Swarm Intelligence-Based Optimization of FACTS Devices: A Review of Operation, Control and Emerging Algorithms

Patricia Khwambala[1], Kumeshan Reddy[2], Senthil Krishnamurthy[3]
Mechatronics Department, Nelson Mandela University, Gqeberha, South Africa[1]
Electrical Department, Nelson Mandela University, Gqeberha, South Africa[2]
Electrical, Electronics and Computer Engineering Department, Cape Peninsula University of Technology, Cape Town, South Africa[3]

***Abstract*—The integration of Flexible AC Transmission System (FACTS) devices into modern power networks plays a pivotal role in enhancing voltage stability, reducing transmission losses, and improving overall power transfer capability. Determining the optimal location and sizing of these devices is a critical task that significantly influences system performance. In recent years, swarm intelligence (SI) algorithms have emerged as powerful optimization tools for addressing such complex, nonlinear, and multi-objective problems in power systems. This study presents a comprehensive review of the application of swarm intelligence techniques, Artificial Bee Colony (ABC), Bacterial Foraging Optimization (BFO), Dragonfly Algorithm (DA), Salp Swarm Algorithm (SSA), and Particle Swarm Optimization (PSO). These algorithms are used to optimize the placement and sizing of FACTS devices, such as Static Var Compensators (SVCs), Thyristor-Controlled Series Capacitors (TCSCs), and Static Synchronous Compensators (STATCOMs). The review highlights the underlying mechanisms, strengths, and limitations by comparing the performance of each algorithm in terms of convergence, optimal location, and sizing of a particular FACT device in a power transfer system to enhance voltage stability, minimize real power losses, and improve system loadability. The review provides a comprehensive resource for researchers and practitioners interested in applying swarm intelligence-based optimization techniques of FACTS devices in power transmission systems.**

Keywords—Swarm intelligence; FACTS devices; power transfer system; voltage stability; power losses

I. INTRODUCTION

The United Nations adopted the Sustainable Development Goals (SDGs) in September 2015 as part of the 2030 Agenda for Sustainable Development, which comprises 17 interconnected goals. SDG 7 focuses specifically on energy to ensure access to affordable, reliable, sustainable, and modern energy for all [11]. One of the many targets for this SDG is to double the global rate of improvement in energy efficiency [12].

Across Africa, electricity grids face significant challenges, which include aging infrastructure, inadequate maintenance, and limited investment [1]. These issues contribute to frequent power outages, voltage instability, and high transmission losses [2]. For instance, Nigeria's power grid frequently collapses due to aging infrastructure and insufficient investment, resulting in significant economic losses.

In South Africa, Voltage stability has been challenged by the integration of variable renewable energy sources, such as solar and wind, into the grid [3]. The intermittent nature of these sources leads to fluctuations in voltage levels [4], especially during peak demand periods. To address this, grid infrastructure needs to be modernized to reduce technical losses.

The escalating complexity and demand in modern power systems necessitate advanced solutions to maintain voltage stability and minimize power losses. Flexible AC Transmission System (FACTS) devices, such as Static Var Compensators (SVCs) [5], Thyristor-Controlled Series Capacitors (TCSCs), and Static Synchronous Compensators (STATCOMs), among others, have emerged as pivotal technologies for enhancing the controllability and efficiency of power networks. The strategic placement and sizing of these devices [6] are critical to achieving optimal system performance.

Traditional optimization methods often struggle with the nonlinearity and multi-objectivity of FACTS device allocation problems. In contrast, swarm intelligence (SI) algorithms, inspired by the collective behavior of social organisms, offer robust and adaptable frameworks for tackling complex optimization challenges [7]. Algorithms in [8] & [9], such as Artificial Bee Colony (ABC), Bacterial Foraging Optimization (BFO), Dragonfly Algorithm, Salp Swarm Algorithm (SSA), and Particle Swarm Optimization (PSO), are some algorithms that have demonstrated efficacy in identifying optimal FACTS placements and sizing that enhance voltage profiles and reduce transmission losses.

Furthermore, incorporating renewable energy sources into power systems increases variability and uncertainty, thereby intensifying the complexity of the optimization process [10]. Studies have shown that optimally incorporating FACTS devices in such contexts can effectively mitigate voltage instability and power losses.

This research effectively bridges the existing gap in the literature by comprehensively reviewing swarm intelligence algorithms and demonstrating their potential to optimally size and place FACTS devices in power systems, thereby enhancing power transfer quality, reducing losses, and strengthening voltage stability across diverse operational and network conditions.

This study provides a research methodology, an overview of FACTS devices, followed by a discussion on the purpose of optimization methods for FACTS devices. It is followed by metaheuristic optimization section that includes swarm intelligence techniques. The summary and conclusion appears in the last section.

II. Research Methodology

This study adopts a systematic quantitative research methodology aimed at evaluating the effectiveness of swarm intelligence algorithms in optimally positioning and sizing Flexible AC Transmission System (FACTS) devices within electrical power networks (IEEE-14 Bus and IEEE-57 bus system). The methodology involves selecting and analysing advanced algorithms such as the Artificial Bee Colony (ABC), Bacterial Foraging Optimization (BFO), Dragonfly Algorithm (DA), Swarm Salp Algorithm (SSA), and Particle Swarm Optimization (PSO). Each algorithm literatues is tested on standard IEEE-bus systems to identify the optimal placement and rating of FACTS devices including SVC, TCSC, and STATCOM, under defined operating constraints.

The research process comprises three stages: 1) Understanding of FACTS devices on power transfer systems, 2) Swarm intelligence algorithms as metaheuristic techniques and its application in optimal positioning of FACTS devices and 3) evaluation of strengths and weakenesses of these specifies algoritms through performance metrics such as power loss reduction, voltage deviation minimisation, and enhancement of overall system voltage stability. Table I gives a detailed study of the objectives and description of FACTS.

TABLE I. Main Study Objectives of Optimization in FACTS Devices

Objective	Description
Optimal Location	Determine the best buses or transmission lines to install FACTS devices on to maximize impact.
Optimal Sizing	Choose the appropriate rating (MVAR or MVA) of the FACTS device to avoid over-/undersizing.
Optimal Control Settings	Find the best operational parameters (e.g., phase angle, voltage magnitude, impedance) to enhance system performance.
Minimizing Power Losses	FACTS can reduce reactive power flows and improve power factor.
Enhancing Voltage Profile	Improve voltage stability by dynamically supporting bus voltages.
Increasing Power Transfer Capability	Help the system carry more load without violating constraints.
Minimizing Investment and Operational Costs	Avoid unnecessary expenditure by efficient placement and control.
Stability Improvement	Improve dynamic and transient stability under disturbances.

Literature reviewed between 2020 and 2025, mainly from Elsevier, ScienceDirect, and IEEE Xplore, forms the foundation of the algorithm selection and performance comparison. The methodology ensures that the reviewed swarm intelligence approaches demonstrate tangible improvements in the efficiency and quality of power transfer by reducing real power losses, improving voltage profiles, and ensuring the reliable operation of modern power systems.

III. Flexible Alternating Current Transmission System Devices

These are advanced power electronic controllers used to enhance the controllability, stability, and efficiency of electrical transmission networks. The optimal sizing and location of Flexible Alternating Current Transmission Systems (FACTS) devices are critical for enhancing the performance of electrical power systems [13]. Optimal placement of FACTS devices involves determining the most advantageous locations within the power system to maximize their benefits. Various optimization techniques have been employed to achieve this, including swarm intelligence techniques.

Jumaat et al. demonstrated the effectiveness of PSO in determining the optimal placement and sizing of multiple FACTS devices in an IEEE 30-bus system, highlighting the significant improvements in system performance achieved through strategic installations [13]. Similarly, [14] found that optimal FACTS device location and sizing can enhance system load ability, thereby improving overall transmission efficiency.

The sizing of FACTS devices is equally important, as it directly influences their operational effectiveness. Proper sizing ensures that the devices can meet the system's reactive power demands while maintaining voltage stability. In [15], it was indicated that systematic sizing of FACTS devices is essential for optimizing voltage profiles and minimizing power system losses.

Research has also shown that combining multiple types of FACTS devices can yield superior results compared to single-device installations. Sekhane and Djamel [16] explored the optimal number and location of FACTS devices, demonstrating that a combination of TCSC and SVC [17] can effectively enhance voltage profiles and minimize losses in electrical power systems.

The impact of FACTS devices on system performance depends on their optimal configuration. The study [19] found that the benefits of FACTS devices are significantly influenced by their location and size, which must be carefully considered to maximize transmission capacity and control flexibility [18]. Additionally, in [19], the authors emphasized the importance of sizing FACTS devices to achieve desired stability margins and improve overall system performance.

Therefore, the optimal sizing and placement of FACTS devices are crucial for achieving maximum effectiveness in power transmission systems.

FACTS devices [20], [21] are generally classified into three main categories based on their operational principles: operational-based devices, reactive impedance-based devices and voltage source-based devices. Each category fulfils distinct functions and is suited to specific applications within the power system.

