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A Review on Improving Power System Stability Using Meta-Heuristic Optimization Algorithms for Power System Stabilizer Tun-ing

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Abstract
In the power system, any change in the input or any disturbance causes oscillations in frequency, voltage, and real and reactive power. The Power System Stabilizer (PSS) stands out as a renowned and effective equipment for damping power system oscillations, extensively explored in studies aimed at enhancing the dynamic stability of power systems. Challenges such as low-frequency fluctuations and the intricate nature of power systems have spurred the application of intelligent methods and optimization algorithms for addressing PSS-related issues. In this paper, a brief review of the studies conducted in the field of meta-heuristic optimization algorithms for PSS design is presented. Meta-heuristic methods are divided into three groups, and based on them, more than 200 articles have been studied in the field of PSS parameter optimization. The balance between exploration and exploitation is a common theme among all meta-heuristic methods. Researchers and practitioners of meta-heuristic optimization methods belong to a wide range of audiences in the fields of power systems optimization, who will benefit from this research.

Keywords: Power System, Intelligent Design, Optimization, Power System Stabilizer.

1. INTRODUCTION

Modern power system networks are extensive and complex, constantly exposed

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to various uncertainties in power system performance [1,2], making them susceptible to instability [3,4].

Also, system anomalies have a negative impact on the stable operation of the power system [5,6]. Today, the use of renewable energies is increasing, and their use has a significant impact on the stability of power systems [7,8]. Disruption in the power system causes oscillations in the frequency, load angle, and voltage of the units; if the power system is stable, these fluctuations disappear within a few seconds, and the system continues to work in new conditions [9,10]. These oscillations in the power system are called low-frequency oscillations (LFO) [11,12], and they are usually in the range of a fraction of a hertz (a few tenths of a hertz) to several hertz and are divided into two types: local (low-frequency oscillations of a power plant unit) and inter-regional (oscillations of the units of one region compared to the units of another region) [13,14]. The stability and integrity of power systems are vulnerable to failures caused by LFOs, emphasizing the importance of damping these fluctuations to enhance system stability and reliability [15,16]. Nowadays, due to the increasing consumption of electrical energy and the increase in power passing through the transmission lines, which is associated with the development of the transmission system, maintaining the dynamic stability of the power system is of particular importance [17,18]. Dynamic instability is caused by the disturbance of the balance between the input mechanical power and the output electrical power and the lack of damping torque [19,20]. In dynamic stability, the amplitude of the disturbance is considered small, and the oscillations are damped after the occurrence of the disturbance [21,22]. Prolonged oscillation damping can harm power system units, emphasizing the importance of the speed of oscillation damping. In addition to frequency and voltage control loops, an additional controller known as the power system stabilizer (PSS) is employed to eliminate transient state fluctuations. Ideally, the PSS should not respond to system frequency changes [23,24].

1.1. A Summary of Optimization Algorithms

In recent years, various optimization techniques, including the crow search algorithm [25], farmland fertility algorithm [26], grey wolf optimization-sine cosine algorithm [27] and genetic algorithms [28,29], and intelligence techniques such as fuzzy logic [30,31] and neural networks [32,33] have been presented to obtain and select optimal PSS parameters under different working points. These new techniques solve non-linear and non-derivable optimization problems, which are difficult to solve with the usual differentiable optimization algorithms, with random and intelligent search methods [34,35]. Optimization algorithms are broadly categorized into heuristic and meta-heuristic groups [36,37]. Algorithms based on meta-heuristics are divided into three groups: evolutionary algorithms such as genetic algorithm (GA) [38,39] and harmony search optimization (HSO) [40,41], swarm-based algorithms such as particle swarm optimization (PSO) [42,43], bacterial foraging optimization (BFO) [44], bat algorithm, cuckoo search optimization (CSO) [45,46], firefly algorithm [47], ant colony optimization (ACO) [48,49] and artificial bee colony (ABC) [50,51], and trajectory-based algorithms such as Tabu search (TS) [52] and simulated annealing (SA) algorithm [53,54].

1.2. Stability and Damping of Oscillations

The power system is one of the most important parts of power transmission [55]. The power system is continuously affected by small or large disturbances [56,57]. Power system stability is the ability of the system's synchronous machines to remain in synchronous mode against any disturbance. Power system stability is divided into three categories: steady-state stability, transient stability, and dynamic stability [58,59].

1.3. Contribution and Paper Organization

There are several papers with results about optimization algorithms from various aspects of the application in the design of power system stabilization to improve oscillation damping.

The study of the application of several meta-heuristic optimization algorithms in six challenges of the power system is presented in [60]. The challenges are optimization of power flow in transmission and distribution networks, optimization of reactive power dispatching, optimization of economic and emission combined dispatching, optimal volt/var control of distribution power systems, and optimization of the size and placement of distributed generation sources. The presented results show the ability of a meta-heuristic optimization algorithm to effectively solve power system problems.

This paper provides a brief review of various meta-heuristic optimization algorithms for tuning PSS parameters that have been reported in the literature during recent years. The significance and the novelty of the research is as follows:

- The use of this paper review as a basis for further research work on the design of stabilizing parameters of the power system in the industry.
- Review of meta-heuristic optimization algorithms used for tuning of PSS for improvement of power system stability.
- Brief review of meta-heuristic optimization algorithms.
- Review of the available types for application of different optimization algorithms.

In this paper, a brief overview of meta-heuristic optimization methods for designing PSS parameters based on the studies is presented.

The structure of this paper is organized as follows. The methods of PSS design optimization algorithms are categorized based on the meta-heuristic technique and presented in Section 2. The application of some meta-heuristic algorithms based on evolution, based on trajectory, and based on bio for the design of PSS parameters are described in Sections 3, 4, and 5, respectively. In power system stability studies, coordinated control between controllers PSS and FACTS is an important problem, for this reason, the use of meta-heuristic methods in coordination between these two controllers is mentioned in Section 6. To overcome the disadvantages of the optimization method, a combination of several methods is used, which is mentioned in Section 7. Finally, Section 8 provides the conclusion of this paper.

2. POWER OSCILLATIONS DAMPING

Currently, an additional controller is necessary to enhance stability in electrical power systems, particularly during system disturbances [61,62]. Usually, there are two types of power oscillation damping (POD) methods [63,64], which include the power system stabilizer (in the generator unit) [65,66] and flexible AC transmission systems (FACTS) controllers (in the transmission system) [67,68]. PSS is a control device for damping low-frequency oscillations [69,70]. The parameters of the power system stabilizer are determined based on the linearized model of the power system at the nominal working point of the system and are used in a wide range. PSS parameters are optimized for damping small disturbance power fluctuations, with the potential to enhance system damping even under large disturbance conditions [71,72].

2.1. Power System Stabilizer Structure

Fig. 1 shows the structure of a conventional PSS (CPSS) with a compensator, which includes a phase compensation block, a twist filter, a limiting block, a gain block, and a washout block that removes the effect of the steady state signal, which is the speed deviation input signal [73,74]. The output signal is regarded as voltage change (U_S). The stabilizer is designed to have a zero output in the steady state. Due to the block that removes the steady state effect, PSS only responds to speed changes [75,76]. In lengthy axles, it is necessary to measure the speed deviation at a number of points on the axis and use this information to calculate the average value of the speed deviation [77,78]. The phase shift of the input signal and signals created by the high-pass filter and low-pass filter must be considered in the phase compensation design [79,80]. The phase compensation blocks with their time constants create suitable pre-phase characteristics for optimal post-phase compensation of input and output signals [81,82].

2.2. Types of Flexible AC Transmission Systems

FACTS controllers are systems based on power electronics and other static equipment that provide power current and voltage control [83,84]. These controllers are used in the power system to improve stability [85,86].

In terms of connection type, FACTS controllers are divided into four types [87] [88]: a) Series compensators such as thyristor-controlled series capacitors (TCSC) [89] and synchronous static series compensators (SSSC) [90,91], b) Shunt controllers such as static VAR compensators (SVC) [92,93] and static synchronous compensators (STATCOM) [94], c) Series-series controllers such as interline power-flow controller (IPFC) [95,96] and thyristor-controlled phase angle regulators (TCPAR) [97,98] and d) Series-shunt controllers such as unified power flow controllers (UPFC) [99,100].

3. OPTIMIZATION ALGORITHMS BASED ON META-HEURISTIC METHODS

Many engineering optimization problems in the real world are very complex in nature, and solving them using optimization algorithms based on numerical, linear, and nonlinear programming methods has been very difficult, and in most cases impossible [101,102]. The field of power system programming requires very complex computer programs, and the design is done in such a way that the programs can be run multiple times for corrective changes [103,104]. Until now, various types of optimization techniques have been used to find optimal or near-optimal solutions to determine the parameters and placement of PSS in the power system [105,106].

