorithm
GWO	Grey Wolf Optimizer
IAE	Integral of Absolute Error
ISE	Integral of Squared Error
ITAE	Integral of Time Absolute Error
ITSE	Integral of Time Squared Error
K_p	Proportional gain
K_i	Integral gain
K_d	Derivative gain

Lmn	Line Margin Index
MVAr	Megavolt-Ampere Reactive (MVAr)
PSS	Power System Stabilizer
PSO	Particle Swarm Optimization
Q	Reactive Power (MVAr)
SSSC	Static Synchronous Series Compensator
STATCOM	Static Synchronous Compensator
SVC	Static VAR Compensator
UPFC	Unified Power Flow Controller
VSF	Voltage Stability Factor
V_{ref}	Reference voltage (p.u.)
V_t	Terminal voltage (p.u.)
w_1, w_2, w_3, w_4	Weights for fitness function components (ISE, ITSE, IAE, ITAE)
α, β	ACO parameters: influence of pheromone and heuristic information
ρ	Evaporation rate in ACO
τ	Pheromone intensity

References

[1] R. Devarapalli, B. Bhattacharyya, N.K. Sinha, B. Dey, Amended GWO approach based on multi-machine power system stability enhancement. ISA transactions, 109, (2021) 152-174. https://doi.org/10.1016/j.isatra.2020.09.016

[2] X. Mei, S. Zhou, Z. Yang, T. Kaizuka, K. Nakano, Enhancing energy harvesting in low-frequency rotational motion by a quad-stable energy harvester with time-varying potential wells. Mechanical Systems and Signal Processing, 148, (2021)107167. https://doi.org/10.1016/j.ymssp.2020.107167

[3] M. Edrah, X. Zhao, W. Hung, P. Qi, B. Marshall, S. Baloch, A. Karcanias, Electromechanical interactions of full scale converter wind turbine with power oscillation damping and inertia control, International Journal of Electrical Power & Energy Systems, 135, (2022) 107522. https://doi.org/10.1016/j.ijepes.2021.107522

[4] J.Shair, X. Xie, H.Li, W.Zhao, W.Liu, A grid-side multi-modal adaptive damping control of super-/sub-synchronous oscillations in type-4 wind farms connected to weak AC grid. Electric Power Systems Research, 215, (2023) 108963. https://doi.org/10.1016/j.epsr.2022.108963

[5] E.S. Bayu, B.Khan, Z. M. Ali, Z.M. Alaas, O.P. Mahela, Mitigation of low-frequency oscillation in power systems through optimal design of power system stabilizer employing ALO. Energies, 15(10), (2022) 3809. https://doi.org/10.3390/en15103809

[6] M. Darabian, A. Bagheri, Design of adaptive wide-area damping controller based on delay scheduling for improving small-signal oscillations, International Journal of Electrical Power & Energy Systems, 133, (2021) 107224. https://doi.org/10.1016/j.ijepes.2021.107224

[7] B. Shao, Q. Xiao, X. Meng, P. Han, W. Ma, Z. Miao, Z. Chen, Medium-frequency and sub-synchronous oscillation analysis of direct-drive wind farms connected to the parallel-compensated AC grid. Electric Power Systems Research, 216, (2023) 109061. https://doi.org/10.1016/j.epsr.2022.109061

[8] K.M. Sreedivya, P.A. Jeyanthy, D. Devaraj, Improved design of interval type-2 fuzzy based wide area power system stabilizer for inter-area oscillation damping, Microprocessors and Microsystems. 83, (2021) 103957. https://doi.org/10.1016/j.micpro.2021.103957

[9] S. Ghaedi, S. Abazari, G. A. Markadeh, Transient stability improvement of power system with UPFC control by using transient energy function and sliding mode observer based on locally measurable information. Measurement, 183, (2021) 109842. https://doi.org/10.1016/j.measurement.2021.109842