A. Operational-Based FACTS Devices

Operational FACTS devices are power electronic controllers that dynamically regulate transmission parameters such as voltage, impedance, and phase angle, to maximize controllability and efficiency in AC networks [16]. According to [17], they form part of shunt controllers, SVC, STATCOM, series controllers, TCSC, Static Synchronous Series Compensator (SSSC), and combined series–shunt controllers, Unified Power Flow Controller (UPFC), Interline Power Flow Controller (IPFC). They help improve voltage support, power-flow control, and stability.

Phase Shifting Transformers (PSTs) [17] are FACTS devices that manage active power flow by altering the phase angle between network buses. There are two types: tap-changing transformers, which adjust winding taps mechanically, and switched-capacitor/reactor hybrids, which rapidly modulate phase conditions via switching elements.

Tap-changing phase-shifting transformers (PSTs) [23] are FACTS devices that regulate active power transfer by adjusting the phase angle via mechanical tap changers. They are widely used to control loop flows, relieve congestion, and improve transmission capacity in interconnected grids [23]. Unlike other power electronic devices, PSTs provide a cost-effective, robust, and low-maintenance solution for enhancing network flexibility and security.

Switched capacitor/reactor phase-shifting transformers (PSTs) modulate active power flow by dynamically altering phase angles through rapid switching of capacitive or inductive elements [24]. In [25], [26], it is reported that hybrid devices combine Thyristor Switched Series Capacitors (TSSC) or Reactors (TSSR) with conventional PSTs to enable fast, discrete phase adjustments, offering advantages such as enhanced congestion relief, improved loop flow management, and better utilization of existing lines. Their mechanical simplicity and sub-cycle responsiveness make them reliable for enhancing grid flexibility and security.

Tap-changing PSTs offer robust, low-maintenance solutions for loop-flow management and congestion relief. At the same time, Thyristor-controlled PSTs (TCPSTs) enhance grid responsiveness through swift, discrete adjustments. Switched-capacitor/reactor phase-shifting transformers (PSTs) complement conventional tap-changing PSTs by enabling faster, more flexible phase-angle control [17], [25]. Both remain essential FACTS assets, with TCPSTs excelling in dynamic environments and tap-based PSTs in long-term stable control. Future work should integrate hybrid PST schemes that combine mechanical reliability with power-electronic agility, optimize deployment in renewable-rich grids, and ensure interoperability through standardized control strategies and modelling.

B. Reactive Impedance-Based FACTS Devices

Reactive impedance-based FACTS devices play a vital role in regulating reactive power flow, maintaining voltage levels, and controlling phase angles within power transmission systems. By performing these functions, they significantly enhance system stability, reliability, and efficiency [43]. The following subsection outlines the primary types of reactive impedance-based FACTS devices commonly used in modern power networks.

Series compensation FACTS devices, such as the Thyristor-Controlled Series Capacitor (TCSC) and the Thyristor Switched Series Capacitor (TSSC), reduce transmission line impedance to enhance active power transfer [56]. They improve system voltage stability, increase transfer capability, and relieve congestion, enabling better utilization of existing corridors without the need for new infrastructure.

The TCSC device integrates a series capacitor with a thyristor-controlled reactor. It is primarily employed to enhance the transmission capacity of power lines by regulating reactive power flow and improving voltage stability [65]. The TCSC in [48] effectively dampens power system oscillations, thereby enhancing overall system stability and dynamic performance. This device can rapidly adjust the transmission line impedance, thereby improving reactive power management and overall system stability.

As shown in Fig. 1, the Thyristor-Controlled Series Capacitor (TCSC) consists of a series capacitor connected to the transmission line and a thyristor-controlled reactor (TCR) [23], [30]. The circuit typically features a capacitor (C) in series with the line and a thyristor-controlled inductor (L) connected in parallel with the capacitor. By adjusting the thyristor firing angles, the capacitor's effective reactance can be dynamically controlled, enabling enhanced power-flow regulation and improved voltage stability within the transmission system.

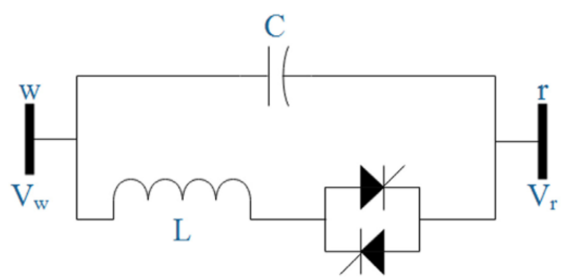

Fig. 1. Thyristor Controlled Series Capacitor (TCSC) circuit [23].

where, jX_{TCR} in Eq. (1), the TCR's effective reactance, is related to the delay angle $\boldsymbol{\alpha}$ in Eq. (2) [30].

$$X_{TCSC} = \frac{jX_{TCR}(-jX_C)}{jX_{TCR}-jX_C} = j\frac{|X_{TCR}|.|X_C|}{|X_{TCR}|-|X_C|} \quad (1)$$

$$X_{TCR}(\alpha) = \frac{\pi X_L}{2(\pi-\alpha)+\sin 2\alpha} \quad (2)$$

Thyristor-Switched Series Capacitors (TSSCs) are discrete FACTS devices in which series capacitors are bypassed or inserted via anti-parallel thyristor valves, enabling stepwise control of line compensation [27]. This configuration reported in [28] enhances active power flow, improves transient stability by damping oscillations, mitigates sub-synchronous resonance risks through fast switching, and reduces maintenance compared to mechanical switches.

They enhance active power transfer, damp power system oscillations, improve transient and voltage stability, and suppress sub-synchronous resonance. TSSCs are valued in dynamic, renewable-rich grids for their fast response, durability, and modular scalability [65]. Their flexibility enables placement optimization to efficiently relieve congestion and maximize existing infrastructure. Economically, they reduce maintenance compared to traditional mechanical switching, while maintaining high reliability under variable loading and fault conditions [17].

Shunt compensation FACTS devices, primarily the Static Var Compensator (SVC) and static synchronous compensator (STATCOM), inject or absorb reactive power to regulate voltage, improve stability, and enhance power transfer capability. SVCs employ thyristor-controlled reactors and switched capacitors, offering robust, economical dynamic var support on transmission grids [30]. Converter-based STATCOMs in [41] and [42] provide faster response, near-constant reactive current at low voltages, and superior flicker and disturbance mitigation, benefiting weak grids and renewable integration. Together, these devices maintain bus voltages, reduce losses, increase loadability, and damp electromechanical oscillations as reported in [29], [30], [41], [42] when coordinated with system controls and protective schemes in modern, converter-dominated networks.

Thyristor-controlled reactors (TCRs) are shunt FACTS elements: a reactor in series with anti-parallel thyristors, whose phase-controlled firing angle continuously varies the inductive susceptance [43]. Integrated into SVCs, TCRs absorb reactive power to regulate bus voltage, increase loadability, and improve transient and small-signal stability [43], [65]. Practical deployment in [65] addresses characteristic harmonics through filters and coordinates with thyristor-switched capacitors to deliver Var control and flicker mitigation at weak transmission nodes and loads.

Thyristor-Switched Capacitor (TSC) is a shunt FACTS element that uses bidirectional thyristor valves to switch capacitor steps, delivering discrete, transient-free reactive power for fast voltage support, power-factor correction, and flicker mitigation. Integrated within SVCs, TSC branches complement TCRs to achieve a wide range with low losses and high reliability [48], [65]. Deployments span transmission and distribution nodes in [65] requiring fast voltage regulation under variable loads and renewable penetration.

C. *Voltage Source-Based FACTS Devices*

Voltage-source-based FACTS devices use self-commutated converters to synthesize controllable AC voltages and currents, enabling fast, continuous control of reactive power and, through series injections, active power flow [38]. Shunt STATCOMs provide near-constant reactive current at low voltages, stabilizing weak grids and supporting inverter-based resources; series SSSC and combined UPFC extend capability to regulate line impedance, voltage, and power flow, improving transfer limits and damping oscillations [38], [53]. Converter in [53] significantly advances dynamic performance, with robust control frameworks and accurate steady-state models now available for planning and Optimal Power Flow (OPF) integration of VSC-based controllers in transmission networks and renewable power systems.

Series voltage-source-based FACTS [56] devices inject controllable AC voltage in series with a line to regulate power flow, boost transfer capability, damp oscillations, and enhance transient stability and reliability margins in converter-dominated grids.

A Static Synchronous Series Compensator (SSSC) is a series VSC-based FACTS controller, as shown in Fig. 2 that injects a controllable quadrature voltage to emulate variable capacitive or inductive reactance and regulate line power flow, raise transfer limits, and damp oscillations. Practical deployment emphasizes robust protection and fault-ride-through using fast varistor/thyristor schemes [56], and system-level coordination for predictability, placement, and security of SSSC-compensated corridors under renewable variability [57]. These capabilities support stability, reliability, and resilience in modern, converter-dominated grid operation.