In the following sections, some of these methods and studies conducted using the aforementioned methods are described. Optimization algorithms are broadly classified into two groups: heuristic and meta-heuristic [107]. Meta-heuristic optimization methods are divided into two groups based on meta-heuristic origins: inspired by nature, such as genetic algorithms, ant colony optimization algorithms, simulated annealing, and particle swarm optimization, and inspired by non-nature, such as Tabu search [108].

4. META-HEURISTIC ALGORITHMS BASED ON EVOLUTIONARY

The main advantages of evolutionary algorithms are resistance to dynamic changes, wide application, ability to combine with other methods, and less difficulty for automatic problem-solving routines [109].

4.1. Harmony Search Optimization (HSO)

The harmony search algorithm is from a series of meta-heuristic algorithms based on nature, and it is conceptualized using the musical process of searching for the perfect state of harmony [110,111]. This algorithm is one of the best optimization methods for single-objective problems, and it uses random search instead of gradient search to provide better solutions for problems [112,113].

As shown in the flowchart of the harmony search algorithm according to Fig. 2, this algorithm includes 5 basic steps. This is how new harmonies are generated, sorted by the objective function values, and will be generated [114].

This method has been used in various studies such as robust and effective regulation of FACTS-PODs of

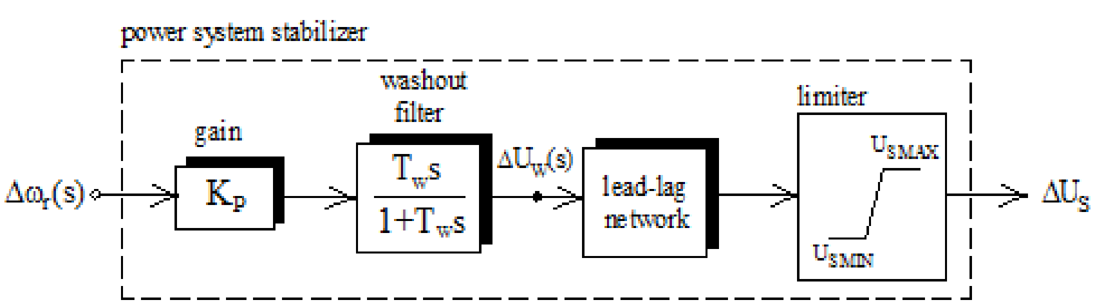

Fig. 1. Structure of conventional power system stabilizer

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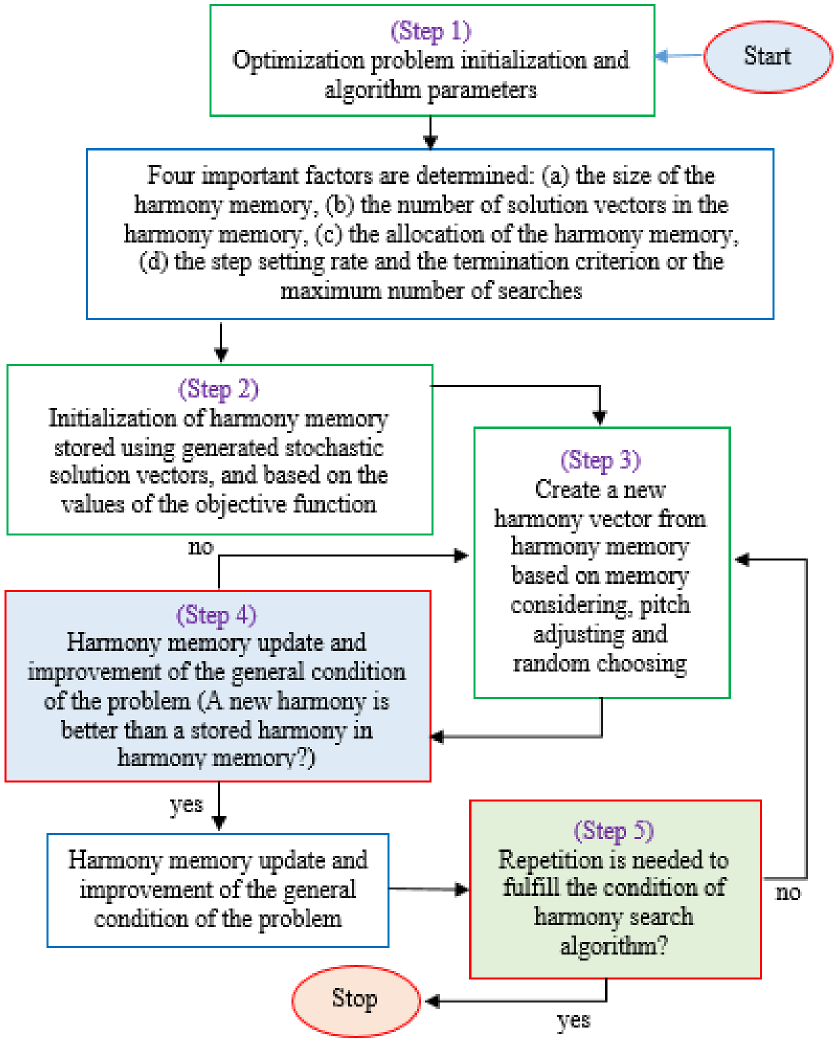

Fig. 2. The flowchart of the harmony search algorithm includes 5 basic steps.

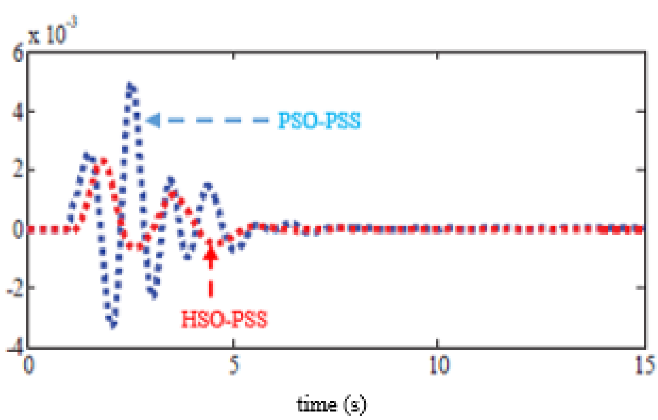

Fig. 3. Speed deviation of generator 2 in 10-machine power system.

interconnected systems [115], determining the optimal location and setting parameters of static synchronous compensator (STATCOM) [116], load frequency control in power systems [117], and optimization of controller parameters in distributed production systems [118].

A harmony search algorithm for multi-machine PSS tuning is presented in order to eliminate local and inter-regional mode oscillations to enhance small-signal stability in [119], where the multi-objective eigenvalue-based optimization problem (max. damping coefficient and damping ratio) are formulated to design PSS parameters. The results of dynamic simulation and eigenvalue analysis in a 10-machine, 39-bus New England test system show that for severe disturbances, in order to reduce LFO, the design with the HS method is superior to the design with the PSO method. The speed deviation of one of the power system generators is shown in Fig. 3.

An HSA-based method for the robust and optimal design of a PSS-connected PID controller for LFO damping of a one-machine infinite bass power system is presented in [120], where the optimization problem is the exact selection of PID controller parameters.

4.2. Genetic Algorithm (GA)

Genetic algorithms, a special type of evolutionary algorithm, employ techniques from evolutionary biology to find optimal formulas for prediction or pattern matching [121,122]. Genetic algorithms are usually a suitable option for prediction techniques based on regression [123,124]. Modeling is a programming technique that uses genetic evolution as a problem-solving model [125,126]. The range of applications of the genetic algorithm is very wide for problem-solving [127,128]. The computational flowchart of the GA optimization method is shown in Fig. 4. A fuzzy power system stabilizer design (FPSS) using an adaptive evolutionary algorithm consisting of a genetic algorithm for global search capability and an evolution strategy for local search is proposed in [129], which is used to optimize membership functions and scaling factors of FPSS. The simulation results show the superiority of FPSS control performance over conventional power system stabilizer (CPSS) for three-phase faults under heavy loads

In [130], a method based on an improved genetic algorithm is proposed for the optimal placement of PSS and their simultaneous adjustment in a multi-machine system. In this method, the minimum number of PSS is used, and their parameters are simultaneously adjusted to move the poles to the left side of the hypothetical axis. Then, by maximizing the damping ratio of mechanical modes, the best place to install PSSs is determined.

