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PSO Algorithm based Static Synchronous Compensator for Enhancing Power System Stability

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Abstract

This study presents a comparative study on the enhancement of power system stability through the optimal tuning of a Static Synchronous Compensator (STATCOM) using Particle Swarm Optimization (PSO), Hybrid Artificial Bee Colony–Particle Swarm Optimization (HABC-PSO), and Honey Badger Optimization (HBO) algorithms. The primary objective is to improve transient stability and mitigate low-frequency and sub-synchronous oscillations in a multi-machine power system. A time-domain objective function is formulated based on critical system performance indices, including generator rotor speed deviation (Δω), rotor angle deviation (Δδ), and bus voltage deviation (ΔV). These indices are used to optimize the proportional-integral (PI) controller parameters of both AC and DC voltage regulators within the STATCOM. The performance evaluation is carried out using the standard Kundur two-area four-machine test system under various disturbance scenarios, such as three-phase faults and sudden load changes. Simulation results are obtained through MATLAB/Simulink and analyzed to assess the effectiveness of each optimization technique in damping inter-area oscillations and enhancing system dynamic response. Comparative analysis reveals that the PSO-based STATCOM significantly improves system damping and reduces settling time compared to the system without STATCOM. However, the PSO algorithm demonstrates superior performance in terms of convergence speed and overall stability enhancement. The HABC_PSO algorithm also shows competitive results. The findings confirm the efficacy of metaheuristic optimization algorithms in tuning FACTS device controllers and contribute to the development of reliable and adaptive strategies for power system stability enhancement in modern grids.

Keywords—*Particle Swarm Optimization (PSO), Static Synchronous Compensator (STATCOM), Transient Stability, Multi-Machine System, HABC-PSO, Honey Badger Optimization (HBO), Rotor Angle Deviation, Inter-Area Oscillation, Voltage Regulation, Metaheuristic Algorithms.*

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Chapter 1: Introduction

1.1 Overview

This thesis investigates the application of Particle Swarm Optimization (PSO) for the optimal tuning of a Static Synchronous Compensator (STATCOM) controller to enhance power system stability in a multi-machine environment [1]. The research is conducted using the standard Kundur two-area four-machine test system, focusing on minimizing rotor angle deviation, speed deviation, and bus voltage fluctuations during disturbances. The performance of the PSO-based approach is compared against Hybrid Artificial Bee Colony–Particle Swarm Optimization (HABC-PSO) and Honey Badger Optimization (HBO) algorithms under identical simulation conditions. The aim is to assess the efficiency, robustness, and damping capability of each algorithm when used for STATCOM controller optimization. In addition, the study evaluates the effectiveness of the optimized STATCOM in improving voltage stability, using indices such as L-index, Voltage Deviation Index (VDI), Voltage Collapse Proximity Index (VCPI), and Sensitivity Index [22]**.** Simulation results demonstrate that all three algorithms improve transient performance and inter-area oscillation damping, with each offering unique advantages in convergence speed, solution quality, and control robustness.

1.2 Power System Stability and Its Challenges

Power system stability refers to the ability of an electrical power system to maintain synchronous operation and return to steady-state conditions following a disturbance [2]. In large interconnected systems, disturbances such as faults, sudden load changes, or generator outages can induce low-frequency or inter-area oscillations, typically between 0.1–1 Hz, where groups of generators oscillate against each other. These oscillations, if not properly damped, can propagate across the network, causing voltage fluctuations, power quality issues, and even cascading failures or blackouts. As modern power systems become more complex and stressed with high penetration of renewable energy sources and decentralized generation, maintaining stability has become increasingly challenging. Therefore, advanced control devices like STATCOM, combined with intelligent optimization techniques, play a critical role in enhancing damping, mitigating low-frequency oscillations, and maintaining voltage security throughout the grid.

1.3 Role of STATCOM in Stability Enhancement

The Static Synchronous Compensator (STATCOM) is a shunt-connected Flexible AC Transmission System (FACTS) device that regulates voltage and improves reactive power compensation in real time [1]. Its fast response and voltage control capabilities make it highly effective in damping oscillations and improving both transient and steady-state stability. However, the performance of a STATCOM significantly depends on the tuning of its internal control parameters, specifically the proportional-integral (PI) gains of its AC and DC voltage regulators. Poorly tuned controllers can lead to underperformance or even instability, especially during large disturbances. Thus, optimal tuning is essential to unlock the full benefits of STATCOM in modern power systems.

1.4 Metaheuristic Algorithms for Controller Tunning

Traditional tuning methods such as trial-and-error, Ziegler-Nichols, or pole-placement often fail to yield optimal results in complex, nonlinear systems. Metaheuristic algorithms have emerged as powerful tools for solving complex optimization problems in control engineering. Among them, Particle Swarm Optimization (PSO) is known for its simplicity, efficiency, and strong global search capability [3]. Hybrid approaches like HABC-PSO combine the strengths of multiple algorithms to enhance convergence speed and escape local minima [4]. Newer algorithms such as Honey Badger Algorithm (HBA) offer novel exploration and exploitation strategies, showing promising results in various engineering applications [5]. These algorithms are particularly suitable for tuning nonlinear controllers like those used in STATCOM, where multiple performance indices must be optimized simultaneously.

1.5 Objectives of the study

The primary objectives of this research are:

- To design and implement a PSO-based STATCOM controller for enhancing power system damping and stability.
- To evaluate and compare the performance of PSO, HABC-PSO, and HBO algorithms for tuning STATCOM PI controllers.
- To analyze rotor speed deviation ($\Delta\omega$), rotor angle deviation ($\Delta\delta$), and bus voltage variation under transient conditions using the Kundur two-area four-machine system.

- To identify the algorithm that offers the best trade-off between computational efficiency, damping performance, and robustness in dynamic conditions.
- To contribute to the development of intelligent, adaptive control strategies for power system stability improvement using advanced optimization techniques.

1.6 Thesis Structure

Chapter 1: Introduction outlines the background, motivation, and significance of power system stability studies. It introduces STATCOM as a key FACTS device, highlights the role of metaheuristic algorithms in controller tuning, and presents the research objectives and scope.

Chapter 2: Literature Review critically reviews existing works on STATCOM applications, optimization algorithms, and stability enhancement methods. It identifies the research gap and establishes the novelty of using advanced metaheuristic approaches for controller tuning.

Chapter 3: Theoretical Analysis describes Kundur's two-area power system, including its modeling framework, generator and excitation system, and inter-area oscillation phenomena. The chapter also explains STATCOM operation, control strategy, and introduces four voltage stability indices (L-Index, VDI, VCPI, and Sensitivity Index) used for analysis.

Chapter 4: Optimization Algorithms presents the mathematical formulation of the objective function, followed by detailed explanations of Particle Swarm Optimization (PSO), Hybrid Artificial Bee Colony–PSO (HABC_PSO), and Honey Badger Algorithm (HBA), including their step-by-step procedures.

Chapter 5: Results and Discussion provides simulation results under different system conditions (without STATCOM, conventional STATCOM, PSO-STATCOM, HABC_PSO-STATCOM, and HBA-STATCOM). The analysis covers transient responses, settling times, rotor angle and speed deviations, and voltage stability indices across bus bars, followed by a comprehensive comparative discussion.

Chapter 6: Conclusion and Future Work summarizes the main findings, emphasizing the effectiveness of the proposed optimization-based STATCOM controllers. It also highlights the role of voltage indices in performance assessment and proposes potential future research directions, including real-time implementation and hybrid optimization strategies.

1.7 Summary

This thesis explores the use of Particle Swarm Optimization (PSO) for optimally tuning a Static Synchronous Compensator (STATCOM) controller to improve stability in a multi-machine power system, modeled using the Kundur two-area four-machine test system. The study aims to reduce rotor angle and speed deviations, voltage fluctuations, and evaluates voltage stability through various voltage stability indices during transient disturbances, comparing PSO with Hybrid Artificial Bee Colony–PSO (HABC-PSO) and Honey Badger Optimization (HBO) algorithms. STATCOM's role in voltage regulation, reactive power compensation, and oscillation damping is highlighted, with emphasis on the need for optimal controller parameter tuning [1]. Metaheuristic algorithms are presented as effective solutions for this nonlinear optimization problem. The research seeks to identify the most efficient, robust, and reliable tuning method, contributing to intelligent, adaptive control strategies for modern power systems facing increasing complexity and renewable integration.

Chapter 2: Literature Review

Researchers have investigated various metaheuristic algorithms to optimize the design and control of STATCOM for improving power system stability. Traditional methods often lack the flexibility to handle nonlinearities and real-time constraints inherent in power systems. Modern algorithms such as Particle Swarm Optimization (PSO), Hybrid Artificial Bee Colony–PSO (HABC_PSO), and Honey Badger Algorithm (HBA) have shown promise in tuning control parameters of STATCOM, enhancing damping performance and transient stability.

2.1 Optimization-Based STATCOM Control

A major line of research applies metaheuristic optimization to tune STATCOM controllers for improved damping, voltage support, and faster stabilization under disturbances.

A hybrid optimization approach was proposed for tuning a Static Synchronous Compensator (STATCOM) to improve power system stability, combining Artificial Bee Colony and Particle Swarm Optimization (HABC-PSO). The method optimally adjusts the Proportional–Integral (PI) gains of the AC and DC voltage regulators to minimize the Integral of Time-multiplied Absolute Error (ITAE) of generator rotor speed deviations, thereby enhancing oscillation damping. Applied to the standard Kundur two-area, four-machine system, the technique was tested under steady-state disturbances and transient events such as sudden load increases. Comparative analysis with a system without STATCOM and with a conventionally tuned STATCOM showed that HABC-PSO significantly improved damping, reduced settling times for rotor angle and speed deviations, and enhanced voltage stability at critical buses [4].

A control scheme was proposed for enhancing multi-machine power system stability using a STATCOM with its AC voltage regulator PI gains optimally tuned via Ant Colony Optimization (ACO). The approach targets damping low-frequency oscillations and reducing voltage deviations following severe disturbances. Tested on the Kundur two-area, four-machine system under a three-phase, six-cycle line-to-ground fault, the ACO-tuned STATCOM was compared with a system without STATCOM and with a conventionally tuned STATCOM. Time-domain simulations demonstrated that the ACO-based controller achieved superior damping performance, markedly reducing the settling times of rotor angle and speed oscillations [1].

A study focused on modeling and voltage control of a solar–wind hybrid microgrid enhanced with a STATCOM whose four PI controllers (AC voltage, DC voltage, and d–q axis current regulators) were optimized using Genetic Algorithm (GA) and Bacteria Foraging Algorithm (BFA). The optimization, based on the Integral of Time-multiplied Absolute Error (ITAE) objective function, aimed to minimize voltage fluctuations at the point of common coupling under variable load conditions. A Simulink model incorporating a DFIG-based wind turbine and solar PV system was used for testing. Comparative results showed that the BFA-tuned controller achieved the best performance with a 15% reduction in voltage fluctuations, followed by the GA-based controller with 10%, both outperforming the conventional PI controller's 8% reduction [6].

Two advanced control schemes were proposed to improve the dynamic performance of the Static Synchronous Compensator (STATCOM) and the Static Synchronous Series Compensator (SSSC). The study focused on enhancing transient stability and damping system oscillations through improved control strategies for these FACTS devices. Detailed modeling and simulation were carried out to evaluate the proposed methods under various disturbance scenarios. Results demonstrated that the enhanced controllers significantly improved system response, reduced oscillation amplitudes, and provided faster voltage regulation compared to conventional control approaches [11].

2.2 Hybrid & Coordinated Control Approaches

This stream integrates multiple controllers or hybrid algorithms to improve damping robustness and convergence characteristics.

An investigation was conducted on optimal coordinated tuning of a Power System Stabilizer (PSS) and STATCOM controller to enhance damping of power system oscillations. Using Particle Swarm Optimization (PSO) and Artificial Bee Colony (ABC), the parameters of both controllers were simultaneously optimized to minimize rotor speed deviations in a Single-Machine Infinite Bus (SMIB) system under fault conditions. Results showed that the coordinated PSS–STATCOM design outperformed individual tuning of either controller, with PSO achieving superior objective function values and faster convergence compared to ABC [8].