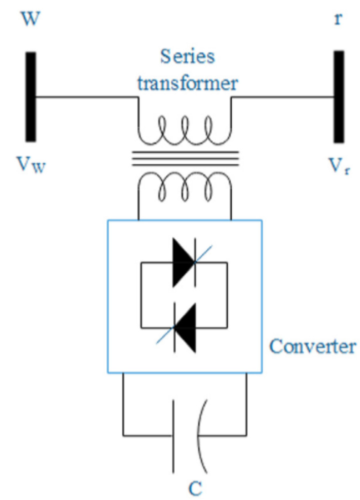

Fig. 2. Static synchronous series compensator circuit [23].

Shunt voltage source converter FACTS devices inject or absorb reactive current to hold bus voltages, stiffen weak grids, and aid renewable integration [53]. Advances in converter topology and control deliver fast response and near constant current, improving transfer margins, flicker mitigation, and oscillation damping in transmission networks.

Static synchronous compensators (STATCOMs) are shunt-voltage-source converter FACTS controllers that inject or absorb reactive current to regulate bus voltage and strengthen weak grids [38]. Compared to SVCs, STATCOMs provide near-constant reactive current at low voltages, faster dynamics, and improved damping of flicker and oscillations [53]. The circuit diagram in Fig. 3 typically includes a voltage source inverter (VSI) connected to a coupling transformer and a DC capacitor [38]. The VSI converts the DC voltage from the capacitor into AC voltage, which can be adjusted to provide the required reactive power.

STATCOMs use voltage-source converters to provide dynamic reactive power support, as shown in Fig. 3. They can respond quickly to changes in system conditions, making them effective for voltage regulation and for improving system stability [38]. STATCOMs are particularly beneficial in systems with high penetration of renewable energy sources, where voltage fluctuations are common. STATCOM [38] can respond rapidly to changes in system conditions, making it effective for voltage regulation and improving power quality [see Eq. (3)].

$$S_{STC} = V_{STC} I_{STC} = V_{STC} V_{STC} Y_{SC} - V_{STC} Y_{SC} V_i \quad (3)$$

where, I_{STC} is the complex conjugate of STATCOM current, V_{STC} is the complex conjugate of STATCOM voltage , and Y_{STC} is the complex conjugate of short-circuit admittance [33].

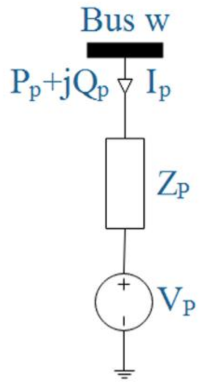

Fig. 3. Static synchronous compensator circuit [23].

Combined VSC-based FACTS devices like the unified power flow controller (UPFC) couple shunt and series converters through a common DC link to regulate bus voltage and line power flow simultaneously, increasing transfer capability and damping oscillations [62]. Recent research advances steady-state models and protection/fault identification for UPFC deployments in transmission corridors.

Unified power flow controllers (UPFCs) combine shunt and series voltage-source converters via a common DC link to independently regulate bus voltage and line power flow. By injecting controllable series voltage and exchanging reactive current, UPFCs increase transfer capability, relieve congestion, and damp electromechanical oscillations while supporting renewables [63]. Recent work provides steady-state models for planning and OPF, and convex formulations for security-constrained economic dispatch in [63] by improving scalability, dispatchability, and reliability.

The UPFC circuit diagram in Fig. 4 typically consists of two voltage-source converters: one connected in series with the transmission line and the other connected to the shunt side. The series converter injects voltage into the line, while the shunt converter regulates the DC link voltage.

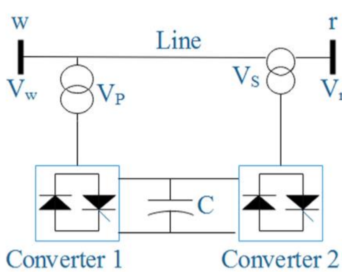

Fig. 4. Unified Power Flow Controller (UPFC) circuit [23].

Static Var Compensator (SVC): SVCs compensate for reactive power and maintain voltage stability in the power system. They consist of a combination of capacitors and inductors controlled by thyristors, allowing for rapid response to voltage fluctuations [38]. The SVC is effective at maintaining voltage within the desired range and responds quickly to changes in load conditions, thereby improving overall power quality [53]. SVCs are widely deployed in transmission networks to enhance power quality and system reliability.

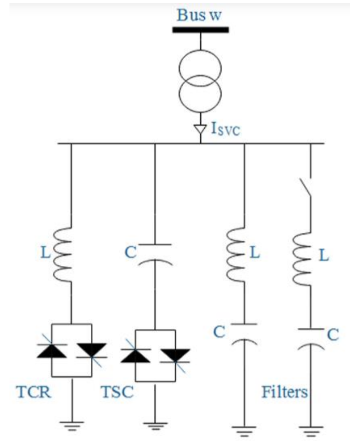

Fig. 5. Static Var Compensator (SVC) circuit [23].

The SVC in Fig. 5 is composed of a combination of capacitors and inductors, controlled by thyristors. The circuit diagram typically shows a bank of capacitors (C) and a bank of inductors (L), with thyristors (T) used to switch the inductors in and out of the circuit as needed. This configuration allows for real-time reactive power compensation [see Eq. (4) and Eq. (5)].

$$X_{SVC} = \frac{X_L(\alpha).X_C}{X_L(\alpha) + X_C} \tag{4}$$

with

$$X_L(\alpha) = X_{L0}\frac{\pi}{2(\pi - \alpha) + \sin 2\alpha} \tag{5}$$

where, X_{L0} is the fundamental frequency reactance of the reactor without thyristor control and α is the firing angle of the valves with respect to the zero-crossing instant of the controller voltage [31].

Thyristor-Controlled Phase Shifter (TCPS): This device controls power flow in transmission lines by adjusting the phase angle of the voltage. TCPS can be particularly useful in managing power flows in meshed networks and alleviating congestion [65]. By controlling the phase angle, the TCPS can effectively manage power flows in the network, helping to ease congestion and improve system stability [48].

The TCPS in Fig. 6, is designed to control the phase angle of the voltage in a transmission line. The circuit diagram typically includes a thyristor-controlled reactor (TCR) connected in series with the transmission line, allowing adjustment of the phase angle by varying the reactor's reactance.

where, T is the operational mode with X_F, X_v. K_1 and K_2 as computational coefficients [32].

Flexible AC Transmission Systems (FACTS) devices enhance power system flexibility, controllability, and stability by dynamically regulating key parameters. They are broadly categorized into operational-based, reactive impedance-based, and voltage source-based devices. Each class functions differently, controlling variables such as impedance, voltage, or phase angle to optimize system performance.

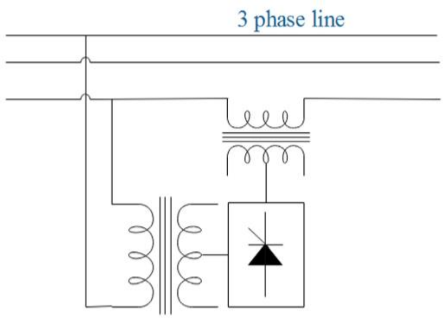

Fig. 6. Thyristor-controlled phase shifter circuit [23].

IV. Optimization Methods for FACT Devices

Optimization methods are critical tools for determining the optimal location, sizing, and operation of FACTS devices in a power system. These methods aim to maximize system performance while minimizing cost and operational issues.

FACTS devices are powerful but expensive tools. Improper placement or operation can lead to:

- Underutilization of expensive equipment.
- Instability or overcompensation.
- Increased system losses or operational costs.

Hence, optimization ensures cost-effective, reliable, and efficient use of FACTS.

Table II presents a consolidated summary of these FACTS device classes, highlighting their control variables, operational principles, and typical applications.

TABLE II. Summary of Operational Characteristics and Applications of FACTS Devices

FACTS Device Type	Reference	Device Name	Configuration	Control Variables	Main Function	Operational Principle	Typical Application
Operational based	[16,17,23,24,27]	TCSC TSR	Shunt, series, combined;	Voltage, Reactive-power, Current, Susceptance, Reactance, Firing-angle, Phase-angle	regulate voltage support vars control flow damp oscillations improve stability	Switch shunt/series reactance, or synthesize voltages, to regulate power flow.	Voltage-regulation, var-support, power-factor-correction, flicker-mitigation, power-flow-control, congestion-relief, stability-enhancement
Reactive Impedance-based	[27,43, 65,28,17]	TCR, TSR	Shunt, series;	firing-angle conduction-angle thyristor-state capacitor-step reactor-current susceptance reactance	voltage-regulation reactive-power-compensation line-impedance-control power-flow-control stability-enhancement oscillation-damping loss-reduction	Phase control thyristors adjust reactors or capacitors, varying impedance continuously	Voltage-regulation, var-support, power-factor-correction, compensation, power-flow-control, congestion-relief, loss-reduction.
Voltage Source-based	38,53,56,57,62]	STATCOM SSSC UPFC	Shunt, series, combined	modulation-index phase-angle injected-voltage reactive-current active-current	voltage-regulation stability-enhancement power-flow-control	Synthesize controllable AC voltage; regulate reactive current; control power flow.	Voltage-regulation, reactive-support, weak-grid-stabilization, renewable-integration, power-flow-control, voltage-stability-enhancement

V. Metaheuristic Optimization Techniques

Metaheuristic optimization techniques (MOT) [34] have emerged as powerful tools for solving complex optimization problems in various fields, including electrical engineering and power systems. These techniques are particularly effective for non-convex, combinatorial problems, such as the optimal placement and sizing of Flexible Alternating Current Transmission Systems (FACTS) devices.