A GA-based optimization approach is presented [131], improving GA optimization performance in terms of solution quality and convergence rate. The method is applied to PSS optimal design in a 16-machine, 68-bus system, showcasing its impact on damping electromechanical oscillations and enhancing the dynamic stability of the system.

In [132], a robust selection of PSS parameters is regarded as an optimization problem in a multi-machine power system, which is solved by the genetic algorithm with a multi-objective function based on eigenvalue. The PSSs are set in such a way that the damped and undamped electromechanical states of all power plants are transferred simultaneously to a designated region in the s-plane.

The genetic algorithm will add an intelligent dimension to the stabilizer during the design of the fuzzy logic power system stabilizer. This will greatly cut down on the time needed for calculations during the design process [133]. In [134], genetic algorithm has been used in the design of fuzzy logic power systems, and stabilizers in multi-machine power systems, so that genetic algorithm has been used to set the centers of membership functions and parameters of fuzzy logic controllers.

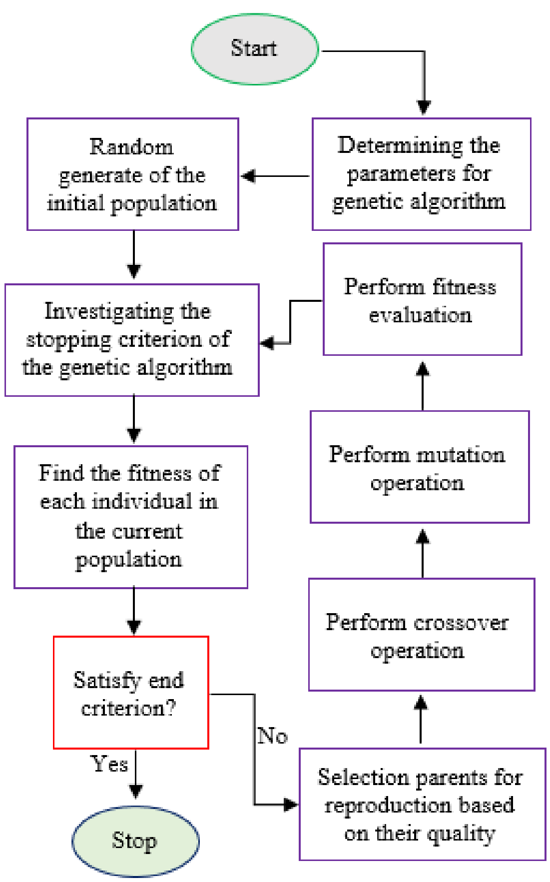

Fig. 4. Flowchart of the genetic algorithm.

5. META-HEURISTIC ALGORITHMS BASED ON TRAJECTORY

5.1. Simulated Annealing Algorithm

The simulated annealing (SA) algorithm, inspired by metallurgical smelting, involves controlled heating and cooling to enhance crystal size and reduce material deformation. In SA, heat liberates atoms from their initial state, placing them in higher energy levels, and gradual cooling allows the atoms to achieve lower internal energy than the initial state [135]. Each step of the SA algorithm replaces the current solution with a near stochastic solution, which depends on the probability of dependence between the values of the corresponding function and the temperature parameter [136]. Also, the global parameter of temperature decreases in a gradient way [137,138]. The simulated annealing method is used only when the search space is discrete. This algorithm is a derivative-free optimization method that does not require sensitivity analysis to evaluate the objective function, which is a good reason for designing the power system stabilizer based on it. The SA algorithm is an unconstrained algorithm that is used for hard designs. According to the flowchart of the SA algorithm shown in Fig. 5, in this algorithm, it first starts from an initial solution and then moves to neighboring solutions in an iteration loop.

In [139], a robust design of multi-machine PSSs using the SA optimization technique is proposed in which SA is used to search for optimal parameter settings of a conventional fixed-structure lead-lag PSS. The robustness of the method compared to the initial parameter settings is one of its advantages. It should be noted that the integration of SA as a derivative-free optimization technique in PSS design significantly reduces the computational burden.

5.2. Tabu Search (TS)

Local search methods often encounter challenges in escaping non-optimal regions. Another meta-heuristic local search method is Tabu search (TS), which is used for mathematical optimization. A key element of the adaptive memory framework of Tabu search is balancing search intensification and variation. Comparing the Tabu search and the genetic algorithm, it can be said that the Tabu search has been a pioneer in the systematic exploration of memory functions in search processes, while genetic algorithms have been pioneers in implementing methods that exploit the idea of combining solutions [140]. This meta-heuristic method is used to find optimal and near-optimal solutions for a wide variety of classical and practical problems [141,142].

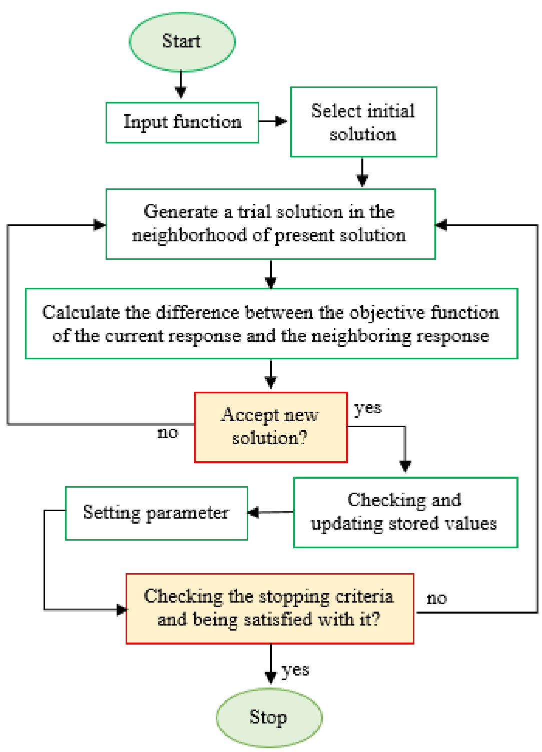

Fig. 5. Flowchart of the simulated annealing algorithm.

A TS-based PSS is presented in [143], where the proposed method uses the TS algorithm to search for optimal settings of conventional lead-lag parameters in PSS. The results show that using the TS algorithm in PSS design significantly reduces the time spent in the design process, and also the TS algorithm leads to the optimal solution without considering the initial guess.

The design of robust PSS in a multi-machine power system as a decentralized controller and a multi-output multi-input system is proposed using the TS algorithm in [144], where a common lead-lag PSS structure is widely used. Also, the robust stability index is considered the objective function to obtain a better stability margin.

6. META-HEURISTIC ALGORITHMS BASED ON BIO

6.1. Particle Swarm Optimization (PSO)

Particle swarm optimization is a global optimization method. PSO is a collective search algorithm modeled on the social behavior of flocks of birds [145,146].

Within the PSO framework, particles traverse the search space, continuously adjusting their positions based on the best locations they have individually encountered and those within their entire neighborhood [147,148]. The overarching steps of the PSO method are elucidated in Fig. 6 [149,150]. PSO algorithm has been used in solving various engineering problems [151,152]. The PSO method for the design of PSS parameters has been proposed in various studies and each of them tries to improve the design parameters [153]. The flexibility to achieve a compromise between conflicting design objectives, overshoot, and control limitation is one of the advantages of using this algorithm in PSS design [154,155].

In [156], using the PSO algorithm with two steps to simultaneously adjust the parameters of the automatic voltage regulator (AVR) and PSS to control voltage fluctuations and damping in a synchronous generator is investigated, in which an objective function based on the time response of the system to the change in the reference voltage is used to analyze the performance of the controllers.

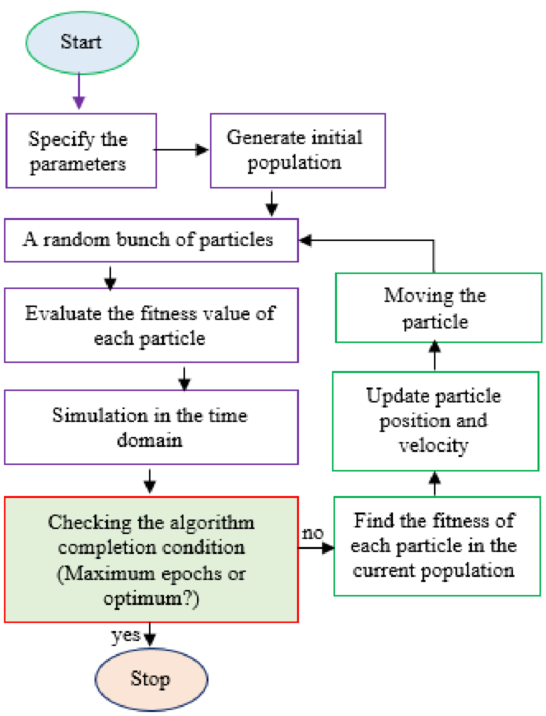

Fig. 6. Flowchart of the PSO algorithm.