A hybrid metaheuristic algorithm integrating Artificial Bee Colony (ABC) and Particle Swarm Optimization (PSO) was developed to combine ABC's strong global search capability with

PSO's efficient local search. Applied to effort estimation in agile software projects, the method demonstrated superior accuracy and robustness compared to standalone ABC and PSO through empirical validation on project datasets. Although the application domain differs, the work offers a strong methodological basis for applying hybrid optimization techniques to complex, nonlinear problems such as controller tuning in power systems [9].

2.3 Foundational Texts and Theoretical Frameworks

Authoritative references establishing modeling techniques, stability concepts, and analytical methods for modern power systems and FACTS devices.

A seminal text provides the foundational theoretical framework for modern power system stability analysis. It comprehensively addresses transient, small-signal, and voltage stability, presenting detailed mathematical models for key components such as synchronous generators, excitation systems, turbines, governors, and FACTS devices like the STATCOM. Notably, it introduces the widely used Kundur two-area, four-machine test system, a benchmark for studying inter-area oscillations. As an authoritative reference, it forms an essential knowledge base for research in power system dynamics and control [2].

A landmark reference widely regarded as the definitive guide in power system dynamics presents a comprehensive treatment of rotor angle stability, small-signal stability, and voltage stability, supported by detailed mathematical modeling of synchronous machines, excitation systems, turbine–governor dynamics, and FACTS devices such as the STATCOM. It also introduces the widely used Kundur two-area, four-machine test system, a benchmark for studying inter-area oscillations and validating control strategies. As an authoritative resource, this work forms an essential foundation for research and practical applications in stability enhancement and control of modern power systems [10].

A comprehensive reference covering the fundamental principles and advanced concepts of power system dynamic behavior was authored. The book addresses transient, small-signal, and voltage stability, along with detailed modeling of synchronous machines, excitation systems, turbine–governor dynamics, and control devices. It also discusses analytical methods for stability assessment and practical strategies for system control under a variety of operating conditions. As a foundational text, it remains a key resource for both academic research and practical applications in stability enhancement and control of large-scale power systems [13].

A specialized reference focuses on the mechanisms, analysis, and prevention of voltage instability in modern power grids. It provides a detailed theoretical foundation for voltage stability phenomena, supported by mathematical models of generators, loads, and reactive power compensation devices. The book covers steady-state and dynamic analysis methods, practical countermeasures, and system design considerations to enhance voltage security. As a seminal work in the field, it remains an essential resource for engineers and researchers working on voltage stability assessment and control [14].

2.4 Algorithmic Foundations for Optimization

Core metaheuristic techniques that underpin modern controller tuning strategies.

The Particle Swarm Optimization (PSO) algorithm was introduced, inspired by the social behavior of bird flocking and fish schooling. PSO is a population-based metaheuristic that iteratively adjusts candidate solutions based on individual and collective experience to locate optimal or near-optimal solutions in complex search spaces. The original work demonstrated PSO’s simplicity, low computational cost, and strong global search capability, leading to its widespread adoption across various engineering optimization problems, including power system controller tuning [12].

2.5 Summary

Previous studies have shown that optimally tuned STATCOM controllers can significantly enhance both dynamic and voltage stability in power systems. Various metaheuristic algorithms, including Particle Swarm Optimization, Artificial Bee Colony, Genetic Algorithm, Bacteria Foraging, and hybrid approaches, have been applied to improve controller performance, offering faster convergence, better damping of oscillations, and improved voltage regulation. Foundational works on power system dynamics, voltage stability, and benchmark test systems provide the theoretical and modeling basis for these advancements. Overall, the literature emphasizes that intelligent optimization techniques, supported by robust theoretical frameworks, are highly effective in addressing the growing challenges of modern, renewable-integrated power grids.

Chapter 3: Theoretical Analysis

3.1 Introduction to Kundur’s Two Area System

The Kundur Two-Area System is a classical benchmark model widely adopted for evaluating power system stability, particularly inter-area oscillations and damping control strategies [2]. The system was introduced by Prabha Kundur in his book Power System Stability and Control and has since been used extensively in academia and industry to assess the performance of supplementary controllers like Power System Stabilizers (PSS) and Flexible AC Transmission Systems (FACTS), including Static Synchronous Compensators (STATCOM) [1].

This section details the structure, components, and dynamic characteristics of the system and serves as the test environment for evaluating PSO, HABC_PSO, and HBA-based STATCOM controllers in this study.

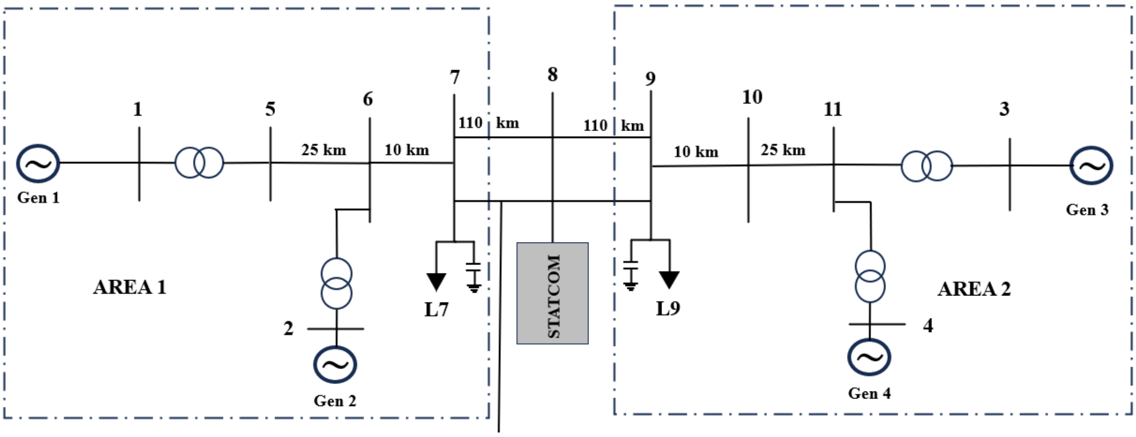


Fig. 3.1: Modified Kundur’s two-area power system with STATCOM

Fig. 3.1 represents the single line diagram of a power system consisting of area 1 and area 2 with tie line and a STATCOM.

3.1.1 System Configuration

The Kundur system consists of two symmetric areas, each comprising two identical synchronous generators. These areas are connected through a weak tie-line that introduces inter-area power exchange dynamics. Each generator supplies a local load and is interconnected via transformers and long transmission lines [2].

The system consists of:

- 11 buses: 4 generator buses, 4 load buses, 2 junction buses, and 1 tie-line bus.

- 4 Synchronous Generators (G1 to G4): 1000 MVA each.
- 2 Areas (Area-1 and Area-2): Interconnected via a high-reactance tie-line.
- Constant Impedance Loads in each area.
- Transmission lines and transformers.

This symmetrical structure allows for balanced initial conditions and facilitates the analysis of inter-area oscillations.

3.1.2 Generator and Excitation System Modeling

Each generator in the system is modeled using a two-axis synchronous machine model that includes the d-axis and q-axis transient reactance. The dynamic model includes:

- Field voltage dynamics,
- Rotor angle and speed,
- Mechanical power input through turbine-governor systems.

Excitation systems are modeled using the IEEE Type ST1A model, which controls the field voltage based on the difference between terminal voltage and reference voltage. These are crucial for voltage regulation and transient performance.

3.1.3 Inter-Area Oscillations

Inter-area oscillations are low-frequency power swings that occur between two or more groups of generators in large, interconnected power systems, such as the Kundur two-area system [2]. In this system, each area comprises multiple synchronous generators, and these areas are connected through relatively weak tie-lines. Due to this weak coupling, a disturbance in one area, such as a sudden load change or a fault, can cause the generators in one area to oscillate against the generators in the other area. These oscillations typically manifest at frequencies in the range of 0.2 to 1 Hz, with the dominant mode in the Kundur system occurring around 0.64 Hz [17].

Low-frequency oscillations (LFOs) are particularly problematic because they are lightly damped under normal operating conditions, meaning that the oscillation amplitudes decay very slowly and can persist for several seconds [18]. If left uncontrolled, these oscillations can grow over time, potentially leading to loss of synchronism, degraded power quality, and even cascading failures across the network. The effects of LFOs on power systems include:

1. **Rotor Angle Instability** – Generators in different areas may swing against each other, increasing rotor angle differences and risking out-of-step conditions.
2. **Voltage Fluctuations** – The oscillating power flow between areas can induce voltage instability at buses, particularly those near tie-lines or heavily loaded nodes.
3. **Increased Mechanical Stress** – Continuous low-frequency swings impose additional mechanical stress on generator shafts and turbines, reducing the operational life of equipment.
4. **Compromised System Reliability** – Unmitigated inter-area oscillations can trigger protective relays, lead to tripping of lines or generators, and reduce overall system reliability.

Because local controllers like conventional excitation systems or Power System Stabilizers (PSS) are often insufficient to provide damping for these weakly coupled inter-area modes, supplemental controllers such as STATCOMs have become essential. Advanced optimization-based tuning of STATCOM controllers ensures that the device can actively inject or absorb reactive power in a coordinated manner, providing effective damping for inter-area oscillations and enhancing overall system stability.

3.1.4 Modification for Transient Analysis

All the power system parameters and values utilized in this study have been sourced from [2]. In Area 2, a resistive load of 1767 MW is initially considered. To conduct a transient analysis, the resistive load in Area 2 has been incrementally increased by 176 MW. The purpose of this analysis is to observe the system's response under three different conditions: without STATCOM, with STATCOM, and with a PSO, HBA and ABC_PSO tuned STATCOM.

3.2 System Parameters

This section outlines the numerical values and technical configurations used in modeling the Kundur Two-Area Power System. These parameters define the electrical and dynamic behavior of the system components, ensuring accurate simulation of power system stability phenomena such as small-signal oscillations and transient response. All parameter values are selected based on standard configurations referenced in Kundur (1994*)* and widely used in related research studies [10].

3.2.1 Generator Parameters

Each of the four synchronous generators (G1 to G4) in the two-area system is identical and modeled using a two-axis transient model. These models represent the dynamic behavior of the internal voltage and rotor angle in response to disturbances and control actions.

Table 3.1: Generator parameter

Parameter	Value	Unit
Rated MVA	900	MVA
Rated Voltage	20	kV
Rated Frequency	60	Hz
Xd (Direct-axis reactance)	1.8	p.u.
Xq (Quadrature-axis reactance)	1.7	p.u.
$X'd$ (Transient reactance)	0.3	p.u.
X'q (Transient quadrature reactance)	0.55	p.u.
X''d (Sub-transient reactance)	0.25	p.u.
T'do (Open-circuit d-axis time constant)	8.0	s
T'qo (Open-circuit q-axis time constant)	0.4	s
H (Inertia constant)	6.5	s
D (Damping coefficient)	0	–
Ra (Armature resistance)	0.0025	p.u.

Table 3.1 shows generators parameter and these are assumed to have identical control settings and operate under the same loading conditions for the base case.

3.2.2 Excitation System Parameters

The generators are equipped with an IEEE Type ST1A excitation system, which provides automatic voltage regulation and enhances transient stability.

Table 3.2: Excitation system parameters

Parameter	**Value**	**Unit**
KA (Gain)	200	–
TA (Time constant)	0.001	s
KE	1	–
TE	0	s
KF	0.	–
TF	0.1	s
VR_{max}	5	p.u.
VR_{min}	-5	p.u.

Table 3.2 shows the excitation parameter and the excitation system influences the voltage response following disturbances and is essential in dynamic simulations.

3.2.3 Governor System Parameters

The governor system is simplified and assumed to be linear for small-signal analysis. It helps regulate mechanical power input to the generator.

Table 3.3: Governor system parameters

Parameter	**Value**	**Unit**
R (Speed droop)	0.05	p.u.
TG (Governor time constant)	0.2	s
TCH (Turbine time constant)	0.3	s

Table 3.3 shows all parameters of governor system and for transient simulations involving large disturbances, a more detailed steam turbine-governor model may be used.

3.2.4 Load Parameters

Loads are modeled as constant impedance for both areas. Each load is supplied by its respective generator pair. The loading is symmetric to allow clear identification of inter-area mode behavior.