Determining the best locations for FACTS devices helps to maximize their effectiveness in enhancing voltage stability and minimizing losses [33, 34, 35]. Studies have shown that metaheuristic techniques can effectively identify optimal locations based on system characteristics and load conditions.

Optimizing the capacity of FACTS devices to ensure they meet the reactive power requirements of the system while minimizing costs [36, 37]. Many studies have focused on optimizing multiple objectives simultaneously [38], such as reducing costs while maximizing system reliability and performance. Metaheuristic techniques are well-suited for handling such multi-objective problems due to their flexibility and adaptability.

Swarm Intelligence (SI) is an area of artificial intelligence that draws inspiration from the collective behavior of social organisms, such as ants, bees, birds, and fish. This paradigm is characterized by decentralized control, self-organization, and the ability to solve complex problems through simple agents interacting with one another and their environment [39, 40]. The concept of swarm intelligence [41] has been widely applied to the positioning and sizing of FACTS devices, leading to the development of various algorithms that leverage its principles for optimization tasks.

Decentralization in swarm intelligence, zero systems operate without central control, with individual agents making decisions based on local information and simple rules, resulting in emergent behavior at the group level. This decentralized approach offers flexibility and robustness in problem-solving [42, 43]. This decentralized nature enables optimal placement of FACTS devices, such as using Particle Swarm Optimization (PSO) to enhance voltage stability and minimize losses [39, 40]. By leveraging local information, these algorithms can adaptively respond to system changes, ensuring devices are placed where needed most. This decentralized nature in [40] contributes to the robustness and adaptability of FACTS devices in power systems, enhancing overall system reliability.

Self-organization is a fundamental property of swarm intelligence (SI) systems, whereby decentralized agents interact locally with one another and their environment to produce coherent, system-level behavior without central control. The emergent phenomenon enables SI systems to adapt to dynamic operating conditions autonomously, enhancing performance without the need for external intervention.

In biological systems, such as ant colonies, simple behavioral rules and local communication mechanisms give rise to complex problem-solving capabilities. This principle has inspired numerous computational optimization techniques [44]. In the context of electric power systems, the self-organizing behavior of SI can be leveraged to optimize the placement and sizing of Flexible AC Transmission Systems (FACTS) devices [45], [46] including Static Var Compensators (SVC), Thyristor-Controlled Series Capacitors (TCSC), and Unified Power Flow Controllers (UPFC), can be coordinated in a distributed manner to enhance voltage stability, improve load-ability, and reduce transmission losses under fluctuating system conditions. Such adaptability allows device configurations to be modified in near-real time based on local measurements, enabling the grid to respond effectively to disturbances and demand variations.

Several metaheuristic optimization methods depicted in Fig. 7 are grouped into swarm-based, physics-based, evolution-based, and human- and socio-inspired algorithms.

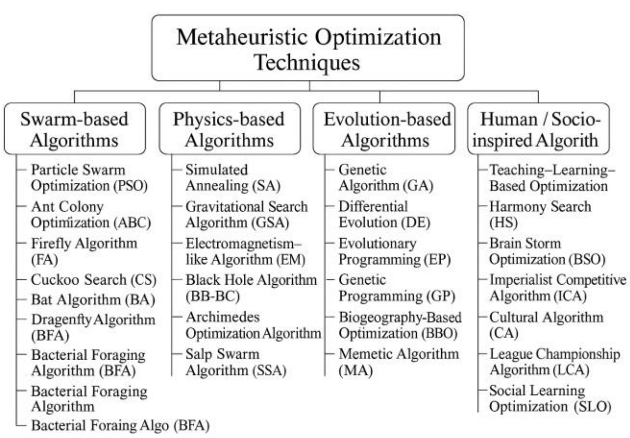

Fig. 7. Metaheuristic optimization techniques including swarm intelligence.

The mechanism of self-organization in SI algorithms is driven by local interactions, in which each agent adjusts its behavior based on immediate surroundings and limited feedback. In optimization frameworks such as Particle Swarm Optimization (PSO), the Grey Wolf Optimizer (GWO), and the Gorilla Troops Optimizer (GTO), this principle enables FACTS devices to be allocated to minimize system losses and maximize voltage stability while respecting system constraints [47, 48, 49]. Self-organization supports the integration of hybrid metaheuristics, such as combining PSO with other search strategies, [46] and [50], enabling dynamic resizing of FACTS devices in response to real-time reactive power demands and ensuring both technical and economic efficiency.

Recent studies confirm that swarm-based self-organization is particularly effective in solving multi-objective FACTS placement problems, simultaneously optimizing cost, stability margin, and power-loss reduction in renewable-integrated networks [44, 47, 48]. The inherent robustness of self-organized SI systems ensures reliable system operation even under significant disturbances, making them a promising approach for modern, adaptive power systems.

Stigmergy is an indirect communication mechanism in which agents influence one another by modifying their shared environment. In swarm intelligence, this principle enables coordinated behavior without direct interaction, as seen in ant pheromone trails. In power systems, staggery facilitates adaptive FACTS device placement and operation [56], [57], where changes in one device’s status inform others’ decisions, improving voltage stability and minimizing losses.

Collective Intelligence: swarm-based optimization harnesses collective intelligence, where a group of simple agents collaborates through local interactions to explore solution spaces more effectively than isolated agents [52]. In nature, bees forage [53] efficiently by responding to local stimuli, demonstrating how collective behaviors emerge from decentralized rules and yield superior performance.

In power systems, this principle directly benefits the distributed placement and sizing of FACTS devices [51], [54]. Rather than relying on centralized control, FACTS units can coordinate through emergent swarm behaviors, enabling adaptive responses to dynamic conditions such as load fluctuations and voltage instability.

One illustrative approach is the Autonomous Groups Particle Swarm Optimization (AG-PSO) method, which applies swarm intelligence to determine optimal SVC locations and sizes, significantly reducing transmission losses [55]. Similarly, hybrid algorithms in [52] combining Genetic Algorithms with PSO (GA-IPSO) optimize the sizing and placement of STATCOM, TCSC, and UPFC in radial power networks, achieving enhanced voltage profile control and reduced system losses.

Emergent collective intelligence also plays a vital role in multi-objective optimization, where objectives such as system cost, stability, and loadability must be balanced. Swarm-based algorithms naturally navigate these trade-offs by dispersing and aggregating candidate solutions, ultimately converging toward Pareto-optimal configurations for FACTS deployment [54]. Fig. 8 shows the unified concept of swarm intelligence.

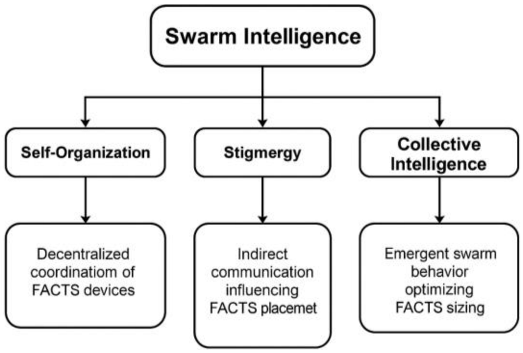

Fig. 8. Swarm intelligence unified conceptual diagram.

Swarm intelligence algorithms are nature-inspired optimization techniques that mimic the collective behavior of biological populations. They provide powerful tools for solving complex engineering problems with adaptability and robustness. The following section explores the Artificial Bee Colony Algorithm (ABC), Bacterial Foraging Optimization (BFO), Dragonfly Algorithm (DA), Salp Swarm Algorithm (SSA), and Particle Swarm Optimization (PSO) as swarm-based algorithms, highlighting their unique characteristics.

A. Artificial Bee Colony Algorithm

The Artificial Bee Colony (ABC) algorithm is a swarm intelligence metaheuristic inspired by the foraging behavior of honeybees. It consists of three types of agents: employed bees, which explore the neighborhood of current food sources; onlooker bees, which probabilistically select promising sources based on the quality shared by employed bees; and scout bees, which abandon depleted sources to discover new ones. Through this decentralized, collaborative process, ABC [63], [66] effectively explores and exploits the search space, making it suitable for complex optimization problems.