Additionally, the modified particle swarm optimization algorithm is used to adjust the parameters of the four-band PSS in [157]. Employing a two-step optimization process, this study takes into account the varied influence levels of each block concerning the frequency characteristic.

In [158], the improvement of the transient stability of the two-area four-machine system using a single-band, single-input PSS is investigated, and PSS parameters are optimized using PSO to increase stability and reduce oscillations. The simulation results show that the transient stability is significantly improved by optimizing the parameters of PSS, and the oscillations are reduced. Fig. 7 shows the speed changes when only PSS is present in the single-machine power system. Stabilizer design has been done using two methods: dolphin echolocation optimization (DEO) and PSO algorithm. Notably, the DEO technique demonstrates a faster settling time than the PSO technique [159].

6.2. Bat Algorithm

The Bat Algorithm (BA) represents a meta-heuristic approach inspired by the social life of bats, boasting several advantages. This algorithm has many advantages, and one of its key advantages is that it can achieve very fast convergence in the early stages by switching from exploration to exploitation. It is therefore an efficient algorithm for applications that require a fast solution.

The design of a CPSS using the bat algorithm to optimize the gain and pole-zero parameters of an objective function based on the eigenvalue shift is presented in [160]. Also, eigenvalues for single-machine power systems with conventional power system stabilizer for two optimized methods BA and PSO are shown in Figs. 8 and 9, respectively.

6.3. Ant Colony Optimization (ACO)

The ant colony algorithm is inspired by studies and observations on ant colonies [161]. In this method, artificial ants by moving on the graph of the problem and by leaving marks on the graph, make the next artificial ants able to provide better solutions to the problem. In this method, it is possible to find the best path in a diagram by calculating numerical problems based on the science of probabilities [162,163]. The general process of the algorithm is shown in Fig. 10 [164].

ACO is used in solving various problems, which can be mentioned to improve the stability of multi-machine power systems. Using the ACO method is based on static synchronous compensators [165], optimal design of radial distribution networks in which the feeding path is known [166], the design of microgrids as an optimization problem to minimize the total costs of the microgrid development plan [167] and the study of coordination between SSSC and PSS in a four-machine power system after the occurrence of a three-phase short circuit [168].

A multi-objective design of a multi-machine power system PSS utilizing the ACO is presented in [169], so that the fine-tuning of PSS parameters is considered as an optimization problem and solved using the ACO method. Simulation results show that PSS design using the ACO method reduces settling time and maximum overshoot more than other techniques such as genetic local search and PSO.

The changes in generator speed in the New England test system in terms of per unit with respect to time for three types of PSS design are shown in Figs. 11, 12, and 13 where PSS parameters utilizing the ACO, BA, and GA, respectively, are designed. As can be seen, among the above three techniques, the bat algorithm has provided better results than the other two approaches and achieved the minimum required damping ratio by reducing the number of iterations [170].

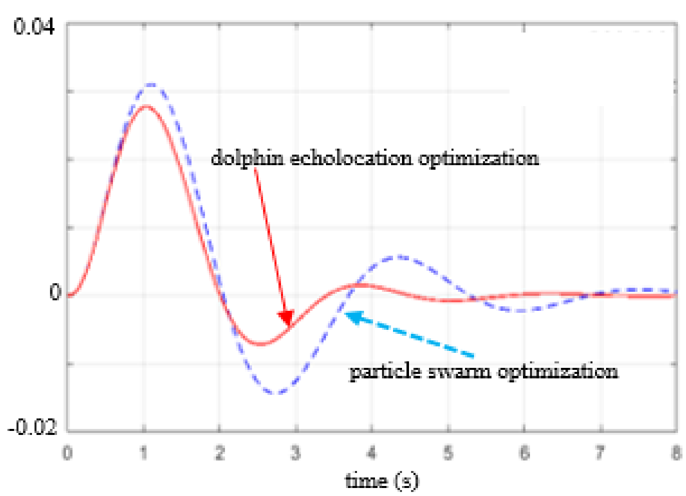

Fig. 7. Response speed changes with independent controller (PSS only).

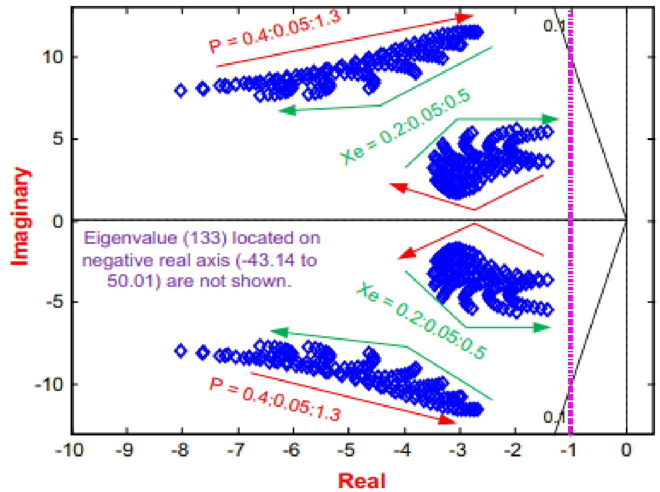

Fig. 8. Power system eigenvalues with BA optimization method.

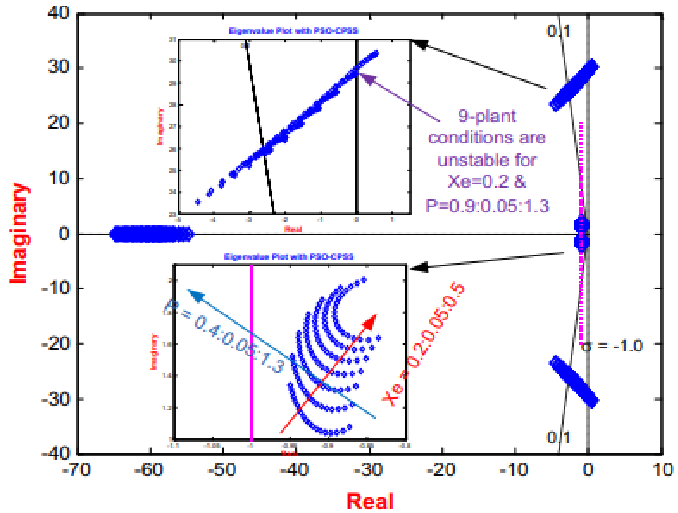

Fig. 9. Power system eigenvalues with PSO optimization method.

6.4. Artificial Bee Colony

The Artificial Bee Colony (ABC) emulates the optimization strategy observed in honey bee colonies [171,172], deriving inspiration from the diverse roles within a hive. This algorithm is inspired by the foraging behavior and collective work of different types of bees [173,174]. The mathematical model of the artificial bee colony has three types of bees: worker bees (finding food and locating it), observer bees (watching the bees at work and helping to find food), and watcher bees (randomly searching for new food source and communicating and coordinating with each other to find the optimal solution in a short time) [175,176]. In this algorithm, the location of the food source represents the solution to the optimization problem, and the amount of nectar represents the appropriateness value of the corresponding solution [177,178]. The process of performing different steps of this method is shown in Fig. 14 [179] [180].

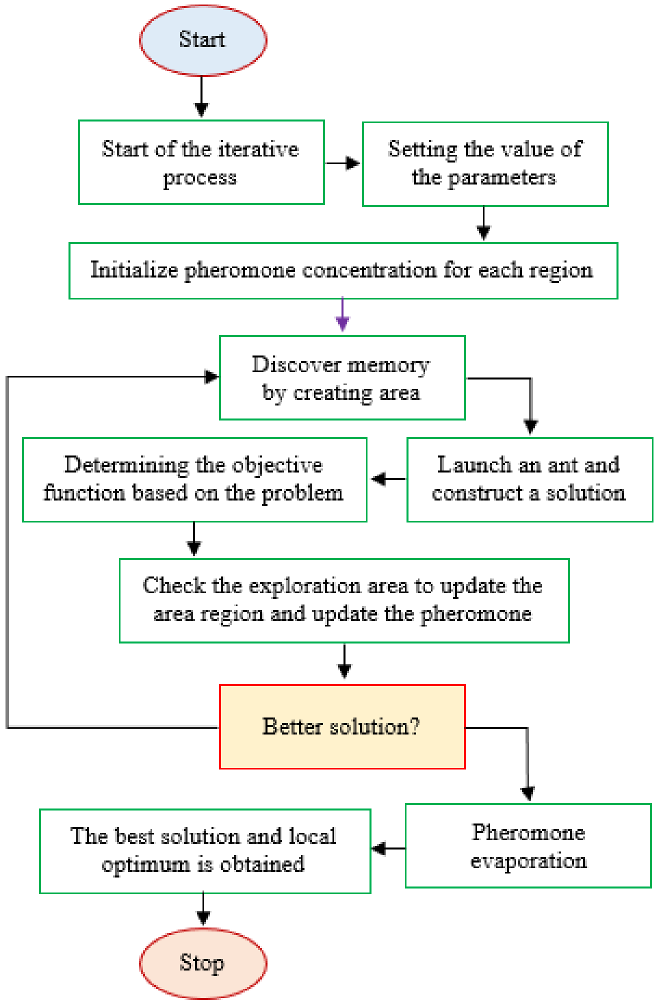

Fig. 10. Flowchart of the ACO algorithm.