Table 3.4: Load parameters

Area	Load (P)	Load (Q)
Area 1	967 MW	100 MVAR
Area 2	1943.7 MW	100 MVAR

Table 3.4 provides load parameter of 2 areas and the load values are selected to reflect a high loading scenario, contributing to low-frequency inter-area oscillations.

3.2.5 Transmission Line and Tie-Line Parameters

The transmission network is modeled using π-equivalent circuits with line charging susceptance's. The tie-line introduces the weak coupling necessary for inter-area oscillation analysis.

Table 3.5: Transmission line & tie line parameters

Line	Reactance (X) (p.u.)	Resistance (R) (p.u.)	Length (approx) (km)
Generator to Load	0.2 – 0.3	0.0	25 Km
Tie-Line	0.25	0.0	220 Km
Transformer	0.1	–	–

Table 3.5 shows the parameter of Transmission and tie line and these parameters are chosen to maintain a low damping margin in inter-area modes, which is ideal for testing damping control strategies.

3.2.6 System Base Values

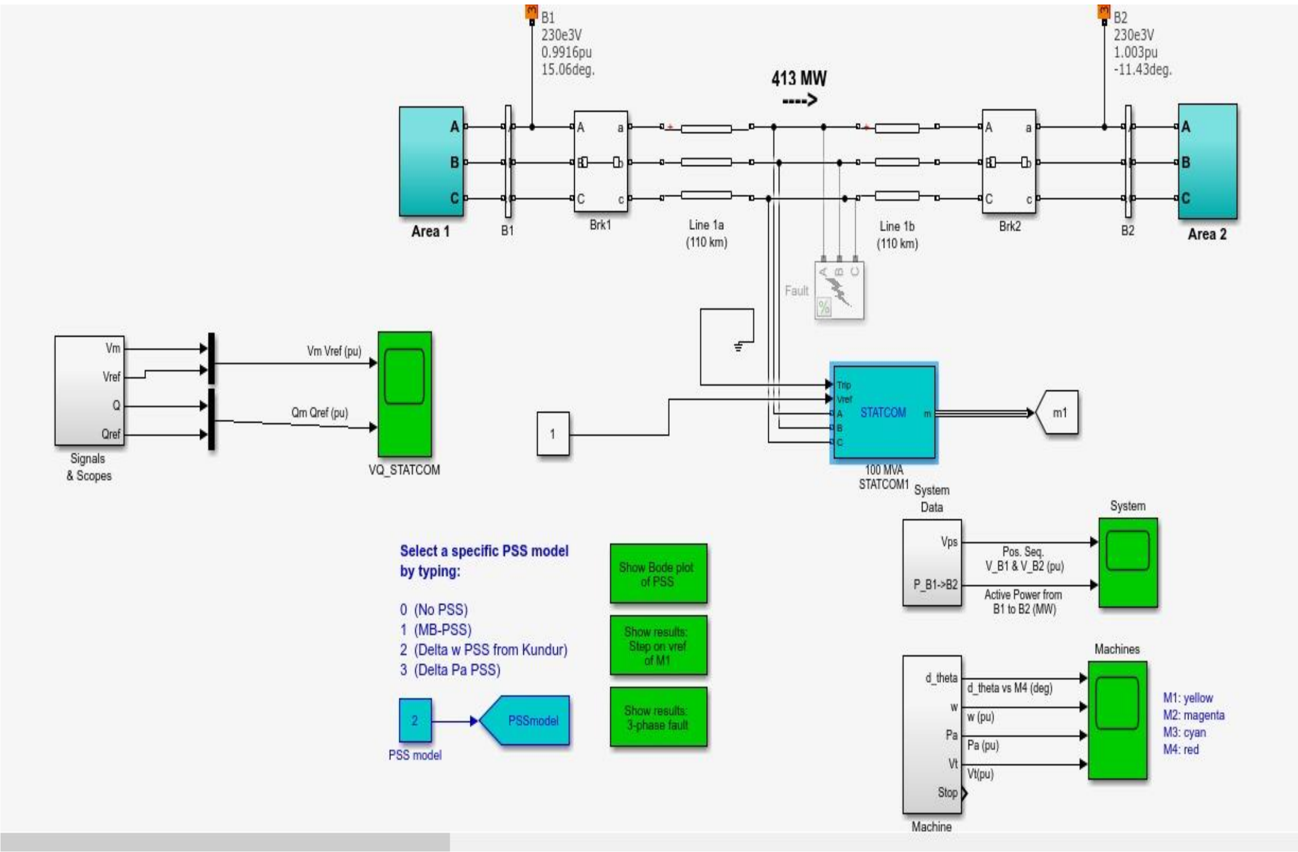
To standardize all per-unit calculations we assume base values of apparent power voltage and frequency from the following table 3.6.

Table 3.6: System base values

Parameter	Value
Base MVA	100
Base kV (Bus)	230
Base Frequency	60 Hz

3.2.7 Simulation in MATLAB/Simulink

The MATLAB implementation of the modified kundur's two-area test system is executed with the help of a Sim-power tool in MATLAB Simulink. The Simulink model of the modified test system has been illustrated in following Fig. 3.2



Select a specific PSS model by typing:

0 (No PSS)
1 (MB-PSS)
2 (Delta w PSS from Kundur)
3 (Delta Pa PSS)

Fig. 3.2: Matlab simulation of Kundur's modified two-area four generator test system with STATCOM.

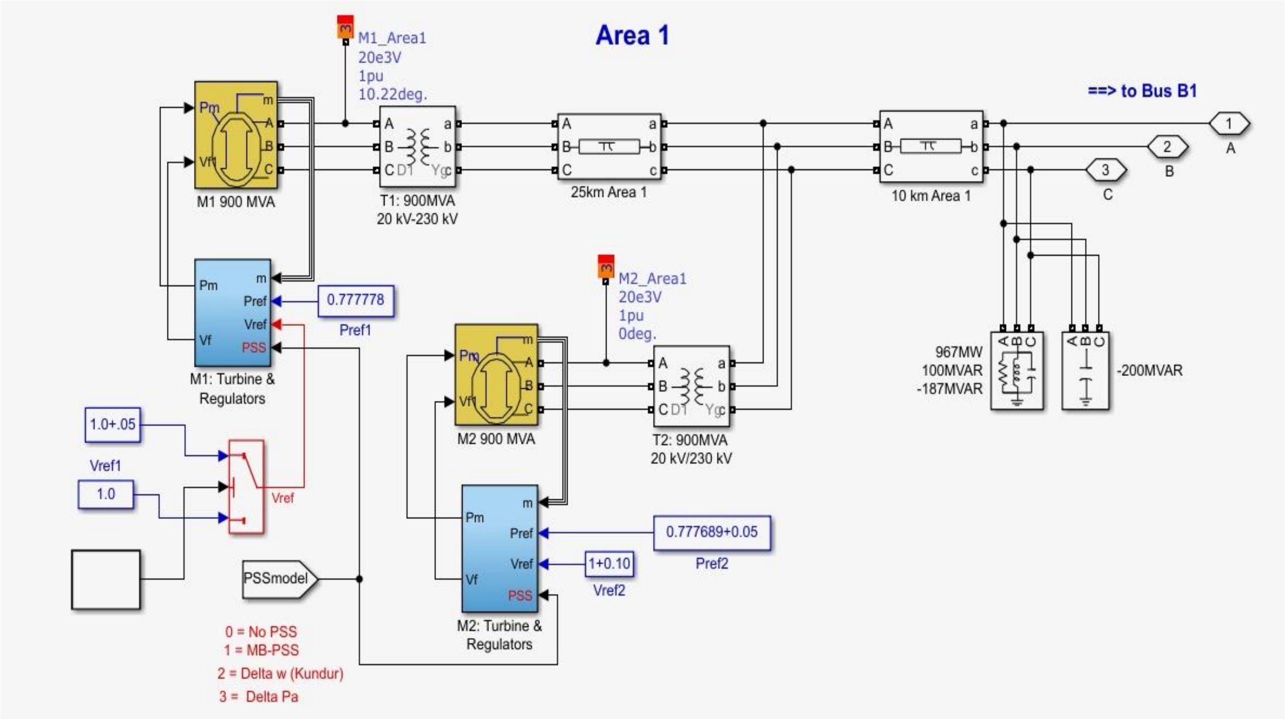


Fig. 3.3: Matlab simulation of Area 1 consisting of two alternators.

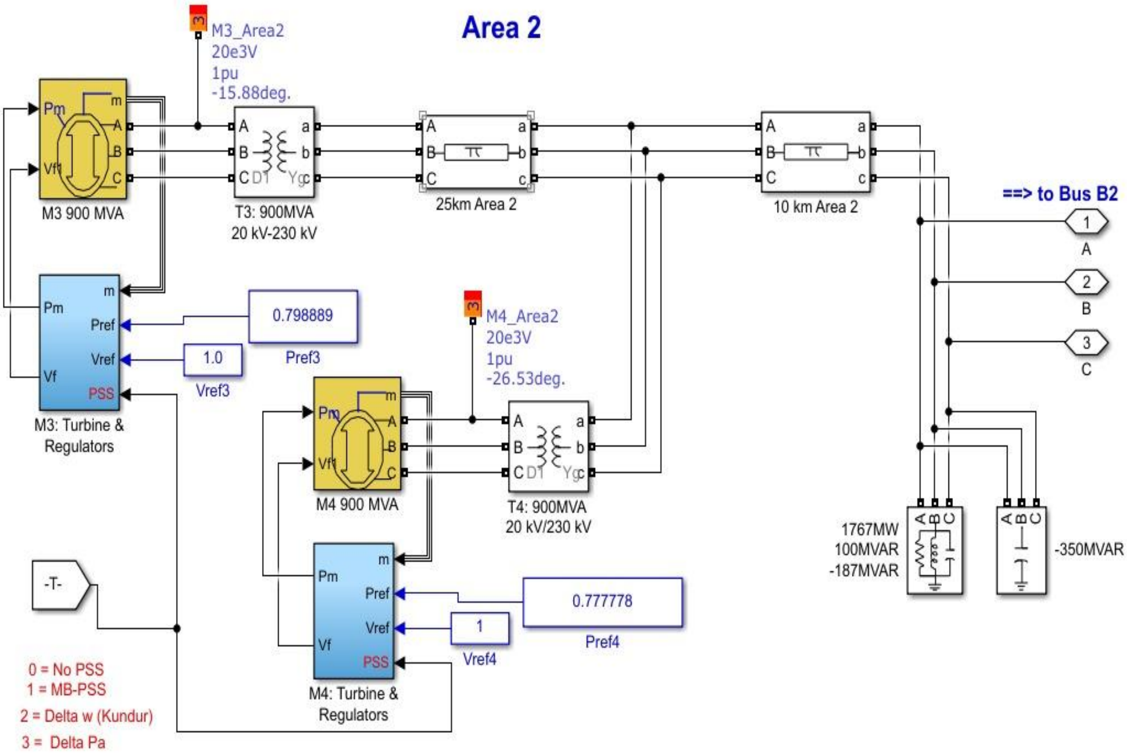


Fig. 3.4: Matlab simulation of Area 2 consisting of two alternators

Fig. 3.3 and Fig. 3.4 shows the Matlab Simulation diagram of 2 area's where each area has 2 alternators with control systems, 1 load area with capacitor bank other equipment's and increasing the load of area 2 for transient analysis.

3.3 Principle of Operation

A STATCOM regulates the voltage at its connection point by generating or absorbing reactive power through the use of a voltage source converter (VSC) [1]**.** The fundamental operation is based on the control of the output voltage magnitude of the converter relative to the bus voltage.

- If $|V_{STATCOM}| > |V_{bus}| \Rightarrow$ STATCOM injects reactive power (capacitive mode)
- If $|V_{STATCOM}| < |V_{bus}| \Rightarrow$ STATCOM absorbs reactive power (inductive mode)

The reactive power exchange is nearly independent of the system voltage, making STATCOM highly effective in low-voltage conditions.