ABC demonstrates strong global exploration capabilities and robustness against local optima, primarily due to its randomized neighborhood search [58], [61]. However, compared to Particle Swarm Optimization (PSO) and Genetic Algorithms (GA), ABC often converges more slowly because its information-sharing mechanism relies heavily on probabilistic sampling rather than deterministic best-solution propagation [64]. Recent studies have improved convergence by integrating Bayesian estimation [58], elite-driven adaptive population scaling [59], and adaptive exploration control [60], resulting in faster convergence without compromising exploration diversity. ABC has been widely applied to the optimal placement and sizing of Flexible AC Transmission Systems (FACTS) to enhance voltage stability and reduce power losses in both small and large-scale networks. For example, Shokouhandeh et al. [61] used ABC for reactive power management with SVC devices, achieving superior improvements in the voltage profile compared with conventional methods. On the IEEE 30-bus system, a multi-objective hybrid ABC significantly minimized active power losses and improved voltage deviation indices [62].

In benchmark case studies, ABC-based optimization has produced measurable performance gains on the IEEE 30-bus system with SVC and TCSC devices. ABC improved voltage stability by 15% and reduced active power losses by 20% [66]. On the IEEE 11-bus system, optimal SVC placement achieved close to 25% loss reduction and noticeable improvement in the voltage profile [61], and in large-scale IEEE 118-bus networks, the ABC algorithm in [66] yielded a 15% absolute power loss reduction while enhancing overall stability.

Strengths of ABC include its high global search capacity, which reduces the risk of local optima entrapment [58],[60]. Simplicity of implementation and adaptability to multi-objective and discrete problems [65]. Weaknesses include slower convergence compared to PSO and GA, due to less structured information sharing [64], [66]—an exploration–exploitation imbalance [67] that can limit the fine-tuning of near-optimal solutions.

Hybridization strategies, such as combining ABC with PSO, can inherit PSO's fast convergence while maintaining ABC's exploration capacity [59], [62]. Adaptive control of search parameters [60] and integration with other metaheuristics such as Firefly or Ant Colony Optimization [67] can also improve convergence and balance.

B. Bacterial Foraging Optimization

The Bacterial Foraging Optimization (BFO) algorithm is a nature-inspired metaheuristic mimicking the foraging behavior of Escherichia coli. BFO employs three primary operations: chemotaxis —bacteria move through tumbling and swimming toward nutrient-rich regions; reproduction —healthiest bacteria replicate, replacing weaker ones; and elimination — dispersal, random removal, or relocation of bacteria to sustain diversity. This collective mechanism guides a swarm of agents through the search space, facilitating efficient global optimization [69].

BFO effectively explores complex, multimodal landscapes and shows robust global search behavior [69]. However, compared with algorithms like PSO, it's known to have a slower convergence rate, attributed to its stochastic movements and the lack of direct global-best information sharing [69], [72]. Nonetheless, modified BFO variants, such as those incorporating adaptive chemotactic step-size or hybrid schemes, have exhibited faster convergence while retaining exploration capacity [69]. BFO has been applied to the optimal placement and sizing of FACTS devices, such as SVCs, TCSCs, STATCOMs, and IPFCs, to enhance voltage stability and reduce power losses in various test networks.

A study using BFO for reactive power and voltage management in IEEE 39-bus systems with UPFC devices demonstrated improved voltage stability and reduced transmission losses [68]. In the IEEE 30-bus system, BFO-based methods significantly improved voltage profiles and reduced losses [70]. BFO optimized DSTATCOM placement in distribution systems [71] with performance gains in voltage regulation and loss reduction.

Strengths of BFO include global exploration, simplicity, and ease of implementation [72]. At the same time, weaknesses include slow convergence, parameter sensitivity, and longer computation time [69, 72]. The weaknesses can be mitigated by hybridizing BFO with PSO [69] or other fast-converging algorithms, by adaptive control of the chemotactic step size, and by incorporating elimination–dispersal and reproduction adaptively.

The BFO algorithm offers a compelling, biologically inspired approach for FACTS device optimization, with proven benefits in voltage stability and power loss reduction. Its global search strength is counterbalanced by slower convergence and parameter sensitivity. Advances through hybrid and adaptive variants are promising routes to enhance convergence speed without sacrificing robustness. As a result, BFO remains a valuable technique in the optimization toolbox for modern power systems.

C. Dragonfly Algorithm

The Dragonfly Algorithm (DA) is a swarm-inspired metaheuristic that models dragonfly swarming behavior, specifically their foraging and predator-avoidance tactics. DA partitions its search process into two pivotal phases: exploration, where agents (dragonflies) travel far to locate promising regions, and exploitation, where collective, neighborhood-based movement guides convergence toward optimal solutions [73]. These behaviors emulate natural local interaction rules — separation, alignment, and cohesion — as optimization operators.

Empirical comparisons reveal that DA features superior exploration capability, enabling rapid coverage of high-dimensional search spaces. In various benchmark studies, DA has outperformed traditional swarm paradigms such as Particle Swarm Optimization (PSO) and Genetic Algorithms (GA) in terms of convergence speed and solution quality, especially on multimodal and high-complexity problems [74].

Recent research has applied DA to the optimal placement and sizing of Flexible AC Transmission Systems (FACTS), notably TCSCs and SVCs, to bolster voltage stability and minimize active power losses, in a Diyala 132 kV network. DA-based optimization of TCSC and SVC configurations resulted in a 15% improvement in voltage stability margin and approximately a 23% reduction in total system losses [75]. On IEEE-30 and IEEE-118 bus systems, DA-enhanced FACTS deployment demonstrated marked improvements in voltage profiles and reduced congestion-induced losses [76].

Strengths of DA include excellent global exploration, fast convergence on complex multimodal problems, and a relatively simple implementation framework [73]. In contrast, its weaknesses include the risk of premature convergence to local optima, dependence on random initialization for stability, and the need for careful parameter tuning [73]. Mitigation of weaknesses includes hybridizing with PSO and DE for guided search, adaptive control of step coefficients, and incorporating parameter self-adaptation techniques [77].

The Dragonfly Algorithm stands as a powerful, nature-inspired approach for FACTS device optimization in power systems. Its strengths lie in swift exploration of solution spaces and effective handling of complex, multimodal problems. Studies have validated DA's ability to significantly improve voltage stability and reduce system losses in a realistic power network. However, DA's stochastic nature can lead to local convergence unless mitigated by hybrid approaches and adaptive parameter tuning. Emerging hybrid designs offer a promising path for combining DA's best traits with accelerated convergence and improved robustness.

D. Salp Swarm Algorithm

The Salp Swarm Algorithm (SSA) is a nature-inspired metaheuristic, modeled on the chain-like swarming behavior of Salps in the ocean [78]. It employs two phases: exploration, in which the leading Salp performs randomized movement across the search space to discover promising regions. The second is exploitation, in which followers update their positions relative to the leader and their neighbors, refining toward optimal solutions [79]. These dynamics foster a balance between global exploration and local exploitation, rendering SSA suitable for complex optimization challenges.

SSA tends to converge more slowly than algorithms such as Particle Swarm Optimization (PSO) and Genetic Algorithms (GA), primarily because of its randomized, leader-follower movement strategy [80], [81]. In highly multimodal landscapes [81], maintaining population diversity becomes challenging, increasing the risk of premature convergence into a local optimum.

SSA has been successfully applied to optimize the placement and sizing of Flexible AC Transmission System (FACTS) devices, such as SVCs and TCSCs, for voltage profile enhancement and power loss minimization, such as on the IEEE 30-bus system. SSA-based optimization resulted in approximately a 15% improvement in voltage stability and a 22% reduction in power losses [79]. On the IEEE 57-bus system, SSA yielded a 12.5% increase in voltage stability and a 20% reduction in losses [82]. In the modified IEEE 14-bus system, optimal FACTS placement via SSA [80] achieved a 16% enhancement in voltage profile stability and an 18% decrease in power losses.

Strengths of SSA include compelling exploration in early search, simple implementation with clear phases, and being well-suited for continuous, nonlinear spaces. In contrast, weaknesses include slow convergence toward the optimum, being prone to local optima in complex landscapes, and poor balance between exploration and exploitation. The mitigation of these weaknesses may be achieved by hybridizing SSA with PSO/DE for faster convergence [81], adaptive leader update, or dynamic control of influence radius [81,82], and incorporating chaotic or opposition-based strategies [78].

The Salp Swarm Algorithm presents an innovative, bio-inspired strategy for optimizing the placement and sizing of FACTS devices in power systems. Its dual-phase structure effectively balances global exploration and local exploitation, resulting in significant reductions in losses and improvements in voltage stability across standard IEEE test systems. However, SSA's slower convergence and vulnerability to local optima highlight its need for augmentation. Hybrid formulations and adaptive strategies promise to enhance SSA's convergence speed and robustness, making it a viable tool for advanced power system optimization.