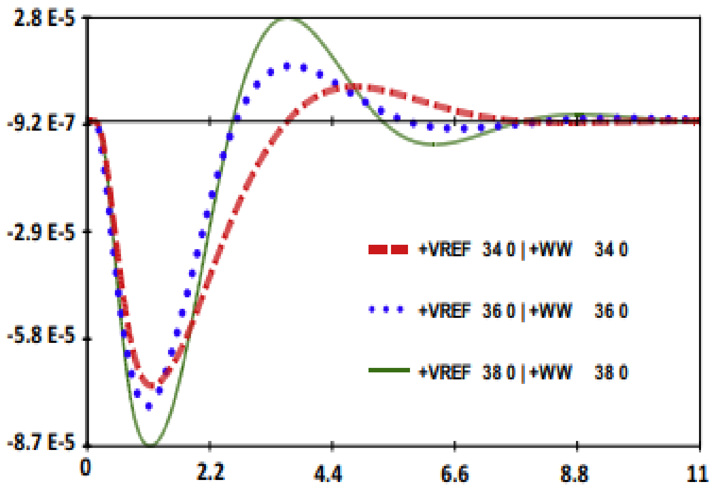

Fig. 11. Designing PSS parameters using ACO.

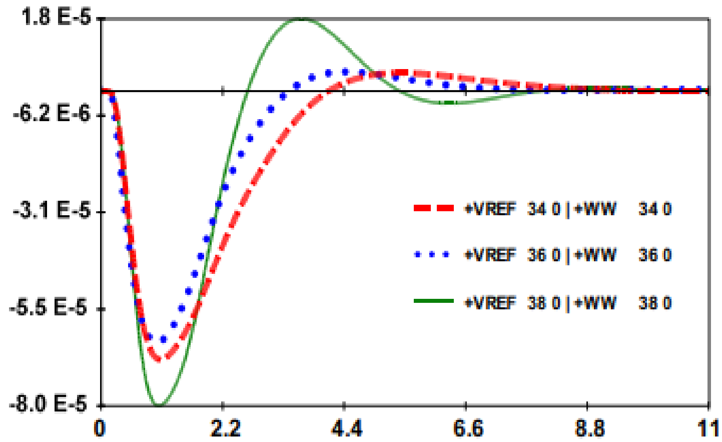

Fig. 12. Designing PSS parameters using BA.

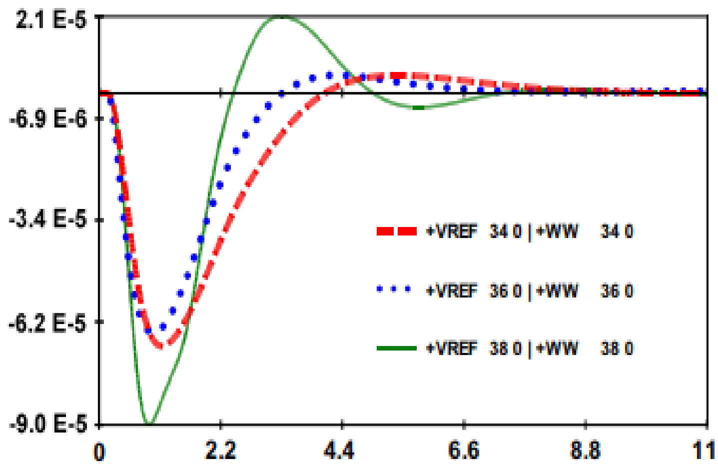

Fig. 13. Designing PSS parameters using GA.

A design procedure for simultaneous coordinated designing of the static synchronous compensator controller (STATCOM) parameters and PSS in a multi-machine power system is developed in [181], that the ABC algorithm is employed to search for optimal controller parameters. A method based on ABC optimization to adjust PSS parameters in a 16-machine, 68-bus power system is proposed in [182], where a multi-objective problem is formulated to optimize a combined set of objective functions.

6.5. Cuckoo Search Optimization

Cuckoo Search Optimization (CSO) algorithm, designed to tackle both non-linear and continuous optimization problems, takes inspiration from the life and behaviors of cuckoo birds [183,184]. This algorithm is inspired by the life of the cuckoo bird [185,186]. CSO algorithm is built based on the optimal lifestyle and interesting features of this species, such as their egg-laying and reproduction [187,188]. Fig. 15 shows the flowchart of the cuckoo optimization

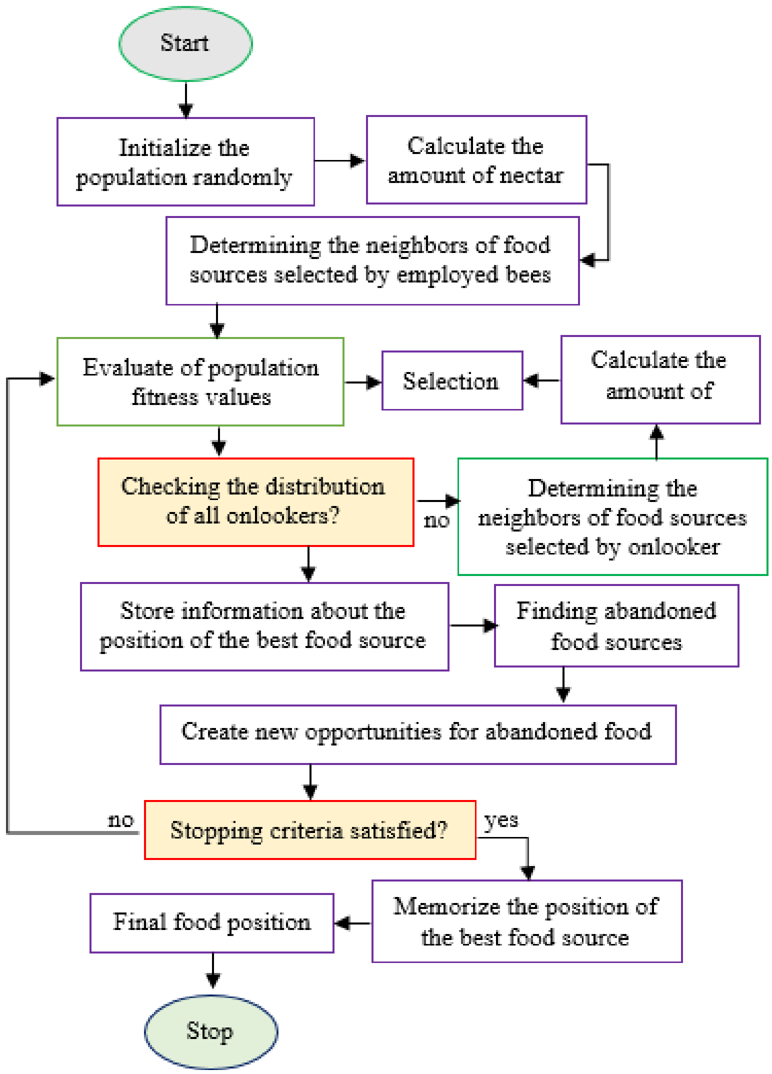

Fig. 14. Flowchart of the artificial bee colony algorithm.

algorithm [189,190]. As can be seen, it starts with the movement of all cuckoos towards a better environment, and the position of the nest is corrected using the flight equation [191]. The cuckoo approach involves stealth, surprise, and speed [192,193].

The meta-heuristic CSO technique for an optimal and robust PSS for multi-machine power systems is designed in [194], and its performance is compared with three other optimization techniques. The typical convergence for PSS design to four optimization methods is shown in Fig. 16. As can be seen, the CSO algorithm has found the best solution faster (18 iterations) compared to HSO (40 iterations), PSO (58 iterations) and GA (90 iterations). The eigenvalue-based multi-objective function is designed to simultaneously control the damping coefficient and the damping ratio to cancel the local and inter-regional LFO modes.