3.3.1 STATCOM Structure

The Static Synchronous Compensator (STATCOM) is a shunt-connected reactive power compensation device utilizing a self-commutated converter, typically a Voltage Source Converter (VSC) [16]. STATCOM has been widely applied in power systems for effective voltage regulation, reduction of temporary overvoltage's, enhancement of steady-state power transfer capacity, improvement of transient stability margins, damping of sub synchronous power system oscillations, and balanced loading of individual phases, among other benefits. As a prominent member of the FACTS device family, STATCOM is highly valued for these advantages. The typical configuration of a STATCOM includes the following components:

- Voltage Source Converter (VSC): Converts DC to AC and controls the output voltage, forming the core of the reactive power compensation.
- DC Capacitor (Energy Storage): Maintains a constant DC link voltage to ensure stable operation.
- AC Reactor: Connects the converter to the power system and smooths the current flow.
- Controller**:** Regulates converter switching for precise voltage and power control, tuned in this study using the Particle Swarm Optimization (PSO) algorithm.

The Fig. 3.5 depicts a STATCOM with a Voltage Source Converter (VSC), showing its connection to the power system via an AC reactor (X) to exchange reactive power (Q) and active power (P).

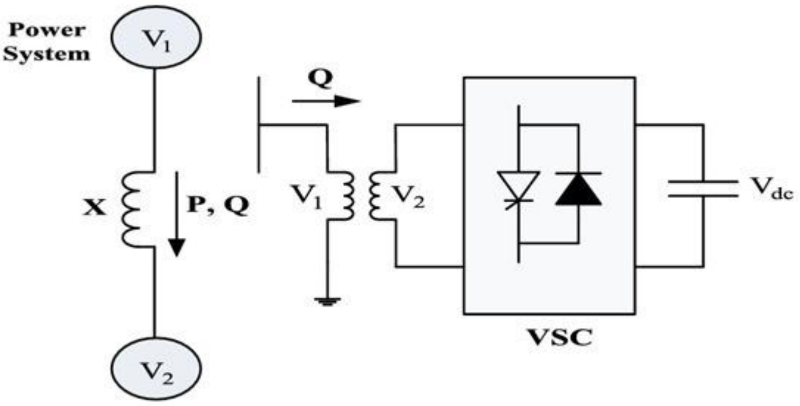


Fig. 3.5: STATCOM with Voltage source converter.

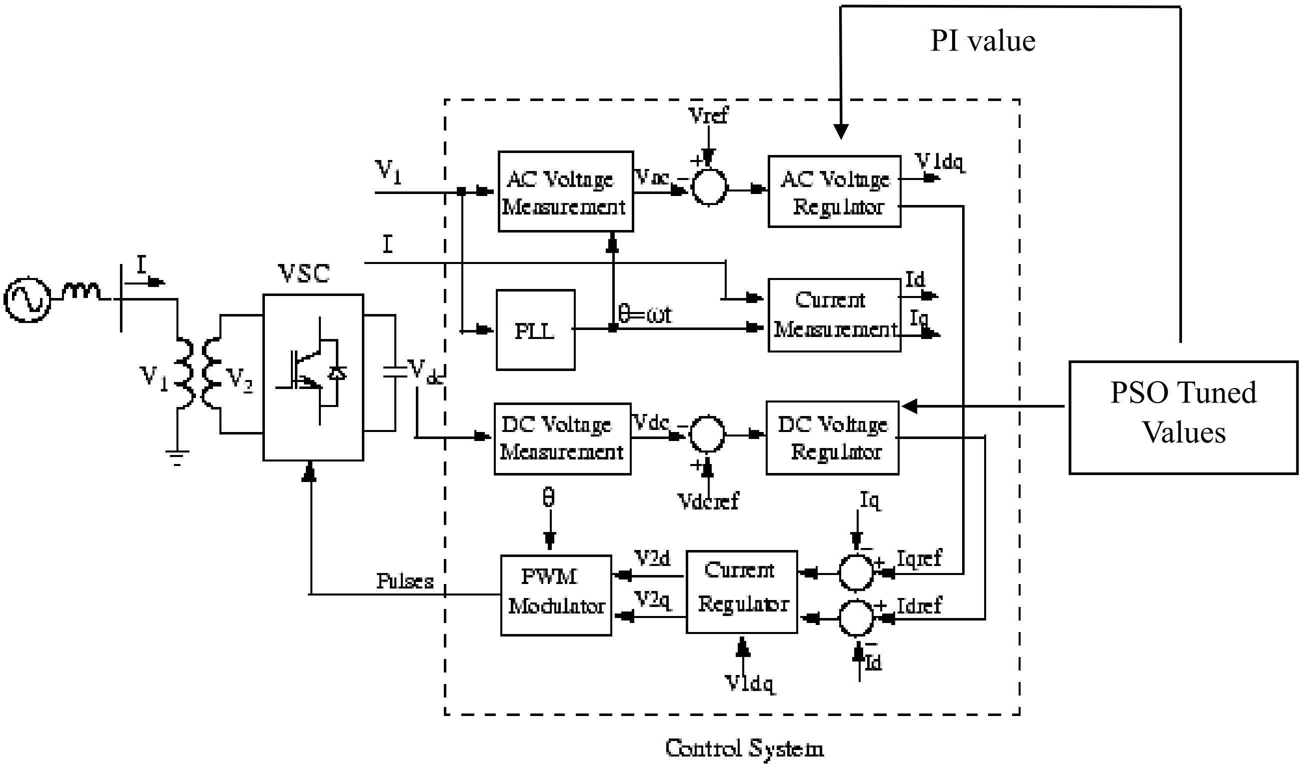


Fig. 3.6: Block Diagram of proposed PSO tuned STATCOM

The controller structure is shown on Fig. 3.6. In this study, a simplified average model of the STATCOM is employed for transient and small-signal stability analysis, neglecting switching harmonics but preserving dynamic behavior. The proposed control strategy involves tuning two Proportional-Integral (PI) controllers—one for the AC voltage regulator and another for the DC voltage regulator—using PSO. This algorithm optimizes the PI gains by simulating a population of particles that adjust their positions based on individual and global best solutions to minimize a time-domain objective function, such as the Integral of Time-weighted

Absolute Error (ITAE) of rotor speed deviations. This iterative optimization, validated through MATLAB/Simulink simulations in the Kundur two-area four-machine system, enables the STATCOM controller—synchronized via a Phase-Locked Loop (PLL) and driven by a PWM modulator—to dynamically inject or absorb reactive power, enhancing transient stability and damping inter-area oscillations.

3.3.2 STATCOM in Kundur's System

In the simulation setup, the STATCOM is placed at Bus 7, which is located near the midpoint of the tie-line between Area-1 and Area-2. This strategic location enables the STATCOM to provide:

- Fast voltage regulation at a critical interconnection point,
- Effective damping of the inter-area mode (~0.64 Hz),
- Stability improvement following disturbances such as faults or load changes.

The parameters of the STATCOM used in this study are shown table 3.7

Table 3.7: STATCOM parameters

Parameter	Value
Nominal Rating	±100 Mvar
DC Link Capacitance	1000 µF
Interface Reactor LsL_sLs	0.05 p.u.
Interface Resistance RsR_sRs	0.001 p.u.
Control Strategy	PI + d–q control
Switching Frequency	– (Average model)

3.3.3 Control Strategy

The objective of controlling STATCOM is to maintain the voltage magnitude at its point of connection while contributing to damping power system oscillations. The control loop typically consists of:

- Inner Current Control Loop: Regulates the d and q components of the current through PI controllers.
- Outer Voltage Control Loop: Maintains the AC bus voltage at the reference value.
- DC Voltage Controller: Maintains constant DC link voltage.

The d-axis current is generally aligned with the system voltage and controls active power, while the q-axis current controls reactive power.

3.3.4 Role of STATCOM in Damping Oscillations

STATCOM enhances damping by dynamically modulating reactive power in response to system deviations. The modulation of voltage magnitude effectively provides damping torque that counteracts rotor oscillations. In this thesis, metaheuristic optimization algorithms (PSO, HABC_PSO, HBA) are employed to tune the PI controller gains of the STATCOM for optimal damping performance.

3.4 Voltage Index

Voltage indices are employed in power system analysis to assess and ensure voltage stability, a critical aspect of maintaining reliable and secure operation under normal and disturbed conditions [16]. Their primary purpose is to quantify the system's ability to maintain acceptable voltage levels at all buses, preventing voltage collapse or instability caused by reactive power imbalances, load variations, or faults. These indices, such as bus voltage deviation, voltage stability margin, and indices like the Line Voltage Stability Index (LVSI) or Voltage Collapse Proximity Indicator (VCPI), serve to identify vulnerable areas, guide the design of control strategies like STATCOM tuning, and evaluate the effectiveness of reactive power compensation. By providing a measurable framework, voltage indices enable engineers to optimize system performance, enhance transient stability, and ensure efficient power transfer, particularly in complex multi-machine systems like the Kundur two-area model, where dynamic responses to disturbances are critical.

3.4.1 L-Index

The L-Index is a recognized voltage stability index used to assess the proximity of a power system to voltage collapse, particularly in load flow studies [23]. It is an approximate indicator derived in the actual domain, providing a measure of voltage stability at a load bus relative to a reference bus. The L-index ranges from 0 to 1, where a value close to 0 indicates a stable condition, and a value approaching 1 signals an impending voltage collapse, making it a useful tool for evaluating the effectiveness of control devices like the STATCOM in maintaining system stability.

The formula for the L-index is expressed in equation (1):

$$\boldsymbol{L_{Index} = 1 - \left|\frac{V_j}{V_i}\right|} \qquad (1)$$

Where:

- V_i: Voltage magnitude at the sending-end bus in per unit.
- V_j: Voltage magnitude at the receiving-end bus in per unit.

3.4.2 Voltage Deviation Index (VDI)

The Voltage Deviation Index (VDI) is a simple yet effective metric used to quantify the deviation of the voltage magnitude at a specific bus from its nominal value, providing insight into voltage stability and quality in a power system [16]. It is particularly useful for assessing the performance of control devices like the STATCOM in maintaining acceptable voltage levels during transient conditions or load variations. The index is calculated as the absolute difference between 1 per unit (p.u.) the nominal voltage—and the actual voltage at bus j in per unit, with lower values indicating better voltage regulation.

The formula for the Voltage Deviation Index is expressed in equation (2):

$$\boldsymbol{VDI = \left|1 - V_{j\,(pu)}\right|} \qquad (2)$$

Where:

- VDI: Voltage Deviation Index at bus j .
- $V_{j\,(pu)}$: Actual voltage magnitude at bus j in per unit.

3.4.3 Voltage Collapse Proximity Index (VCPI)

The Voltage Collapse Proximity Index (VCPI) is a voltage stability index designed to measure the proximity of a power system to voltage collapse, particularly useful for identifying critical buses or lines where instability may occur due to excessive reactive power demand or load stress [16]. This index helps evaluate the effectiveness of control measures, such as the STATCOM, in preventing voltage collapse by assessing the voltage difference between two buses relative to the sending-end voltage. A higher VCPI value indicates a greater risk of voltage collapse, with values approaching 1 signaling critical instability, while lower values suggest a stable condition.

The formula for the Voltage Collapse Proximity Indicator is expressed in equation (3):

$$\boldsymbol{VCPI} = \frac{|\boldsymbol{V_i} - \boldsymbol{V_j}|}{|\boldsymbol{V_i}|} \qquad (3)$$

Where:

- V_i: Voltage magnitude at the sending-end bus in per unit.
- V_j: Voltage magnitude at the receiving-end bus in per unit.

3.4.4 Sensitivity Index

The Sensitivity Index (VQ_index) is a voltage stability index that measures the sensitivity of voltage variations to changes in reactive power, providing insight into the system's ability to maintain voltage stability under varying load conditions [24]. It is particularly useful for analyzing how effectively a device like STATCOM can regulate voltage by adjusting reactive power flow, making it a valuable tool for assessing control performance. The index is derived from the ratio of voltage difference to reactive power difference between two buses, with a lower value indicating better voltage control and stability, while a higher value may signal potential instability.

The formula for the Sensitivity Index is expressed in equation (4):

$$\boldsymbol{VQ_{Index}} = \frac{\Delta \boldsymbol{V}}{\Delta \boldsymbol{Q}} \qquad (4)$$

Where:

- VQ_{Index}: Sensitivity Index.
- $\Delta V = V_i - V_j$ is the Voltage difference between buses i and j in per unit.
- $\Delta Q = Q_i - Q_j$ is the Reactive power difference between buses i and j in per unit.