E. Particle Swarm Optimization

Particle Swarm Optimization (PSO) is a prominent metaheuristic inspired by the collective behavior of birds or fish schools. Introduced by Kennedy and Eberhart in 1995, PSO features a swarm of particles, each representing a candidate solution, with associated positions and velocities [83]. Each particle tracks its own best-known position (pBest) as well as the swarm's best position (gBest). Velocity updates combine inertia, cognitive attraction to pBest, and social attraction to gBest, enabling particles to converge on optimal solutions [84], collaboratively.

PSO is known for its fast convergence, facilitated by its dual communication mechanism (particles sharing both personal and global bests) [83]. Comparative studies have shown that PSO often outperforms classic algorithms such as Genetic Algorithms and Differential Evolution in both convergence speed and solution quality on benchmark functions [84]. However, rapid convergence can sometimes lead PSO [85] to prematurely settle on local optima, especially in highly multimodal search landscapes.

TABLE III. SUMMARY OF SWARM INTELLIGENCE ALGORITHMS APPLIED TO FACTS DEVICES

Optimization Technique	References	Key Features	Objectives	FACTS Devices Applied To	Advantages	Limitations	Applications
Artificial Bee Colony (ABC)	[4,58,61,62,63,64,66]	Exploration – ability to avoid local optima, Adaptation - balances exploration and exploitation. Optimization as it achieves near optimal solutions.	Efficient global search. Balanced exploration and exploitation and Optimization of complex problems	SVC, TCSC, STATCOM	-Global exploration ability -Simplicity and fewer parameters -Robustness across problems	-Slow convergence -Sensitivity to parameters -Risk of premature abandonment	IEEE 30-bus: +15% voltage stability, −20% losses; IEEE 11-bus: −25% losses; IEEE 118-bus: −15% losses
Bacterial Foraging Algorithm (BFO)	[68,69,70,71,72]	Chemotaxis, Swarming – enhances information sharing. Elimination - removes unfit bacteria. Adaptation.	-Effective problem solving - Maintain diversity - Global optimization	SVC, TCSC, STATCOM, IPFC, DSTATCOM, UPFC	-Effective global search -Maintains population diversity -Good at avoiding local optima	Complex due to many parameters -Slow convergence -Highly sensitive	IEEE 39-bus (UPFC): improved voltage & reduced losses; IEEE 30-bus: improved voltage & reduced losses; Distribution: improved voltage & reduced losses
Dragonfly Algorithm (DA)	[73,74,75,76,77]	Separation, Distraction – moves away from poor solutions. Attraction – moves towards good solutions	-Simulate swarm dynamics -Balance search phases -Optimize complex systems	TCSC, SVC	-Strong balance between exploration and exploitation -Performs well on multimodal optimization problems	-Can stagnate if diversity is lost -Requires careful parameter control for stability	Diyala 132kV: +15% voltage stability, −23% losses; IEEE 30/118-bus: improved voltage & reduced congestion losses
Salp Swarm Algorithm (SSA)	[78,79,80,81,82]	Leader – guides toward the best solution. Exploitation – refines solutions. Relatively fast convergence.	-Model chain movement -Enhance Exploration and exploitation -Achieve convergence.	SVC, TCSC	-Simple structure with leader-follower dynamics -Efficient in both global and local search phases -Fast convergence	-May get trapped in local optima -Limited exploitation ability in late iterations.	IEEE 30-bus: +15% voltage stability, −22% losses; IEEE 57-bus: +12.5% voltage stability, −20% losses; IEEE 14-bus: +16% voltage stability, −18% losses
Particle Swarm Optimization (PSO)	[83,84,86,87]	Particles for search, Balances global and local search and fast convergence, Ensures broad search	-Leverage social learning -Balance exploration and exploitation -Optimize high-dimensional problems	TCSC, SVC, STATCOM, IPFC	-Fast convergence -Simple due to a few parameters -Effective balance on personal and social learning (Pbest and gbest)	-Prone to premature convergence -Exploration ability decreases over time -May require hybridization for high-dimensional problems.	IEEE 14-bus: +20% voltage stability; IEEE 57-bus (IPFC): +15% voltage stability, −22% losses

PSO has been widely used to optimize the placement and sizing of FACTS devices such as TCSC, SVC, and STATCOM in power systems to enhance voltage stability and reduce power losses. For example, the PSO-based hybrid method applied to the IEEE 14-bus system demonstrated notable improvements in the voltage profile and a 20% reduction in losses [86]. On the

IEEE 57-bus system, PSO-optimized Interline Power Flow Controller (IPFC) [87] deployment yielded qualitative improvements in voltage and losses, reporting 15% voltage enhancement and 22% loss reduction.

Strengths include high convergence speed, intuitive and straightforward implementation, and well-established and extensively studied. The PSO weaknesses include premature convergence, difficulties with complex, multimodal problems, and large-scale issues that increase computational burden [85]. These can be mitigated by hybridizing with exploration-rich methods such as DE or Firefly, Adaptive inertia weight, or velocity strategies to balance exploration and exploitation [84], and by Parallel or distributed PSO implementations to accelerate computation.

PSO is a widely used swarm intelligence algorithm that exhibits rapid convergence and a straightforward implementation [83]. It has been applied successfully to the placement and sizing of FACTS devices, yielding improvements in voltage stability and loss reduction in test power networks. While fast convergence is a strong advantage, it also increases the risk of getting stuck in local optima. Hybrid approaches, adaptive mechanisms, and parallel implementations offer promising avenues to enhance PSO's robustness and scalability for complex, real-world FACTS optimization tasks.

Artificial Bee Colony (ABC), Bacterial Foraging Optimization (BFO), Dragonfly Algorithm (DA), Salp Swarm Algorithm (SSA), and Particle Swarm Optimization (PSO) represent widely applied swarm intelligence techniques, each inspired by distinct natural behaviors. These algorithms demonstrate strengths in exploration, exploitation, and adaptability across a range of optimization challenges. Table III provides a consolidated summary of their key principles, merits, limitations, and typical applications in power system optimization.

VI. Conclusion

Swarm intelligence algorithms have proven to be powerful metaheuristic optimization tools for the optimal allocation of Flexible AC Transmission System (FACTS) devices, which are vital for improving power system performance and stability. Review studies on algorithms such as the Artificial Bee Colony, Bacterial Foraging Optimization, Dragonfly Algorithm, Salp Swarm Algorithm, and Particle Swarm Optimization demonstrate their effectiveness in addressing the complex, multimodal challenges of FACTS device placement, including TCSC, SVC, and STATCOM. Over time, these algorithms have evolved through hybridization and refinement, significantly enhancing their optimization capabilities. Their adaptability to varying operational conditions makes them indispensable for improving system reliability, reducing transmission losses, and maintaining voltage stability. Future research should focus on advancing these techniques and integrating them with emerging technologies, such as artificial intelligence, renewable energy systems, and smart grid frameworks, to meet the growing, dynamic needs of the global energy sector.

References

[1] Dagnachew A, Lucas P, van Vuuren D. The role of decentralized systems in providing universal electricity access in Sub-Saharan Africa – A model-based approach van Vuuren D, *Energy (2017) 139 184-195*

[2] Kirli D, Hampp J, Kiprakis A, PyPSA meets Africa: Developing an open source electricity network model of the African continent, *IEEE AFRICON Conference (2021) 2021-September.*

[3] Mzamo N, Manditereza P, Frequency control strategies in a renewable energy intensive power system: Options for South Africa, *IOP Conference Series: Earth and Environmental Science (2022) 994(1).*

[4] Sagel V, Rouwenhorst K, Faria J, Leveraging Green Ammonia for Resilient and Cost-Competitive Islanded Electricity Generation from Hybrid Solar Photovoltaic-Wind Farms: A Case Study in South Africa, *Energy and Fuels (2023) 37(18) 14383-1439*

[5] Dekaraja B, Saikia L, Impact of energy storage and flexible alternating current transmission devices in combined voltage and frequency regulation of multiarea multisource interconnected power system, *Energy Storage (2022) 4(3).*

[6] Das A, Dawn S, Ustun T, A Strategy for System Risk Mitigation Using FACTS Devices in a Wind Incorporated Competitive Power System, *Sustainability (Switzerland) (2022) 14(13).*

[7] Seyyedabbasi A, Kiani F, Sand Cat swarm optimization: a nature-inspired algorithm to solve global optimization problems, *Engineering with Computers (2023) 39 2627-2651*

[8] Wang, Houzhu, Jingzhong Zhu, and Wenping Li. "An improved back propagation neural network based on differential evolution and grey wolf optimizer and its application in the height prediction of water-conducting fracture zone." *Applied Sciences* 14, no. 11 (2024): 4509.

[9] Mohammad A, Pradeep J, et al. Optimizing FACTS Device Placement Using the Fata Morgana Algorithm: A Cost and Power Loss Minimization Approach in Uncertain Load Scenario-Based Systems, *International journal of computation, (2025)18(1).*

[10] Lee D, Joo S, Economic Analysis of Large-Scale Renewable Energy (RE) Source Investment Incorporating Power System Transmission Costs, *Energies (2023) 16(21).*

[11] Ashby, Michael F. *Materials and sustainable development*. Butterworth-Heinemann, 2022.