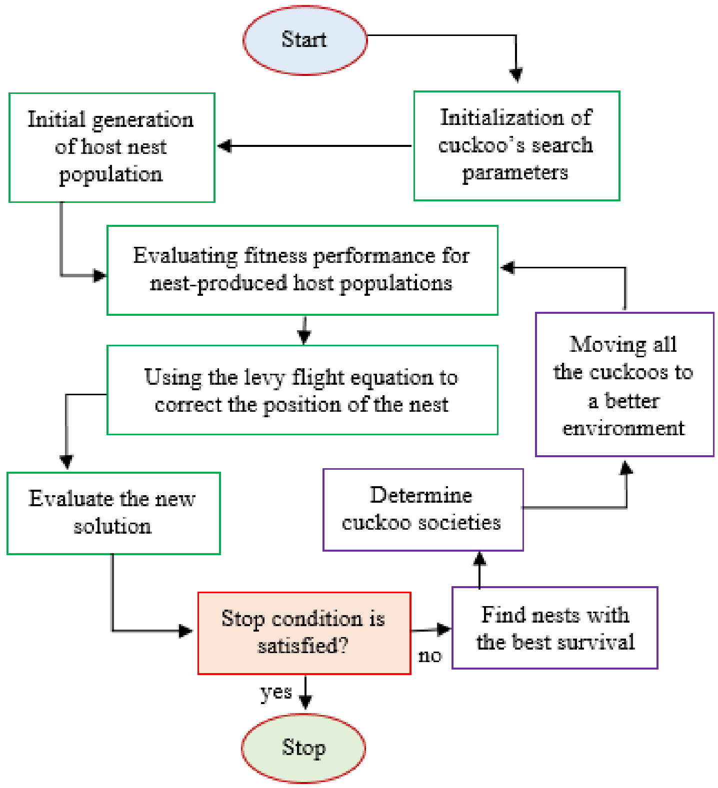

Fig. 15. Flowchart of the cuckoo optimization algorithm.

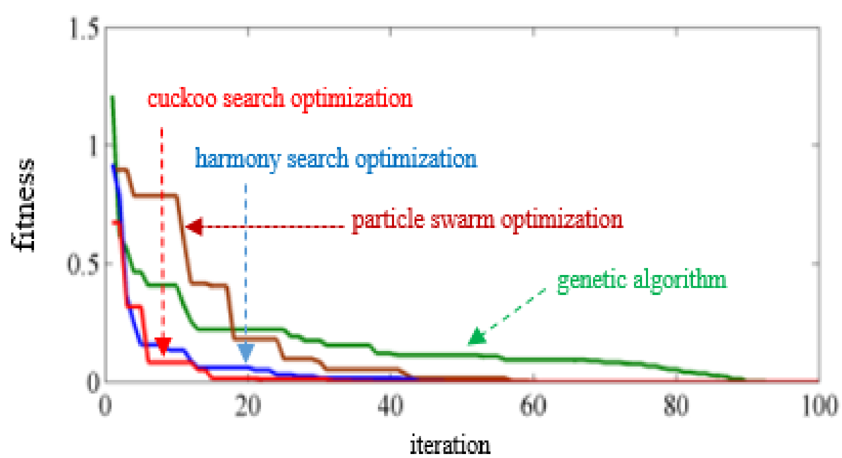

Fig. 16. Convergence characteristics of four different optimization techniques.

In a three-machine power system, with a 20% increase in mechanical torque for generator 1 as a small disturbance, the speed changes between machines 1 and 2 in rad/s under different loading conditions are shown in Figs. 17 and 18. In this system, STATCOM parameters are designed in two methods. It can be seen that the power system with CS is more stable than GA. Also, the average settling time required to reduce power system fluctuations is less with CS than with GA [195].

6.6. Bacterial Foraging Optimization (BFO)

Widely acclaimed for its effectiveness in distributed optimization and control, the Bacterial Foraging Optimization (BFO) algorithm finds applications in addressing diverse optimization problems [196,197]. The BFO algorithm has been considered in various studies such as optimal power flow in dynamic environments [198], find the optimal location of the FACTS controller [199] and distributed optimization and control [200]. The classical BFO algorithm has two disadvantages, which are fixed size and weak communication between bacteria [201]. This algorithm has poor convergence behavior towards complex optimization problems compared to other nature-inspired optimization techniques [202,203].

In [204], the controller design problem is formulated as an optimization problem, and the BFO algorithm is used to search the PSS parameters. The simulation results show the effect of the proposed controller in different loading conditions, as well as its superiority compared to GA and the conventional method in a wide range of operating conditions and system configurations.

In [205], BFOA-based PSS is proposed for oscillation damping, where PSS design with different loading conditions and system configurations is considered as an optimization problem. BFOA has also been used to search for optimal controller parameters by minimizing the time domain objective function.

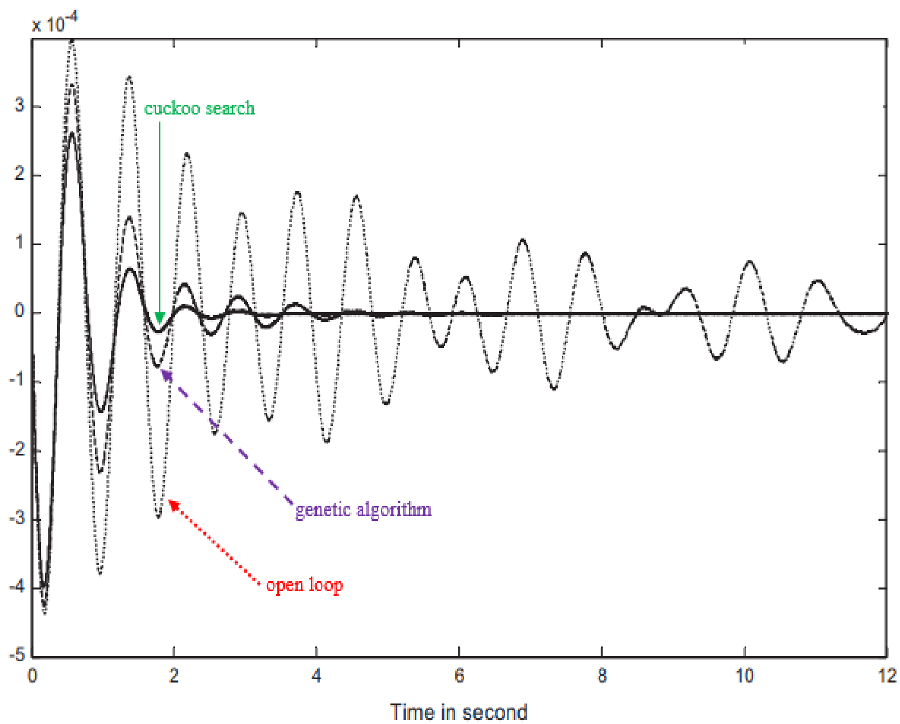

Fig. 17. Speed changes between machines 1 and 2 under normal load conditions.

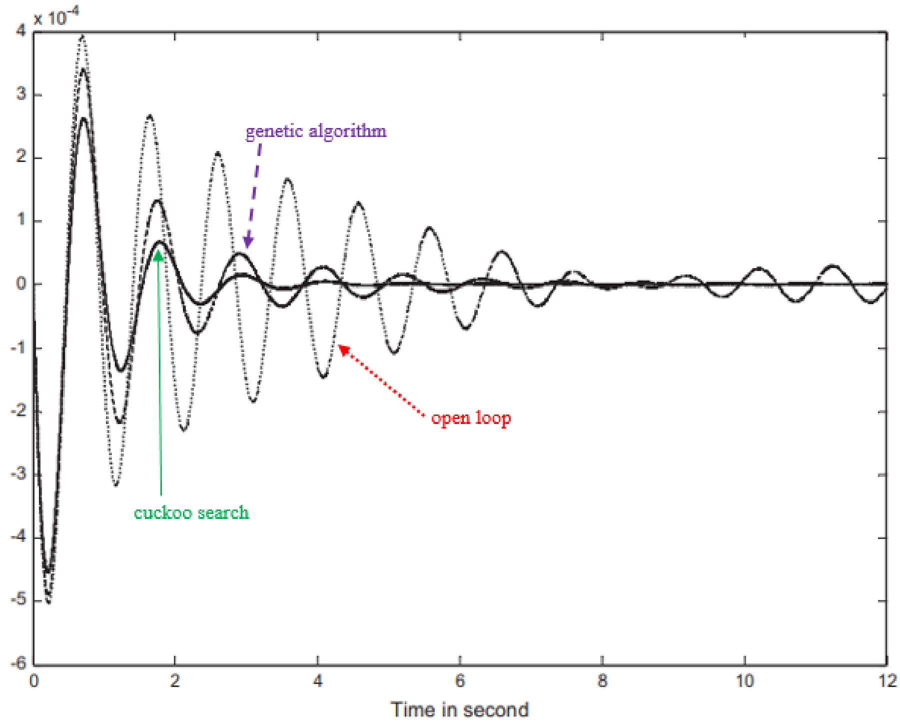

Fig. 18. Speed changes between machines 1 and 2 under light load conditions.