[10] A. W. Khawaja, N.A.M. Kamari, M.A.A.M. Zainuri, Design of a damping controller using the sca optimization technique for the improvement of small signal stability of a single machine connected to an infinite bus system. Energies, 14(11), (2021) 2996. https://doi.org/10.3390/en14112996

[11] S. Behzadpoor, I.F. Davoudkhani, A.Y. Abdelaziz, Z.W. Geem, J. Hong, Power System Stability Enhancement Using Robust FACTS-Based Stabilizer Designed by a Hybrid Optimization Algorithm. Energies, 15(22), (2022) 8754. https://doi.org/10.3390/en15228754

[12] J.P. Therattil, J. Jose, P.R.N. Prasannakumari, A.G. Abo-khalil, A.S. Alghamdi, B.G. Rajalekshmi, K. Sayed, Hybrid control of a multi-area multi-machine power system with FACTS devices using non-linear modelling. IET Generation, Transmission & Distribution, 14(10), (2020) 1993-2003. https://doi.org/10.1049/iet-gtd.2019.1165

[13] M.I.H. Pathan, M.J. Rana, M.S. Shahriar, M. Shafiullah, M.H. Zahir, A. Ali, Real-time LFO damping enhancement in electric networks employing PSO optimized ANFIS. Inventions, 5(4), (2020) 61. https://doi.org/10.3390/inventions5040061

[14] S. Behera, A.K. Barisal, N. Dhal, D.K. Lal, Mitigation of power oscillations using hybrid DE-PSO optimization-based SSSC damping controller. Journal of Electrical Systems and Information Technology, 6(1), (2019) 1-17. https://doi.org/10.1186/s43067-019-0007-y

[15] M. Eslami, M. Neshat, S.A. Khalid, A novel hybrid sine cosine algorithm and pattern search for optimal coordination of power system damping controllers. Sustainability, 14(1), (2022) 541. https://doi.org/10.3390/su14010541

[16] E. Solomon, B.Khan, I. Boulkaibet, B. Neji, N.

Khezami, A. Ali, A. Pascual Barrera, E. Mitigating Low-Frequency Oscillations and Enhancing the Dynamic Stability of Power System Using Optimal Coordination of Power System Stabilizer and Unified Power Flow Controller. Sustainability, 15(8), (2023) 6980. https://doi.org/10.3390/su15086980

[17] M. Eslami, H. Shareef, A. Mohamed, M. Khajehzadeh, A survey on flexible AC transmission systems (FACTS), Organ, 1, (2012) 12.

[18] M. Eslami, H. Shareef, A. Mohamed, M. Khajehzadeh, (2011) Coordinated design of PSS and SVC damping controller using CPSO. International Power Engineering and Optimization Conference, IEEE, Malaysia. https://doi.org/10.1109/PEOCO.2011.5970394

[19] M. Eslami, H. Shareef, A. Mohamed, M. Khajehzadeh, (2011) Optimal location of PSS using improved PSO with chaotic sequence, In International Conference on Electrical, Control and Computer Engineering, IEEE, Malaysia. https://doi.org/10.1109/INECCE.2011.5953886

[20] M. Eslami, H. Shareef, A. Mohamed, M. Khajehzadeh, PSS and TCSC damping controller coordinated design-using GSA. Energy Procedia, 14, (2012) 763-769. https://doi.org/10.1016/j.egypro.2011.12.1008

[21] M. Eslami, H. Shareef, A. Mohamed, M. Khajehzadeh, Particle swarm optimization for simultaneous tuning of static var compensator and power system stabilizer. Przegląd Elektrotechniczny (Electrical Review), 87, (2011) 343-347.