[12] United Nations, The Sustainable Development Goals Report, 2023.

[13] Dash, Stita Pragnya, K. R. Subhashini, and J. K. Satapathy. "Optimal location and parametric settings of FACTS devices based on JAYA blended moth flame optimization for transmission loss minimization in power systems." *Microsystem Technologies* 26, no. 5 (2020): 1543-1552.

[14] Vanitha P.V, Niramathy K, Improvement of Transmission Line Loadability Using Multi Type FACTS Devices, *International Journal of Electrical Power Engineering, (2020), 13(4), 56 - 60.*

[15] Chorghade, Aditya, and Vandana A. Kulkarni Deodhar. "FACTS devices for reactive power compensation and power flow control–recent trends." In *2020 International conference on industry 4.0 technology (I4Tech)*, pp. 217-221. IEEE, 2020.

[16] B. H. Alajrash, "A comprehensive review of FACTS devices in modern power systems," *Sustainable Energy, Grids and Networks*, 2024.

[17] M. Chethan, "A review of FACTS device implementation in power systems," *Journal of Engineering and Applied Sciences*, SpringerOpen, 2024.

[18] Benabid, F., & Boudour, M. The influence of the location and size of FACTS devices on the transmission capacity and control flexibility in power systems. *International Journal of Electrical Power & Energy Systems*, (2024)138.

[19] Marouani, Ismail, Tawfik Guesmi, Badr M. Alshammari, Khalid Alqunun, Ahmed S. Alshammari, Saleh Albadran, Hsan Hadj Abdallah, and Salem Rahmani. "Optimized FACTS devices for power system enhancement: applications and solving methods." *Sustainability* 15, no. 12 (2023): 9348.

[20] Sabo, A., Dabo, A. I., Tureta, K. A., Isah, A. I., Dauda, A. I., Abbah, U., … & Yusuf, A. Facts devices as a solution to power industries problems: a review. *European Journal of Theoretical and Applied Sciences, (2024) 2(3), 82-87*

[21] Chethan, M. and Kuppan, R. (2024). A review of facts device implementation in power systems using optimization techniques. *Journal of Engineering and Applied Science, (2024) 71(1).*

[22] Kamel, Salah, Mohamed Abokrisha, Ali Selim, and Francisco Jurado. "Power flow control of power systems based on a simple TCSC model." *Ain Shams Engineering Journal* 12, no. 3 (2021): 2781-2788.

[23] Ahmad, A. A. L., and R. Sirjani. Optimal placement and sizing of multi-type FACTS devices in power systems using metaheuristic optimisation techniques: an updated review cumulative gravitational search algorithm opposition gravitational search algorithm, Ain Shams Eng. J. 11 (3)(2020) 611–628.

[24] Al Mashhadany, Yousif, Ahmed K. Abbas, and Sameer Algburi. "Study and analysis of power system stability based on FACT controller system." *Indonesian Journal of Electrical Engineering and Informatics (IJEEI)* 10, no. 2 (2022): 317-332.

[25] J.Li, "Application of thyristor controlled phase shifting transformer excitation impedance switching control to suppress short-circuit fault current level," *Frontiers of Engineering Management*, 2018

[26] An Implemented Approach of Fuzzy Logic Based Controlled STATCOM. (2015). *International Journal of Applied Engineering Research*, 10(23), 43543-43549.

[27] C.A. Ordóñez, A.Gómez-Expósito, and J.M. Maza-Ortega, "Series Compensation of Transmission Systems: A Literature Survey," *Energies*, vol.14, no.6, article 1717, 2021

[28] D. Kalpaktsoglou, A. Tsiakalos, S. Pouros, and M. Roumeliotis, "Comparison between Thyristor Switched Series Capacitors and Thyristor Switched Parallel Capacitors for Wind Power Systems," *WSEAS Trans. Power Syst.*, vol. 15, pp. 149–157, Nov. 2020

[29] Abdelsattar, M., Fawzy, S., & Sayyad, A. (2022). "Voltage stability improvement of an Egyptian power grid-based wind energy system using STATCOM." *Wind Energy*, 25(3), 452-469.

[30] Ahmed, Muhanad. "Enhanced static voltage stability and short circuit monitoring performance and optimization of future onshore AC power systems." (2022).

[31] Chethan, Muddu, and Ravi Kuppan. "A review of FACTS device implementation in power systems using optimization techniques." *Journal of Engineering and Applied Science* 71, no. 1 (2024): 18.

[32] Liu J, Hao X, Wang X et al, Application of Thyristor Controlled Phase Shifting Transformer Excitation Impedance Switching Control to Suppress Short- Circuit Fault Current Level, Journal Mod. Power System, Clean Energy (2018) 6(4): 821 – 832.

[33] Jokojeje R.A, Adejumobi I.A, et al, Application of STATCOM in Improving Power SystemPerformance: A Case Study of the Nigeria 330KV Electricity Grid, Nigerian Journal of technology, (2015), 34(3): 564 – 572.

[34] Sulaiman, A., & Mustaffa, N. Optimal placement of FACTS devices using metaheuristic techniques for voltage stability enhancement. *International Journal of Electrical Power & Energy Systems*, (2022)133,

[35] Amarendra, B., Madhusree, S., & Meena, K. Location optimization of FACTS devices using an improved particle swarm optimization method. *Electric Power Systems Research*, (2018)159, 221-230.

[36] Jain, A. A comprehensive review of various metaheuristic algorithms for optimal sizing of FACTS devices considering cost and performance. *Renewable and Sustainable Energy Reviews*, (2023)174.

[37] Awad, A. Optimal planning of FACTS devices using hybrid metaheuristic techniques to minimize operational costs. *IEEE Transactions on Power Systems*, (2023)38(1), 256-267.

[38] P. Singh and N. Senroy, "Steady-State models of STATCOM and UPFC using flexible holomorphic embedding," *Electric Power Systems Research*, vol. 199, Art. no. 107390, Oct. 2021.

[39] Gautam, A. Fundamentals of Swarm Intelligence: A Comprehensive Overview and Applications in Artificial Intelligence. Journal of Artificial Intelligence Research, (2024)68, 123-145.

[40] Jumani, Touqeer Ahmed, Mohd Wazir Mustafa, Ali S. Alghamdi, Madihah Md Rasid, Arbab Alamgir, and Ahmed Bilal Awan. "Swarm intelligence-based optimization techniques for dynamic response and power quality enhancement of AC microgrids: A comprehensive review." *IEEE Access* 8 (2020): 75986-76001.

[41] Sharma, Sandeep, Saket Gupta, Mohd Zuhaib, Vijay Bhuria, Hasmat Malik, Abdulaziz Almutairi, Asyraf Afthanorhan, and Mohammad Asef Hossaini. "A comprehensive review on STATCOM: paradigm of modeling, control, stability, optimal location, integration, application, and installation." *IEEE Access* 12 (2023): 2701-2729.I.

[42] Mehouachi, M. Abbes, and S. Chebbi, "Design of a high power D-STATCOM based on the isolated dual-converter topology," *Int. J. Electr. Power Energy Syst.*, vol. 106, pp. 401–410, 2019.

[43] Nwozor, Obinna Eugene. "A review of the functional and analytical characteristics of thyristor controlled series capacitor (TCSC) in electric power system." (2020).

[44] P. P. Biswas, P. Arora, R. Mallipeddi, P. N. Suganthan, and B. K. Panigrahi, "Optimal placement and sizing of FACTS devices for optimal power flow in a wind-power-integrated electrical network," *Neural Computing and Applications*, 2021 vol. 33, no. 12, pp. 6753–6774

[45] M. H. Sulaiman, P. P. Biswas, P. Arora, R. Mallipeddi, P. N. Suganthan, and B. K. Panigrahi, "Optimal placement and sizing of FACTS devices for optimal power flow using metaheuristic optimizers," *Results in Control and Optimization*, vol. 8, p. 100 - 145, 2022.

[46] G. H. Reddy and D. Kumar, "Optimal sizing and allocation of DG and FACTS device in radial distribution systems using Fractional Lévy Flight Bat Algorithm," *IFAC-PapersOnLine*, vol. 55, no. 1, pp. 277–282, 2022

[47] K. Pal, S. Saha, and S. Ghosh, "Optimal location of FACTS devices with EV charging stations in power networks using Particle Swarm Optimization," *Electric Power Systems Research*, 2024

[48] Alghaythi, Mamdouh L., Gerald Christopher Raj Irudayaraj, Senthil Kumar Ramu, Praveenraj Govindaraj, and Indragandhi Vairavasundaram. "Mathematical Modeling and Analysis of Capacitor Voltage Balancing for Power Converters with Fewer Switches." *Sustainability* 15, no. 13 (2023): 10698.