7. COORDINATED DESIGN OF FACTS CONTROLLER AND PSS

To overcome the inability of the power system stabilizer to damp the low-frequency oscillations in the power system when abnormal faults occur, the FACTS-based damping controller is used, and the coordination between them is presented as an optimization problem [206,207]. In power system stability and power system oscillations reduction, coordinated control between PSS and FACTS controllers is one of the important problems of designers [208,209]. In this section, some studies conducted in the field of coordinated design FACTS controller and PSS using meta-heuristic methods are mentioned.

The modified harmonic search algorithm for the coordinated design of multiple PSS and TCSC for effective damping of oscillations in [210] is investigated, and the simulation results in the experimental power system with the simulation results obtained from GA, PSO, HAS, and bacterial swarm optimization are compared.

The BFO algorithm is utilized to determine PSS and TCSC parameters in [211], which aims to synchronize the settings of these controllers, and LFO damping in electric power systems. This method has been applied in a power system of two areas with 4 generators, 10 buses, and 15 transmission lines, and the simulation results show the damping of fluctuations.

The BFO algorithm is suggested for the simultaneous coordinated design of PSS and static variable compensator (SVC) in a multi-machine power system in [212]. This algorithm is used to search for optimal controller parameters, and by minimizing the objective function (taking into account the speed deviations between generators), the stability performance of the system is improved.

In [213], TCSC and PSS controller parameters are designed to increase the stability and oscillation damping in nonlinear four-machine power systems by velocity update relaxation PSO or GA algorithms. The simulations show that using both of the above controllers at the same time makes the power system more stable and cuts down on oscillations. Using the velocity update relaxation PSO algorithm instead of the GA speeds up the process of stopping power system oscillations. The rotor angle of generator 1 is shown in Fig. 19. As can be seen, the damping response of the rotor angle with the coordination design by the PSO method is better than with the coordination design by the GA scheme.

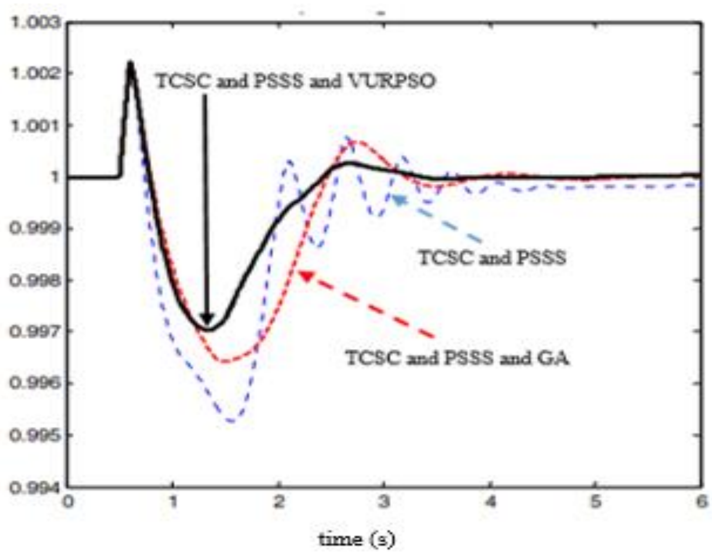

Fig. 19. Rotor angle of the generator 1 for three different design coordination between PSS and TCSC.

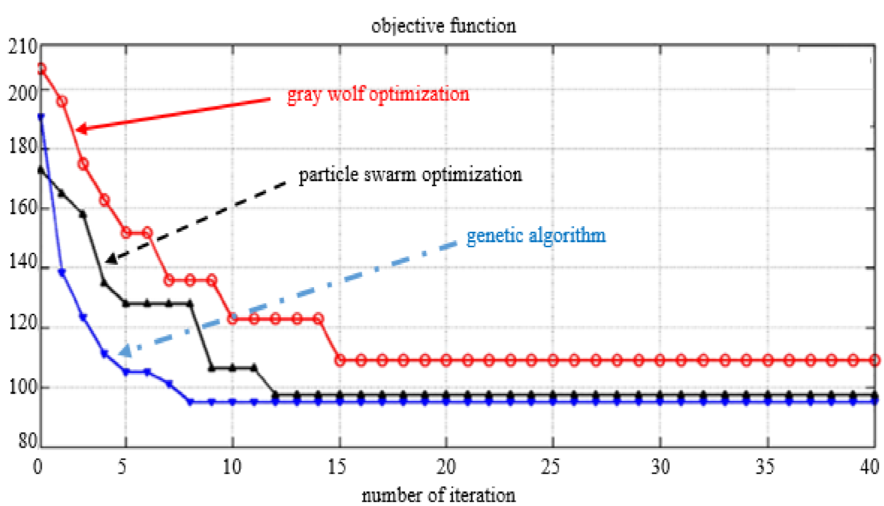

Fig. 20. Comparison of convergence between three optimization methods.

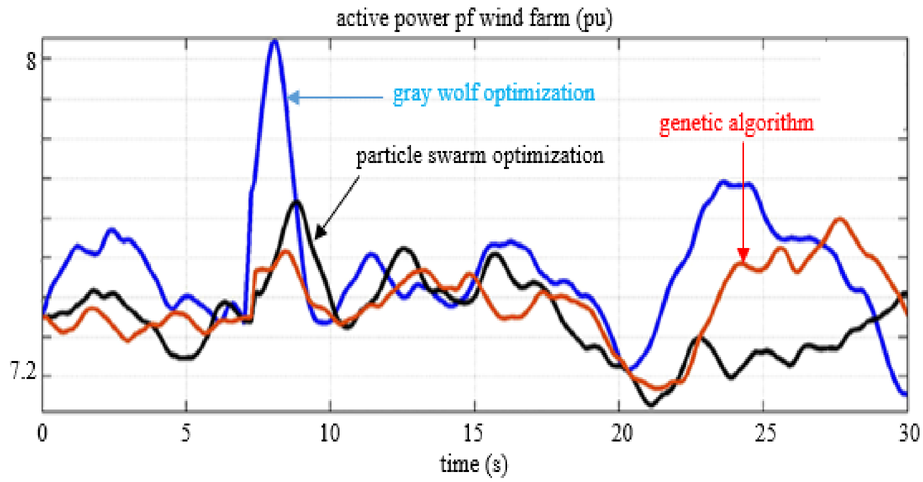

Fig. 21. Transient response of active power flow of DFIG-based wind farm.

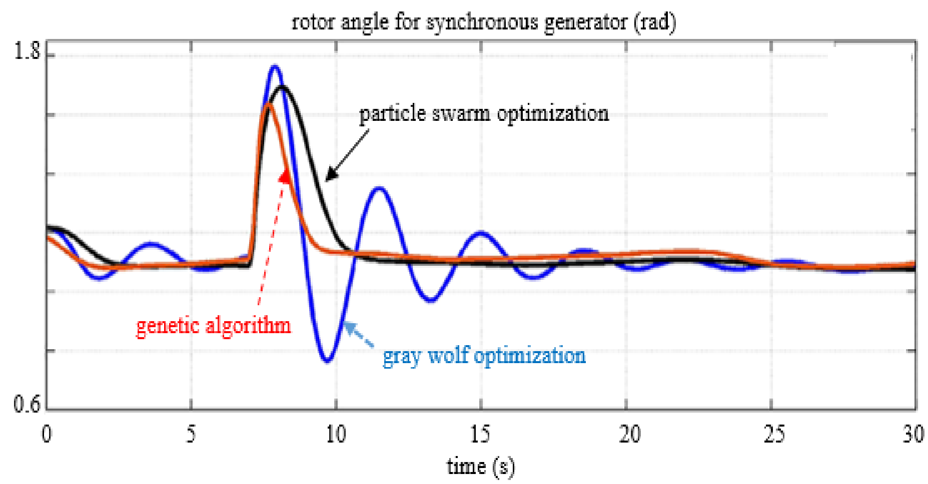

Fig. 22. Transient response of rotor angle of synchronous generator.