3.5 Summary

This chapter presents the theoretical foundation and system configuration for evaluating damping control strategies in power systems, focusing on a modified Kundur Two-Area Four-Machine Test System integrated with a STATCOM. The model incorporates detailed generator, excitation, governor, load, and transmission line parameters, enabling accurate simulation of inter-area oscillations and transient stability phenomena. A STATCOM is strategically placed at the tie-line midpoint to provide fast voltage regulation and enhanced damping of the 0.64 Hz inter-area mode. Its control system, based on PI regulators in d-q reference frame, is tuned using metaheuristic optimization algorithms PSO, HBA, and HABC_PSO to minimize rotor speed deviations via the ITAE criterion. Simulink is used for implementing and testing the system under various load disturbance scenarios, enabling comparative performance evaluation of the optimized controllers in improving voltage stability, transient performance, and oscillation damping.

Chapter 4: Optimization Algorithms

This chapter presents the control strategy and optimization framework adopted to improve the dynamic stability of the Kundur Two-Area Power System. A Static Synchronous Compensator (STATCOM) is used as a supplementary damping controller, and its performance is enhanced by optimally tuning its internal control parameters using three evolutionary metaheuristic algorithms: Particle Swarm Optimization (PSO) **[**11]**,** Hybrid Artificial Bee Colony–PSO (HABC_PSO)**,** and the Honey Badger Algorithm (HBA)**.**

The chapter is organized to introduce each algorithm's working principles and their application to the STATCOM controller, followed by the formulation of the optimization problem and the simulation setup.

4.1 Overview of Optimization Approaches

Metaheuristic optimization algorithms are inspired by natural phenomena such as animal behavior, biological evolution, or physical processes. They are particularly suitable for solving complex, nonlinear, and high-dimensional problems where traditional gradient-based optimization methods fail or perform poorly.

In this study, three such algorithms are applied to tune the proportional-integral (PI) controller of the STATCOM:

- PSO: Inspired by social behavior of birds/fish.
- HABC_PSO: Combines ABC's exploration and PSO's exploitation.
- HBA**:** Inspired by foraging behavior of honey badgers with strong convergence capabilities.

The aim of these algorithms is to minimize a time-domain-based objective function that quantifies the power system's transient response quality after a disturbance.

4.2 Objective Function

In the context of improving power system stability through optimal tuning of a Static Synchronous Compensator (STATCOM), selecting a suitable performance index is crucial. The primary goal of the controller is to minimize oscillations and restore synchronous operation following disturbances. For this purpose, the Integral of Time-weighted Absolute Error (ITAE) is adopted as the objective function in the optimization process.

The ITAE criterion provides a comprehensive evaluation of system performance by integrating the absolute value of speed deviations over time, further multiplied by time itself. This time-weighting feature penalizes prolonged deviations more severely than those that are quickly corrected, thereby encouraging fast and well-damped system responses.

The ITAE function employed in this research is mathematically defined following equation (5)

$$\boldsymbol{ITAE} = \int_{0}^{\boldsymbol{T_{sim}}} 1000[\Delta_{\boldsymbol{\omega}1}] + [\Delta_{\boldsymbol{\omega}2}] + [\Delta_{\boldsymbol{\omega}3}] + [\Delta_{\boldsymbol{\omega}4}]\, \boldsymbol{t.d} \tag{5}$$

Where:

- $\Delta\omega_1(t)$, $\Delta\omega_2(t)$, $\Delta\omega_3(t)$, $\Delta\omega_4(t)$ represent the instantaneous deviations in angular speed of the four synchronous generators in Kundur's Two-Area System,
- t denotes time in seconds,
- Tsim is the total simulation duration,
- The constant 1000 is a weighting factor applied to $\Delta\omega_1(t)$ to emphasize the importance of damping oscillations in the generator most affected by inter-area oscillations (typically Generator 1 in Area 1).

This formulation serves several important functions:

- The use of absolute values ensures that both positive and negative deviations are equally penalized, avoiding error cancellation.
- The multiplication by time (t) increases the penalty for errors that persist, thereby driving the optimization algorithms to find controller settings that quickly suppress oscillations.
- By summing the speed deviations across all generators, the function captures the overall system dynamic behavior rather than focusing on a single machine.
- The inclusion of a higher weight for $\Delta\omega_1(t)$ reflects its critical role in inter-area oscillation modes and ensures that the controller design prioritizes stability in the most sensitive region.

The ITAE value is minimized using three optimization algorithms—Particle Swarm Optimization (PSO), Hybrid Artificial Bee Colony–PSO (HABC_PSO), and the Honey Badger

Algorithm (HBA) each searching for the optimal proportional and integral gains of the STATCOM's voltage regulator. A lower ITAE value corresponds to a faster and more stable response, reduced oscillation amplitude, and improved rotor speed synchronization.

This performance index is particularly effective for tuning controllers in multimachine systems, where the goal is not only to stabilize an individual generator but also to preserve the overall coherence of the interconnected network.

This formulation of the objective function allows for a fair and comprehensive comparison among different optimization methods and provides a quantifiable measure of control performance under identical disturbance conditions.

4.3 Particle Swarm Optimization (PSO)

Particle Swarm Optimization is a population-based method inspired by the social behavior of bird flocks and fish schools. In PSO, each particle in the swarm represents a potential solution and moves through the search space influenced by its own best-known position and the swarm's global best-known position. Fig. 4.1 illustrates the flowchart of the PSO algorithm, where the position and velocity of each particle are iteratively updated using two main components: the cognitive component (personal learning) and the social component (collective learning). The balance between exploration and exploitation is governed by inertia weight and acceleration coefficients. Over successive iterations, particles converge toward optimal or near-optimal solutions [19].

4.3.1 Algorithm Procedure (PSO)

- Initialization - Randomly place particles in the search space with initial positions and velocities.
- Fitness Evaluation - Calculate the fitness value of each particle based on the objective function.
- Update Personal Best - For each particle, compare its current fitness with its best fitness so far; update if improved.
- Update Global Best - Identify the particle with the best fitness in the entire swarm.
- Velocity Update - Adjust each particle's velocity considering its personal best and the global best position.
- Position Update - Move each particle to its new position using the updated velocity.

- Stopping Check – If the stopping criteria (e.g., maximum iterations or acceptable fitness) are met, end the process; otherwise, return to step 2.

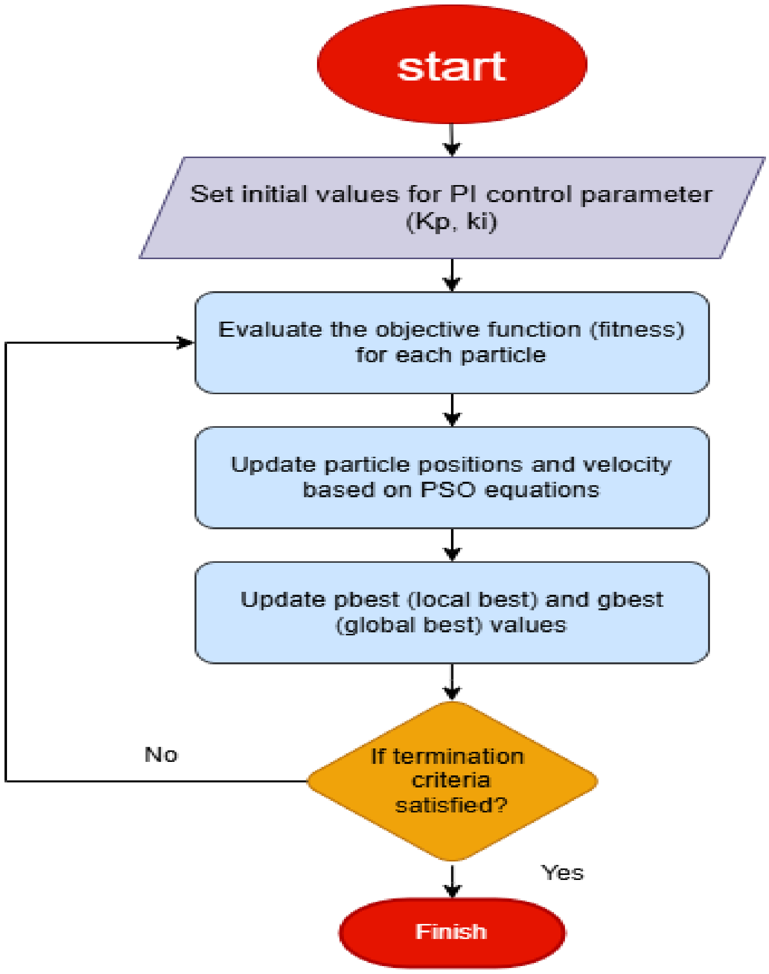


Fig. 4.1: Flowchart of PSO algorithm

4.4 Hybrid Artificial Bee Colony–PSO (HABC_PSO)

The HABC-PSO algorithm combines the global exploration capability of the Artificial Bee Colony (ABC) algorithm with the fast local convergence ability of PSO. The ABC component mimics the foraging behavior of honey bees, using employed bees, onlooker bees, and scout bees to explore multiple regions of the search space and maintain population diversity [4]. Fig. 4.2 illustrates the flowchart of the HABC-PSO algorithm, where once promising solutions are identified, the PSO component refines these solutions by adjusting positions and velocities toward the best-known solutions, accelerating convergence. This hybridization leverages the strengths of both algorithms, improving robustness, convergence speed, and the probability of finding the global optimum [20].

4.4.1 Algorithm Procedure (HABC_PSO)

- Initialization – Generate an initial population of solutions (food sources) randomly. Assign half of them to the Artificial Bee Colony (ABC) phase and half to the Particle Swarm Optimization (PSO) phase.
- Fitness Evaluation – Evaluate the objective function for all solutions.
- Employed Bee Phase (ABC) – Each employed bee explores a new solution in the neighborhood of its assigned food source and retains the better one.
- Onlooker Bee Phase (ABC) – Onlooker bees choose food sources based on fitness probability and search for improved solutions.
- Scout Bee Phase (ABC) – Replace abandoned food sources with new randomly generated ones if they fail to improve after a set number of trials.
- PSO Velocity Update – For solutions in the PSO phase, update velocities based on personal best and global best positions.

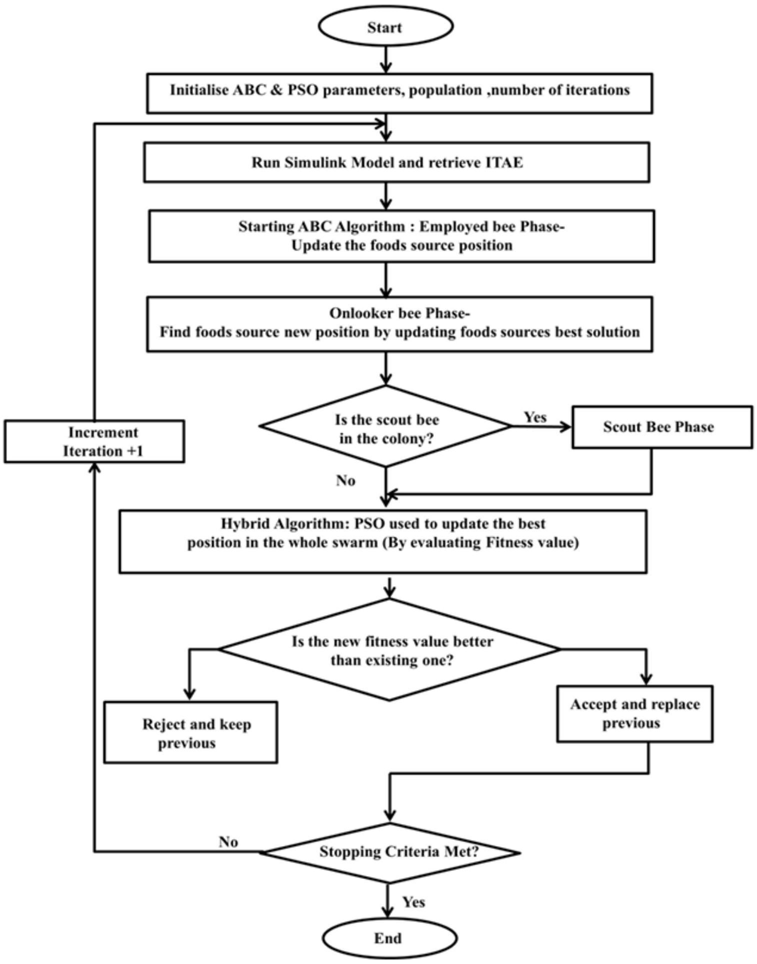


Fig. 4.2: Flowchart of HABC_PSO algorithm

- PSO Position Update – Move each PSO particle to a new position using its updated velocity.
- Hybrid Integration – Exchange best solutions between ABC and PSO phases to balance exploration and exploitation.
- Stopping Check – If the termination criteria are met, output the best solution; otherwise, return to step 2.