[49] M. H. Alqahtani, et al., "Enhanced power-grid performance through Gorilla Troops Optimizer: Optimal TCSC allocation for loss reduction and voltage improvement," *Heliyon*, vol. 10, no. 3, e 26073, Mar. 2024

[50] U. M. Ngei, et al., "Optimal sizing and placement of STATCOM, TCSC, and UPFC for combined optimization of losses and voltage profile," *Heliyon*, vol. 10, no. 3, e 25815, Mar. 2024

[51] M. Chethan, et al., "AS review of FACTS device implementation in power systems: Analytical and meta-heuristic approaches," *Journal of Engineering and Applied Sciences*, SpringerOpen, 2024

[52] U. M. Ngei, et al., "Optimal sizing and placement of STATCOM, TCSC, and UPFC for combined optimization of losses and voltage profile," *Heliyon*, vol. 10, no. 3, e25815, Mar. 2024

[53] X. Wu, M. Wang, M. Shahidehpour, S. Feng, and X. Chen, "Model-free adaptive control of STATCOM for SSO mitigation in DFIG-based wind farm," *IEEE Transactions on Power Systems*, vol. 36, no. 6, pp. 5282–5293, 2021.

[54] M. Aljaidi, "Optimizing FACTS Device Placement Using the Fata Algorithm (FATA)," *Analog Integrated Circuits and Signal Processing*, 2025

[55] A. A. Shehata, et al., "Optimal placement and sizing of FACTS devices based on Autonomous Groups Particle Swarm Optimization technique," *Archives of Electrical Engineering*, vol. 70, no. 2, pp. 207–226, 2021

[56] E. Bashar, D. Rogers, R. Wu, L. Ran, M. Jennings, T. C. Green, and P. Mawby, "A new protection scheme for an SSSC in an MV network by using a varistor and thyristors," *IEEE Trans. Power Del.*, vol. 36, no. 1, pp. 102–113, 2021

[57] M. M. Elhabashy, H. M. Sharaf, and D. K. Ibrahim, "Reliable protection for staticsynchronous series compensated double-circuit transmission lines based on positive sequence active power calculations using PMUs," *Electr. Power Syst. Res.*, vol. 223, Oct. 2023.

[58] C. Wang, P. Shang, and P. Shen, "An improved artificial bee colony algorithm based on Bayesian estimation," *Complex & Intelligent Systems*, vol. 8, pp. 4971–4991, Apr. 2022

[59] R. Lin, "EABC-AS: Elite-driven artificial bee colony algorithm with adaptive population scaling," *Applied Soft Computing*, vol. 150, , 2025,

[60] S. Alsamia, E. Koch, H. Albedran, and R. Ray, "Adaptive Exploration Artificial Bee Colony for Mathematical Optimization," *AI*, vol. 5, no. 4, pp. 2218–2236, Nov. 2024

[61] H. Shokouhandeh, S. Jalilzadeh, and R. Alizadeh, "Optimal management of reactive power considering voltage and location of control devices using Artificial Bee Algorithm," *Applied Sciences*, vol. 12, no. 1, p. 27, Jan. 2022

[62] T. Zheng *et al*., "Fault identification scheme for UPFC compensated transmission line based on characteristic voltage active injection," *Int. J. Electr. Power Energy Syst.*, vol. 137, Art. no. 107851, 2022

[63] X. Wu, R. Wang, Y. Wang, and L. Wang, "A novel UPFC model and its convexification for security-constrained economic dispatch," *IEEE Transactions on Power Systems*, vol. 37, no. 6, pp. 4202–4213, Nov. 2022.

[64] Q. Li, S.-Y. Liu, and X.-S. Yang, "Influence of initialization on the performance of metaheuristic optimizers," *arXiv preprint*, arXiv:2003.03789, Mar. 2020.

[65] Peters Barbosa, João Pedro, and João Alberto Passos Filho. "New methodologies for SVC modeling in the power flow problem based on sigmoid functions." *Electrical Engineering* 106, no. 1 (2024): 971-981.

[66] U. Pandey, A. S. K. Reddy, and V. Kumar, "Applications of artificial intelligence in power system operation, control and planning," *Clean Energy*, vol. 7, no. 6, pp. 1199–1218, Dec. 2023.

[67] Sulaiman, Mohd Herwan, and Zuriani Mustaffa. "Optimal placement and sizing of FACTS devices for optimal power flow using metaheuristic optimizers." *Results in Control and Optimization* 8 (2022): 100145.

[68] S. R. Inkollu and V. R. Kota, "Optimal setting of FACTS devices for voltage stability improvement using PSO adaptive GSA hybrid algorithm," *Engineering Science and Technology, an International Journal*, vol. 19, no. 2, pp. 102–110, Apr. 2016.

[69] B. Khan, "Optimal integration of DSTATCOM using improved bacterial foraging search algorithm," *Optimization and Engineering*, vol. 23, pp. 1477–1494, 2022

[70] Edward JB, Rajasekar N, Sathiyasekar K, Senthilnathan N, Sarjila R. An enhanced bacterial foraging algorithm approach for optimal power flow problem including FACTS devices considering system loadability. ISA transactions. 2013 Sep 1;52(5):622-8.

[71] Devi S, Geethanjali M. Application of modified bacterial foraging optimization algorithm for optimal placement and sizing of distributed generation. Expert Systems with Applications. 2014 May 1;41(6):2772-81.

[72] U. M. Ngei *et al.*, "Optimal sizing and placement of STATCOM, TCSC, and UPFC for combined optimization of losses and voltage profile," *Heliyon*, vol. 10, no. 3, e25815, Mar. 2024,

[73] A. Mirjalili, "Dragonfly algorithm: a new meta-heuristic optimization technique for solving single-objective, discrete, and multi-objective problems," *Neural Computing and Applications*, vol. 27, pp. 1053–1073, 2016.

[74] Alshinwan M, Abualigah L, Shehab M, Elaziz MA, Khasawneh AM, Alabool H, Hamad HA. Dragonfly algorithm: a comprehensive survey of its results, variants, and applications. Multimedia Tools and Applications. 2021 Apr;80(10):14979-5016.

[75] Hocine S, Djamel L. Optimal number and location of UPFC devices to enhence voltage profile and minimizing losses in electrical power systems. International Journal of Electrical & Computer Engineering (2088-8708). 2019 Oct 15;9(5).

[76] Alhaider MM. Optimal Placement of Capacitor in the Distribution Grids using Dragonfly Algorithm. In2023 4th International Conference on Communications, Information, Electronic and Energy Systems (CIEES) 2023 Nov 23 (pp. 1-6). IEEE.

[77] Debnath S, Baishya S, Sen D, Arif W. A hybrid memory-based dragonfly algorithm with differential evolution for engineering application. Engineering with Computers. 2021 Oct;37(4):2775-802.

[78] A. R. Al-Muthanna, M. Abdul-Majeed, and Z. A. Al-Mashhadani, "Improved salp swarm algorithm using opposition-based learning for engineering optimization," *Applied Soft Computing*, vol. 114, p. 108023, Feb. 2023, doi:10.1016/j.asoc.2021.108023.

[79] Hegazy AE, Makhlouf MA, El-Tawel GS. Improved salp swarm algorithm for feature selection. Journal of King Saud University-Computer and Information Sciences. 2020 Mar 1;32(3):335-44.

[80] Abd El-sattar S, Kamel S, Ebeed M, Jurado F. An improved version of salp swarm algorithm for solving optimal power flow problem: S. Abd el-sattar et al. Soft Computing. 2021 Mar;25(5):4027-52.

[81] Abed-Alguni BH, Paul D, Hammad R. Improved Salp swarm algorithm for solving single-objective continuous optimization problems. Applied Intelligence. 2022 Dec;52(15):17217-36.

[82] Kar MK, Kanungo S, Alsaif F, Ustun TS. Optimal Placement of FACTS Devices Using Modified Whale Optimization Algorithm for Minimization of Transmission Losses. IEEE Access. 2024 Sep 11.

[83] Chethan M, Kuppan R. A review of FACTS device implementation in power systems using optimization techniques. Journal of Engineering and Applied Science. 2024 Dec;71(1):18.

[84] Nayeem GM, Fan M, Akhter Y. A time-varying adaptive inertia weight based modified PSO algorithm for UAV path planning. In2021 2nd International Conference on Robotics, Electrical and Signal Processing Techniques (ICREST) 2021 Jan 5 (pp. 573-576). IEEE.

[85] J. Wang and L. Zheng, "Hybrid PSO–Firefly algorithm for multimodal optimization with enhanced exploration," *Swarm and Evolutionary Computation*, vol. 68, p. 100894, May 2022.

[86] Ngei UM, Nyete AM, Moses PM, Wekesa C. Optimal sizing and placement of STATCOM, TCSC and UPFC using a novel hybrid genetic algorithm-improved particle swarm optimization. Heliyon. 2024 Dec 15;10(23).

[87] Rashmi MC, Raghu CN. Review on Hybrid Power Flow Controllers in Practical Power Systems. In2023 Fourth International Conference on Smart Technologies in Computing, Electrical and Electronics (ICSTCEE) 2023 Dec 8 (pp. 1-6). IEEE.