[22] E. Akbari, M. Mollajafari, H.M.R. Al-Khafaji, H. Alkattan, M. Abotaleb, M. Eslami, S. Palani, Improved salp swarm optimization algorithm for damping controller design for multimachine power system. IEEE Access, 10, (2022) 82910-82922. https://doi.org/10.1109/ACCESS.2022.3196851

[23] V. Kumar, V. Sharma, A.P. Kumar, Y. Arya, S. Chikkam, A state-of-the-art review on concurrent voltage and frequency regulation problems in renewable integrated power networks. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 47(1), (2025) 16-49. https://doi.org/10.1080/15567036.2025.2462799

[24] A. Sharma, N. Singh. Enhancing multi-area microgrid stability with virtual damping and energy storage inertia techniques using hybrid lyrebird-Pattern search optimized PI-(1+ DD) controller. Journal of Energy Storage, 124, (2025) 116830. https://doi.org/10.1016/j.est.2025.116830

[25] J. Mahadevan, R. Rengaraj, A. Bhuvanesh, Application of multi-objective hybrid artificial bee colony with differential evolution algorithm for optimal placement of microprocessor-based FACTS controllers. Microprocessors and Microsystems, (2021) 104239. https://doi.org/10.1016/j.micpro.2021.104239

[26] P. Kotsampopoulos, P. Georgilakis, D.T. Lagos, V. Kleftakis, N. Hatziargyriou, Facts providing grid services: Applications and testing. Energies, 12(13), (2019) 2554. https://doi.org/10.3390/en12132554

[27] E. Naderi, M. Pourakbari-Kasmaei, H. Abdi, An efficient particle swarm optimization algorithm to solve optimal power flow problem integrated with FACTS devices. Applied Soft Computing, 80, (2019) 243-262. https://doi.org/10.1016/j.asoc.2019.04.012

[28] D. Khamari, R.K. Sahu, T.S. Gorripotu, S. Panda, Automatic generation control of power system in deregulated environment using hybrid TLBO and pattern search technique. Ain Shams Engineering Journal, 11(3), (2020) 553-573. https://doi.org/10.1016/j.asej.2019.10.012

[29] P.R. Sahu, P.K. Hota, S. Panda, Modified whale optimization algorithm for coordinated design of fuzzy lead-lag structure-based SSSC controller and power system stabilizer. International Transactions on Electrical Energy Systems, 29(4), (2019) e2797. https://doi.org/10.1002/etep.2797

[30] Y. Lee, H. Song, A reactive power compensation strategy for voltage stability challenges in the Korean power system with dynamic loads. Sustainability, 11(2), (2019) 326. https://doi.org/10.3390/su11020326

[31] M. Ćalasan, T. Konjić, K. Kecojević, L. Nikitović, Optimal allocation of static var compensators in electric power systems. Energies, 13(12), (2020) 3219. https://doi.org/10.3390/en13123219

[32] G. Zhang, W. Hu, D. Cao, J. Yi, Q. Huang, Z. Liu, F. Blaabjerg, A data-driven approach for designing STATCOM additional damping controller for wind farms. International Journal of Electrical Power & Energy Systems, 117, (2020) 105620. https://doi.org/10.1016/j.ijepes.2019.105620

[33] J.G. Jamnani, M. Pandya, Coordination of SVC and TCSC for management of power flow by particle swarm optimization. Energy Procedia, 156, (2019) 321-326. https://doi.org/10.1016/j.egypro.2018.11.149

[34] A. Movahedi, A.H. Niasar, G.B. Gharehpetian, Designing SSSC, TCSC, and STATCOM controllers using AVURPSO, GSA, and GA for transient stability improvement of a multi-machine power system with PV and wind farms. International Journal of Electrical Power & Energy Systems, 106, (2019) 455-466. https://doi.org/10.1016/j.ijepes.2018.10.019

Authors Contribution Statement

Chandan Kumar Sah: Conceptualization, Methodology, Investigation, Formal analysis, Writing - Original Draft. A.S. Kannan: Conceptualization, Formal analysis, Writing - Review & Editing. Both the authors read and approved the final version of the manuscript.

Funding

The authors declare that no funds, grants or any other support were received during the preparation of this manuscript.

Competing Interests

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

Data Availability

The data supporting the findings of this study can be obtained from the corresponding author upon reasonable request.

Has this article screened for similarity?

Yes