4.5 Honey Badger Algorithm (HBA)

The Honey Badger Algorithm (HBA) is a relatively recent metaheuristic inspired by the intelligent foraging behavior of honey badgers, which utilize both digging and honey-finding strategies. Fig. 4.3 presents the flowchart of the HBA algorithm, where two main phases are simulated: the digging phase (exploration) and the honey phase (exploitation). In the digging phase, candidate solutions explore the search space broadly to avoid local optima, while in the honey phase, they intensively exploit promising regions based on the best solutions found so far. The algorithm adaptively controls its step size and search direction by considering environmental factors, allowing for both diversification and intensification during optimization [21].

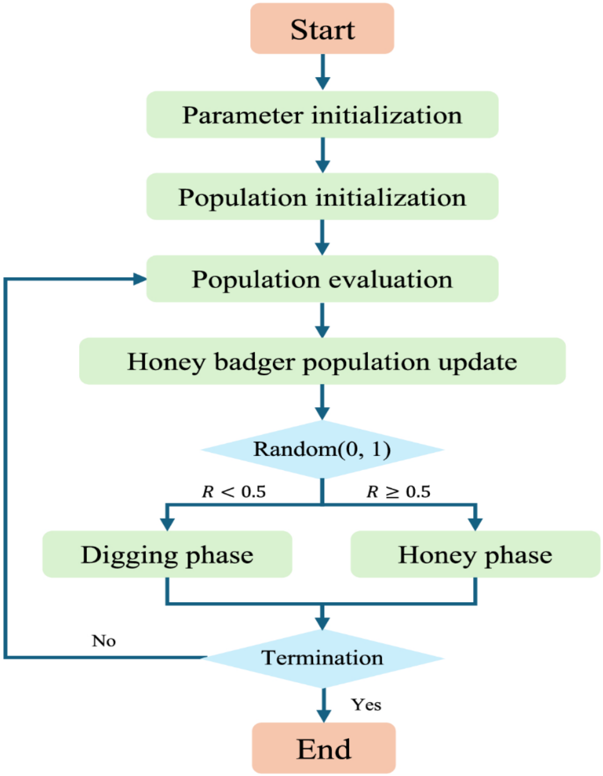


Fig. 4.3. Flowchart of HBA algorithm

4.5.1 Algorithm Procedure (HBA)

- Initialization - Generate an initial population of honey badgers (candidate solutions) randomly within the search space.
- Fitness Evaluation - Evaluate each solution using the objective function to measure its quality.
- Setting the Prey - Identify the best solution in the current population, considered as the prey (target).
- Density Factor Update - Calculate and update the density factor, which decreases over iterations to balance exploration and exploitation.
- Exploration Phase (Digging Mode) - Some honey badgers randomly search the environment by updating their positions in a wide range to explore new areas.
- Exploitation Phase (Honey Mode) - Other honey badgers move directly toward the prey using intensified search around the best solution.
- Position Update - Update the positions of honey badgers according to the chosen phase (digging or honey mode).
- Selection of Best Solution - Compare new solutions with previous ones and retain the best solutions for the next iteration.
- Stopping Check - If the termination criteria (e.g., maximum iterations or acceptable error) are met, stop and return the best solution; otherwise, return to step 2.

4.6 Summary

This chapter presented the control strategy based on STATCOM and explained the modeling and application of three metaheuristic optimization algorithms—PSO, HABC_PSO, and HBA—for PI controller tuning. The problem formulation defined a multi-objective function targeting improved system damping and dynamic response. The next chapter will present and compare the simulation results to evaluate the effectiveness of each optimization technique.

Chapter 5: Results and Discussion

This chapter presents the simulation results obtained by applying Particle Swarm Optimization (PSO), Hybrid Artificial Bee Colony–PSO (HABC_PSO), and the Honey Badger Algorithm (HBA) for tuning the STATCOM controller integrated into the Kundur Two-Area System. The system is subjected to several types of disturbances to assess the performance of each control approach. Results are compared based on critical time-domain and frequency-domain performance metrics including settling time, damping ratio, and Integral of Time-weighted Absolute Error (ITAE).

5.1 Result Analysis (PSO)

After applying the PSO-based optimization, the best Integral of Time-weighted Absolute Error (ITAE) value obtained under the given operating conditions is **175.112**, indicating a significant improvement in system performance. The corresponding optimized parameters of the STATCOM PI controllers, which directly contribute to enhanced damping and voltage regulation, are summarized in Table 5.1.

Table 5.1: ITAE and PI values of STATCOM for PSO

Parameters	Values	ITAE
K_{P_ac}	2.0321	175.112
K_{I_ac}	0	
K_{P_dc}	2.6813	
K_{I_dc}	0.4992	

Case 1: Transient Analysis with Proposed PSO STATCOM

All system parameters and values employed in this research are derived from the modeling framework presented in Chapter 3. In the test system, Area 2 is initially subjected to a resistive load of 1767 MW, which is then progressively increased by 176 MW to perform transient stability analysis. This incremental loading is intended to evaluate system robustness under stressed operating conditions. The dynamic response of the system is examined under three scenarios: without STATCOM compensation, with a conventional STATCOM, and with a PSO-optimized STATCOM controller.

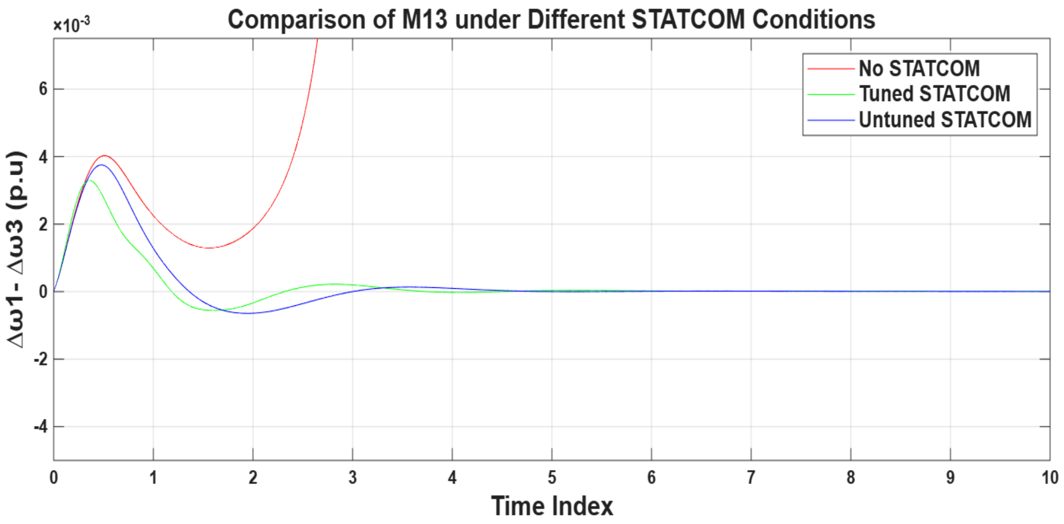


Fig. 5.1: Rotor speed deviation between generator 1 and 3 in (p.u) for PSO

Fig. 5.1 depicts the comparative generator speed deviations between Generator 1 and Generator 3, where the conventional STATCOM demonstrates noticeable damping improvement, while the PSO-tuned STATCOM exhibits markedly superior performance by effectively minimizing oscillations.

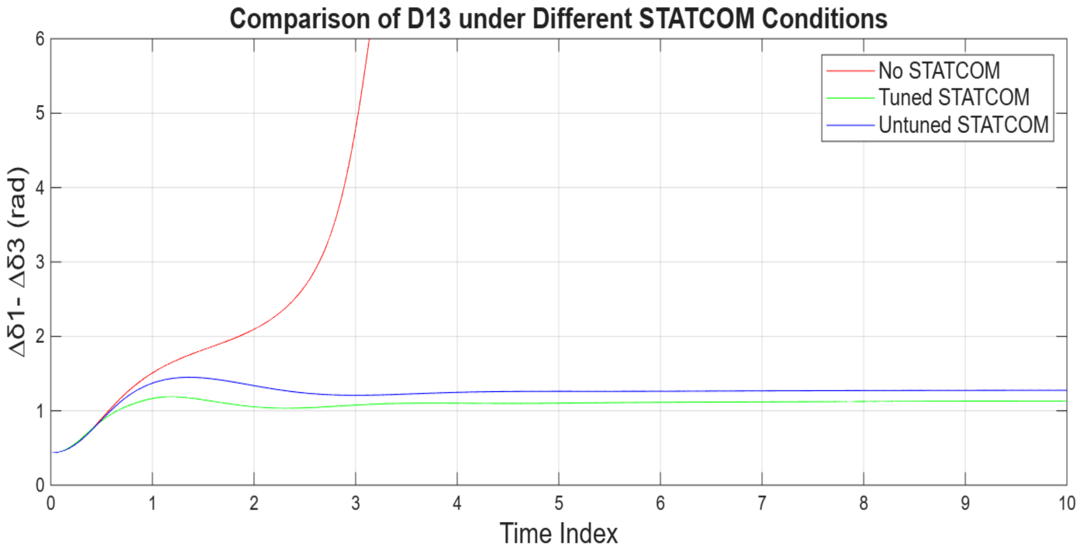


Fig. 5.2: Angle fluctuation between generator 2 and 4 in (p.u) for PSO

Fig. 5.2 highlights the rotor angle stability enhancement, confirming that the optimization-based controller achieves faster settling and improved synchronism compared to the uncompensated and uncompensated cases.

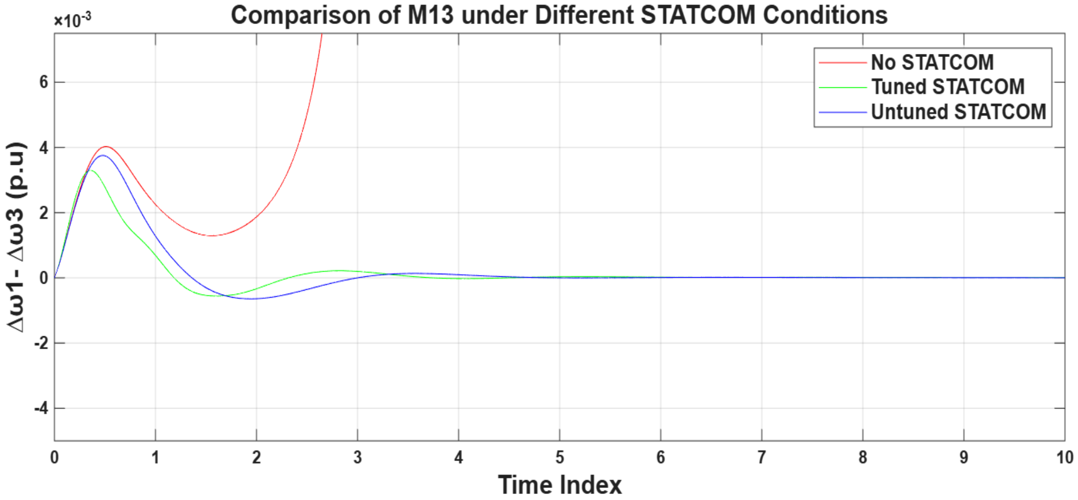


Fig. 5.3: Voltage fluctuation in bus-bar 7 in area 1 in (p.u) for PSO

Furthermore, as shown in Fig. 5.3, under increased loading conditions in Area 2, the PSO-STATCOM provides enhanced voltage profile regulation, thereby maintaining system stability and reliability more effectively than the traditional STATCOM implementation.

Case 2: Analysis Voltage Index

To evaluate the voltage stability performance of the system, 4 established indices—L-index, Voltage Deviation Index (VDI), Voltage Collapse Proximity Indicator (VCPI), and Sensitivity Index-are utilized in this study. Their theoretical basis and formulations were presented in chapter 3.4 section and values are comes from Matlab workspace.

Table 5.2: Voltage Index Comparison for PSO across Bus Bars 7–9

Voltage Index	Value
L-Index	0.0597
VDI	0.0433
VCPI	0.0597
Sensitivity Index	0.0378

While the computed results under different operating scenarios are summarized in Table 5.2 Together, these indices provide complementary insights, covering proximity to collapse, voltage deviation, system margin, and sensitivity to load changes, thus ensuring a reliable assessment of voltage stability.

5.2 Result Analysis (HABC_PSO)

After applying the HABC_PSO-based optimization, the best Integral of Time-weighted Absolute Error (ITAE) value obtained under the given operating conditions is **360.065**, indicating a significant improvement in system performance. The corresponding optimized parameters of the STATCOM PI controllers, which directly contribute to enhanced damping and voltage regulation, are summarized in Table 5.3

Table 5.3: ITAE and PI values of STATCOM for HABC_PSO

Parameters	Values	ITAE
K_{P_ac}	34.4422	360.065
K_{I_ac}	823.8337	
K_{P_dc}	1.4669	
K_{I_dc}	0.4946	

Case 1: Transient Analysis with Proposed HABC_PSO STATCOM

All system parameters utilized in this study are based on the modeling framework outlined in Chapter 3. In the test system, Area 2 is initially loaded with 1767 MW, and the load is gradually increased by 176 MW to conduct transient stability analysis. The system's dynamic response is evaluated under three scenarios: without STATCOM, with a conventional STATCOM, and with an HABC-PSO optimized STATCOM controller**.**

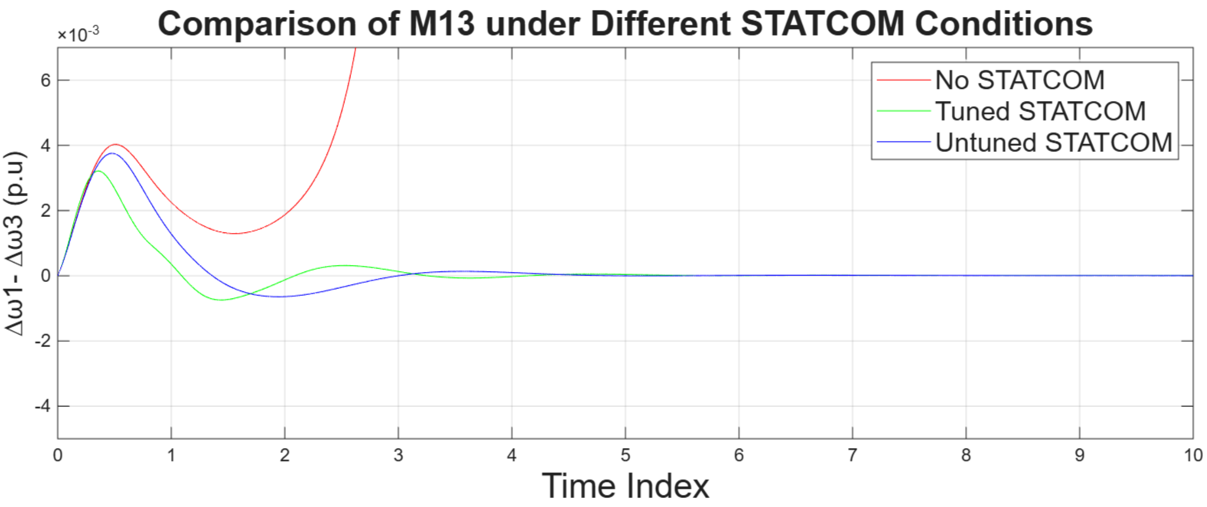


Fig. 5.4: Rotor speed deviation between generator 1 and 3 in (p.u) for HABC_PSO

Fig. 5.4 depicts the comparative generator speed deviations between Generator 1 and Generator 3, where the conventional STATCOM demonstrates noticeable damping improvement, while the HABC_PSO-tuned STATCOM exhibits markedly superior performance by effectively minimizing oscillations.

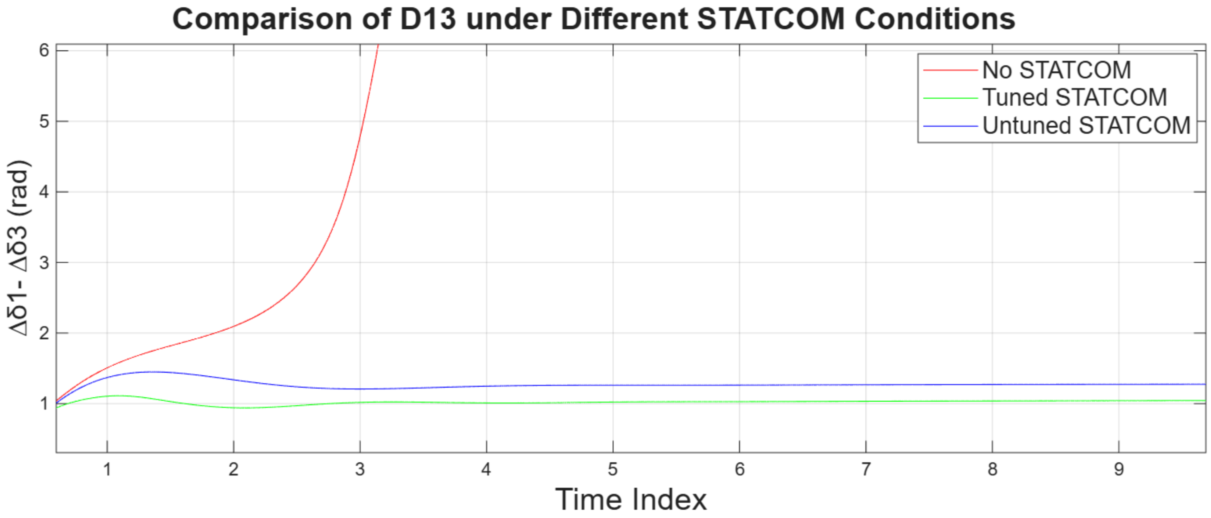


Fig. 5.5: Angle fluctuation between generator 2 and 4 in (p.u) for HABC_PSO

Fig. 5.5 highlights the rotor angle stability enhancement, confirming that the optimization-based controller achieves faster settling and improved synchronism compared to the uncompensated and uncompensated cases.

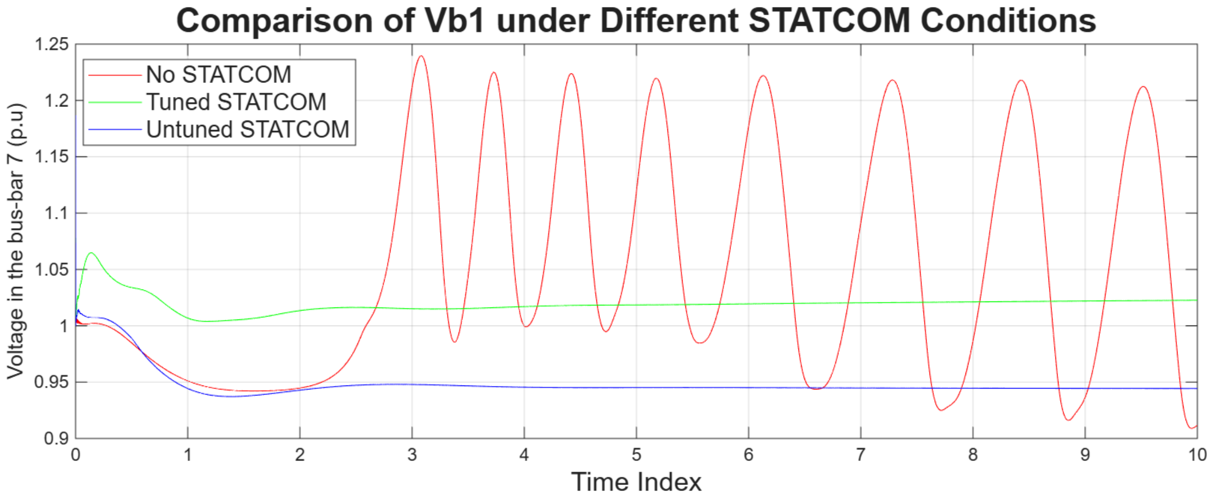


Fig. 5.6: Voltage fluctuation in bus-bar 7 in area 1 in (p.u) for HABC_PSO

Furthermore, as shown in Fig. 5.6, under increased loading conditions in Area 2, the HABC_PSO-STATCOM provides enhanced voltage profile regulation, thereby maintaining system stability and reliability more effectively than the traditional STATCOM implementation.

Case 2: Analysis Voltage Index

To evaluate the voltage stability performance of the system, 4 established indices—L-index, Voltage Deviation Index (VDI), Voltage Collapse Proximity Indicator (VCPI), and Sensitivity Index-are utilized in this study. Their theoretical basis and formulations were presented in chapter 3.4 section and values are comes from Matlab workspace.

Table 5.4: Voltage Index Comparison for HABC-PSO across Bus Bars 7–9

Voltage Index	Value
L-Index	0.057
VDI	0.042
VCPI	0.057
Sensitivity Index	0.0642

While the computed results under different operating scenarios are summarized in Table 5.4 Together, these indices provide complementary insights, covering proximity to collapse, voltage deviation, system margin, and sensitivity to load changes, thus ensuring a reliable assessment of voltage stability.

5.3 Result Analysis (HBA)

After applying the HBA-based optimization, the best Integral of Time-weighted Absolute Error (ITAE) value obtained under the given operating conditions is **175.29**, indicating a significant improvement in system performance. The corresponding optimized parameters of the STATCOM PI controllers, which directly contribute to enhanced damping and voltage regulation, are summarized in Table 5.5

Table 5.5: ITAE and PI values of STATCOM for HBA

Parameters	Values	ITAE
K_{P_ac}	1	175.29
K_{I_ac}	0.001	
K_{P_dc}	0.0012	
K_{I_dc}	0.001	

Case 1: Transient Analysis with Proposed HBA STATCOM

All system parameters utilized in this study are based on the modeling framework outlined in Chapter 3. In the test system, Area 2 is initially loaded with 1767 MW, and the load is gradually increased by 176 MW to conduct transient stability analysis. The system's dynamic response is evaluated under three scenarios: without STATCOM, with a conventional STATCOM, and with an HBA optimized STATCOM controller**.**

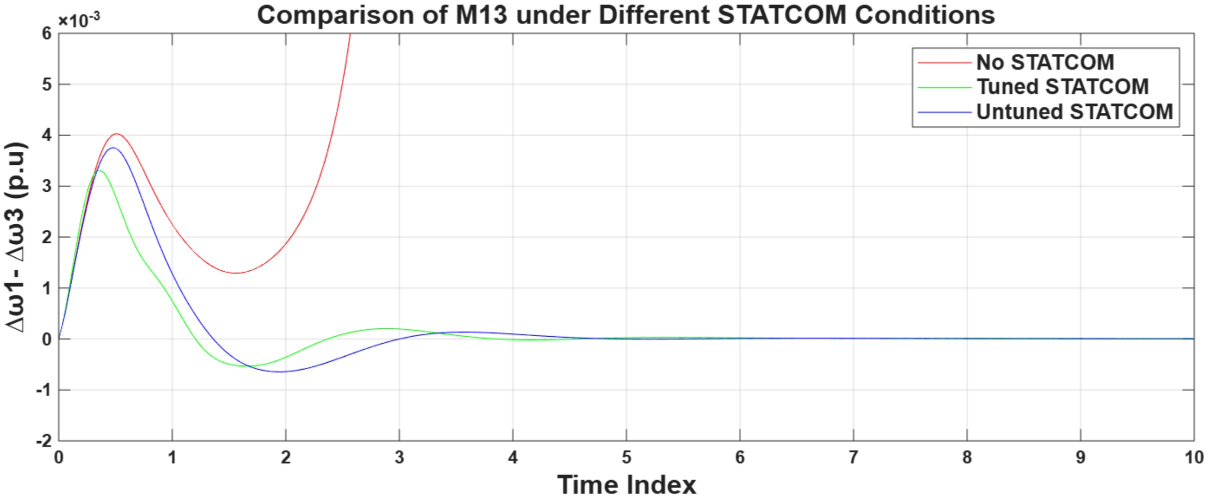


Fig. 5.7: Rotor speed deviation between generator 1 and 3 in (p.u) for HBA

Fig. 5.7 depicts the comparative generator speed deviations between Generator 1 and Generator 3, where the conventional STATCOM demonstrates noticeable damping improvement, while the HBA-tuned STATCOM exhibits markedly superior performance by effectively minimizing oscillations.

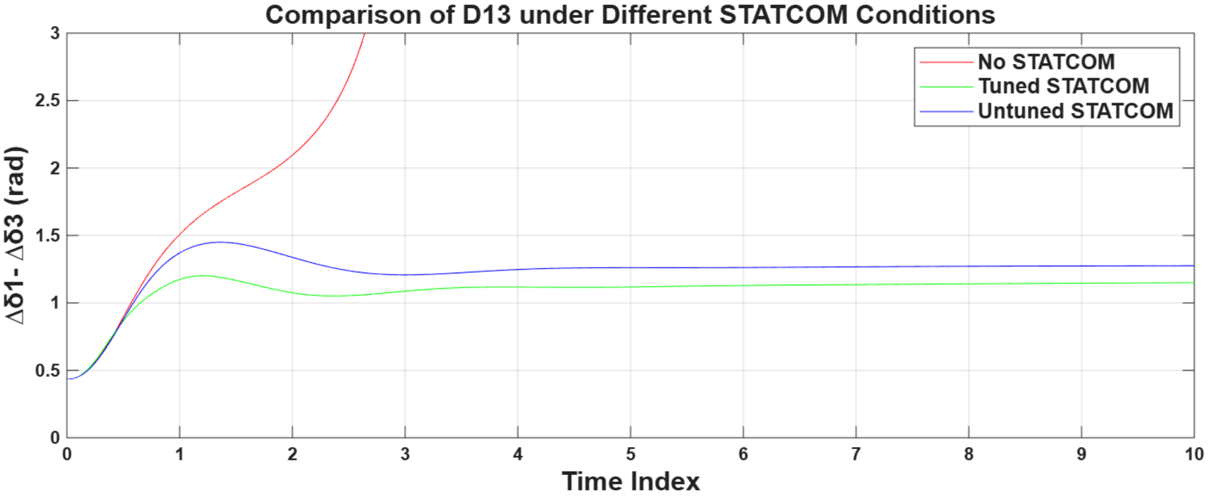


Fig. 5.8: Angle fluctuation between generator 2 and 4 in (p.u) for HBA

Fig. 5.8 highlights the rotor angle stability enhancement, confirming that the optimization-based controller achieves faster settling and improved synchronism compared to the uncompensated and uncompensated cases.

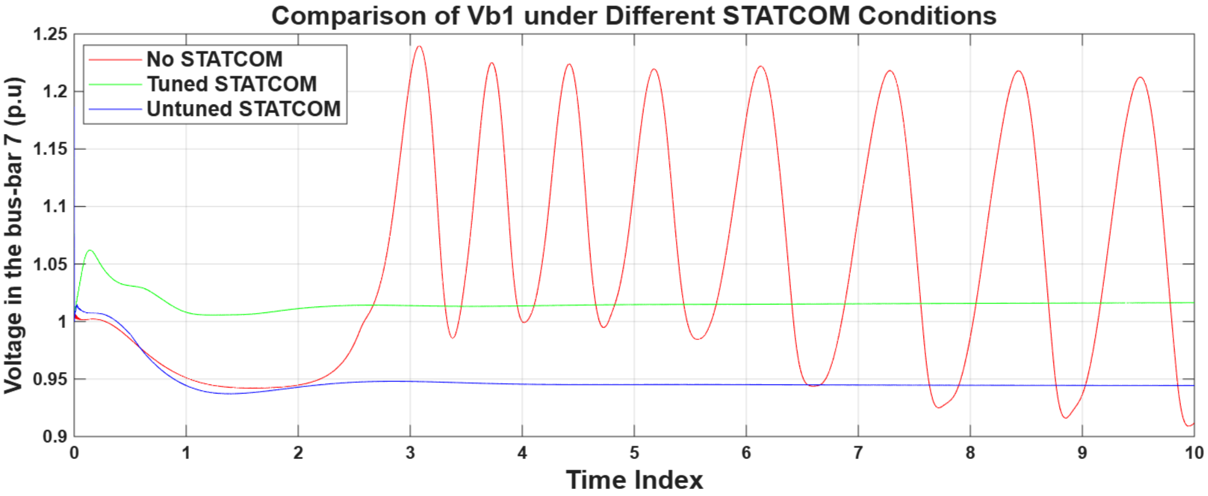


Fig. 5.9: Voltage fluctuation in bus-bar 7 in area 1 in (p.u) for HBA

Furthermore, as shown in Fig. 5.6, under increased loading conditions in Area 2, the HBA-STATCOM provides enhanced voltage profile regulation, thereby maintaining system stability and reliability more effectively than the traditional STATCOM implementation.

Case 2: Analysis Voltage Index

To evaluate the voltage stability performance of the system, 4 established indices—L-index, Voltage Deviation Index (VDI), Voltage Collapse Proximity Indicator (VCPI), and Sensitivity Index-are utilized in this study. Their theoretical basis and formulations were presented in chapter 3.4 section and values are comes from Matlab workspace.

Table 5.6: Voltage Index Comparison for HBA across Bus Bars 7–9

Voltage Index	Value
L-Index	0.06
VDI	0.0446
VCPI	0.06
Sensitivity Index	0.0353

While the computed results under different operating scenarios are summarized in Table 5.6 Together, these indices provide complementary insights, covering proximity to collapse, voltage deviation, system margin, and sensitivity to load changes, thus ensuring a reliable assessment of voltage stability.

Table 5.7: Performance analysis of the Transient State

Techniques	**Settling Time (s)**			
	$\Delta_{\omega 1} - \Delta_{\omega 3}$	$\Delta_{\omega 2} - \Delta_{\omega 4}$	$\Delta_{\delta 1} - \Delta_{\delta 3}$	$\Delta_{\delta 2} - \Delta_{\delta 4}$
No STATCOM	Uncompensated			
Untuned STATCOM	4.1248	4.1365	9.080	8.95
PSO STATCOM	**3.4226**	**3.5358**	**6.9675**	**8.3762**
HABC-PSO STATCOM	3.8155	4.9925	6.8837	8.6346
HBA STATCOM	3.4908	3.6172	7.0214	8.38

Table 5.7 depicts the settling times obtained from the transient stability analysis under different compensation techniques. The uncompensated system exhibits prolonged oscillations, highlighting the necessity of reactive power support. Incorporation of a conventional STATCOM reduces the settling time, but the improvement remains limited. The PSO-optimized STATCOM demonstrates the best overall performance, achieving the lowest settling times for both generator speed deviations and rotor angle deviations, thereby ensuring faster system stabilization. The HABC-PSO and HBA-based STATCOM controllers also provide notable enhancements over the untuned STATCOM, though their performance is comparatively less effective than PSO. These results emphasize the superiority of PSO in tuning STATCOM controllers for enhancing transient stability.

5.4 Discussion

The simulation results and voltage stability index analysis collectively demonstrate the effectiveness of optimization-based STATCOM controllers in enhancing power system stability. The transient response analysis, as shown in Table V, reveals that the uncompensated system suffers from prolonged oscillations, which are significantly mitigated through the incorporation of STATCOM. However, the untuned STATCOM exhibits limitations in reducing settling time effectively. Among the optimization techniques, the PSO-based STATCOM provides the most favorable performance, achieving faster damping of oscillations in both generator speed and rotor angle deviations compared to other approaches. The HABC-PSO and HBA-based STATCOM controllers also improve system response relative to the conventional STATCOM, but their performance remains slightly inferior to that of PSO. This highlights the superior capability of PSO in fine-tuning controller parameters for transient stability enhancement.

The findings from the voltage stability indices further validate these observations. As detailed in Chapter 4, indices such as L-index, VDI, VCPI, and the Sensitivity Index (Table VI) quantify system stress and proximity to voltage collapse. Across the considered bus bars, the PSO-tuned STATCOM consistently achieves lower index values, indicating better voltage support and improved margin against instability. Both HABC-PSO and HBA approaches provide notable improvements compared to the uncompensated and untuned cases, ensuring enhanced voltage regulation under increased load conditions.

Overall, the combined analysis of transient responses and voltage indices demonstrates that optimization algorithms significantly strengthen both dynamic and static stability. In particular, PSO-based tuning emerges as the most effective approach, ensuring faster damping of oscillations, reduced settling times, and improved voltage stability margins. These results confirm that metaheuristic optimization, when applied to FACTS devices such as STATCOM, offers a robust framework for enhancing power system resilience under stressed operating conditions.

Chapter 6: Conclusion and Future Works

6.1 Conclusion

The research presented in this thesis demonstrates the effectiveness of optimization-based control strategies for enhancing the performance of STATCOM in improving power system stability. By employing metaheuristic algorithms, particularly PSO, HBA, and HABC-PSO, the PI controller parameters of STATCOM were optimally tuned, leading to significant improvements in system dynamics under various operating conditions. The comparative analysis revealed that the optimized STATCOM controllers were able to achieve faster settling times, reduce oscillations, and improve both transient and steady-state stability when compared to the uncompensated system and conventional STATCOM.

A key outcome of this study is the observed improvement in rotor speed deviations and rotor angle differences between generators. The PSO-based STATCOM achieved rotor deviation reductions of **17.02%** and **14.52%**, while angle deviation improvements reached **23.26%** and **6.41%**, respectively, showcasing its superior damping capability. Similarly, the hybrid HABC-PSO controller exhibited enhanced robustness by combining global exploration and fast local convergence, thereby ensuring stable operation even under stressed loading conditions.

Furthermore, the voltage stability of the system was evaluated using four widely recognized indices: L-index, Voltage Deviation Index (VDI), Voltage Collapse Proximity Indicator (VCPI), and Sensitivity Index. The analysis confirmed that optimized STATCOM controllers effectively minimized index values across critical bus bars, thereby preventing instability and ensuring reliable operation under increased loading scenarios. Among the tested approaches, the HABC-PSO and HBA algorithms provided superior voltage stability margins compared to conventional STATCOM, highlighting their potential as reliable solutions for future power systems.

In summary, this study establishes that algorithm-based STATCOM tuning not only improves dynamic response but also enhances voltage stability, making it a robust strategy for modern interconnected grids facing increasing load demand and operational uncertainties.

6.2 Future Work

1. Integration of Renewable Energy Sources

Future studies could explore the effectiveness of PSO, HABC-PSO, and HBA-based STATCOM controllers in power systems with high penetration of renewable energy sources such as solar PV and wind. This would assess the algorithms' performance under variable generation and intermittency conditions.

2. Multi-Objective Optimization

Extending the current work to a multi-objective optimization framework could simultaneously consider transient stability, voltage stability, power loss minimization, and cost of reactive power support. Algorithms like NSGA-II or multi-objective PSO could be applied for this purpose.

3. Real-Time Implementation and Hardware-in-the-Loop (HIL) Testing

Future research could involve real-time testing of the optimized STATCOM controllers using HIL simulation or laboratory-scale prototypes, validating the algorithms under practical constraints and noise measurement.

4. Incorporation of Adaptive and Intelligent Control Techniques

Combining metaheuristic optimization with adaptive or fuzzy logic-based controllers could improve STATCOM performance under rapidly changing operating conditions, enhancing robustness and system resilience.

5. Application to Large-Scale Multi-Area Power Systems

Expanding the study to larger, more complex power systems with multiple areas, diverse loads,

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