Robust tuning of proportional integral derivative PSS and SVC using genetic algorithms in multi-machine power systems (4-machines, 10 buses, two area systems) is presented in [214], where the location of PSS and SVC is determined using participation factors and the residue method, respectively.

A comparative analysis of two controllers, including PSS and STATCOM, to improve small signal stability and transient stability in wind power systems has been investigated in [215], where a genetic algorithm is used for tuning the parameters of two controllers. Three methods of gray wolf optimization (GWO), PSO, and GA have been used to optimize the parameters for transient stability, and a comparison has been made between them. The convergence of these three optimization methods for the same objective function and constraints is compared in Fig. 20. It is observed that GWO, PSO, and GA converge to 109.138, 97.526, and 95.162, respectively. Figs. 21 and 22 show the transient response of the active power of a double-fed induction generator-based wind farm and the rotor angle of a synchronous generator for design parameters with three optimization methods, respectively. As can be seen, the design with the GA method had a greater effect on reducing fluctuations than the other two methods

8. COMBINED OPTIMIZATION METHODS

The amalgamation of various optimization methods enables the utilization of the unique advantages each brings to the power system stabilizer design [216]. A hybrid meta-heuristic algorithm for designing a fractional order multi-band power system stabilizer is proposed in [217] to improve the dynamic stability of multi-machine power systems, which is a dynamic combination of genetic algorithm and standard particle swarm optimization algorithm to solve the optimization problem (setting PSS parameters multiple bands) is used. The convergence of PSO and GA-PSO dynamic hybrid for the 9-bus and three-car system is shown in Fig. 23. It can be seen that the hybrid method converges faster than PSO.

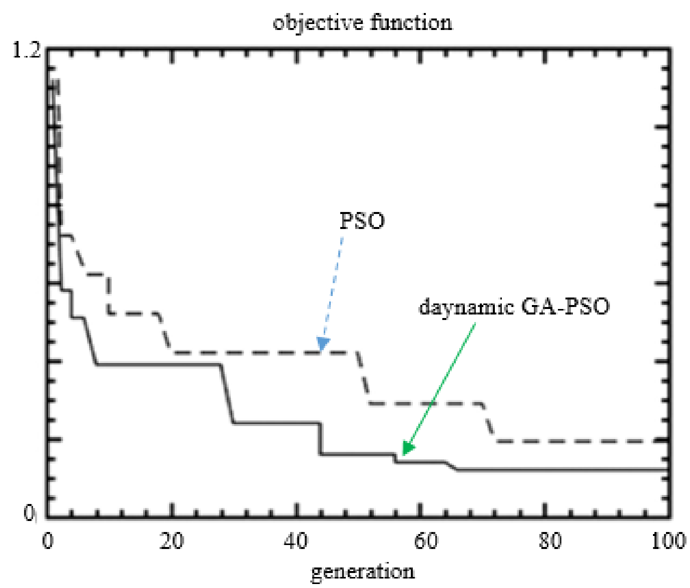

Fig. 23. Comparison of convergence of combined optimization methods.

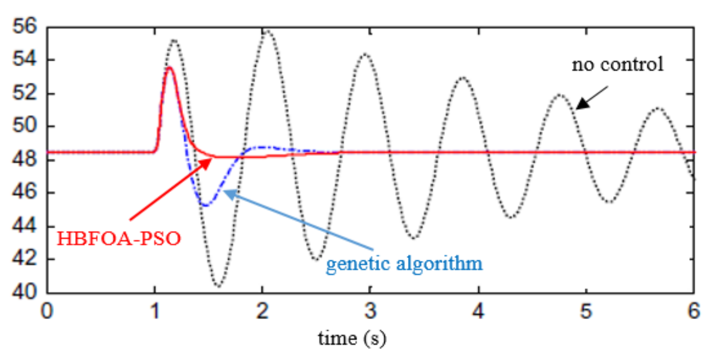

Fig. 24. The effect of the 3-cycle fault in the middle of the transmission line on the power angle under normal loading conditions.

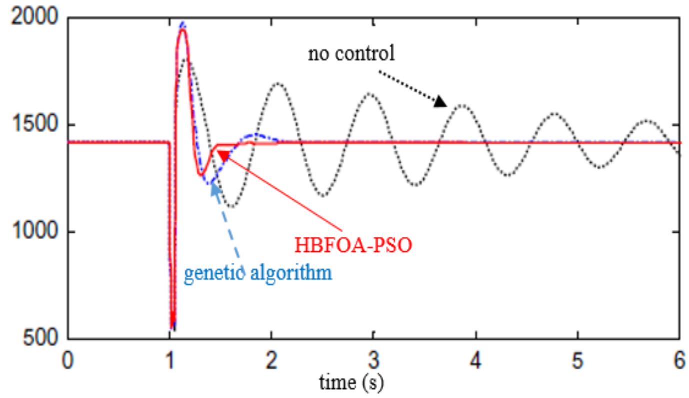

Fig. 25. The effect of the 3-cycle fault in the middle of the transmission line on the tie-line power under normal loading conditions.

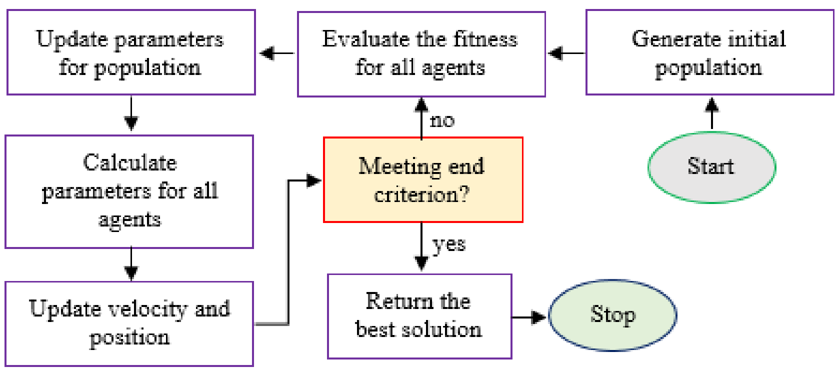

Fig. 26. Flowchart for a hybrid algorithm example.

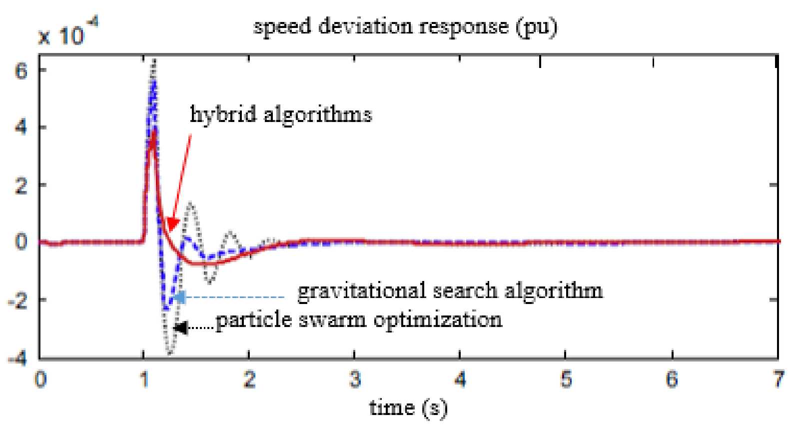

Fig. 27. System speed deviation under small disturbances under heavy load conditions.

Addressing the limitations of GA and TS, an enhanced hybrid tabu-genetic algorithm is introduced in [218]. This integration leverages the global search capabilities of GA and the local optimization proficiency of TS, culminating in effective coordination between PSS and SVC. Simulation results affirm the efficacy of this amalgamated approach in damping electromechanical oscillations and fortifying power system stability.

Additionally, in [219], STATCOM, additional POD, and PSS are used to improve the stability of power systems in the transmission network, which is utilized to optimize the controller parameters from an advanced intelligent optimization algorithm (the idea of hybrid GA and PSO algorithm to overcome the local convergence problem PSO is employed). Also, voltage control and STATCOM damping control are considered for the objective function, which is to eliminate the LFO. Coordination to improve the stability of a power system for PSS and SSSC is proposed in [220], where hybrid bacteria foraging optimization algorithm and particle swarm optimization (HBFOA–PSO) are used to search for optimal controller parameters. The effect of the fault in the middle of the transmission line on the power angle and power passing through the transmission line under normal loading conditions is shown in Figs. 24 and 25, respectively. As can be seen, the combined optimization method has a greater effect on the response.

To minimize generator fuel cost, a combined tabu search and simulated annealing method for optimal power flow control with four types of FACTS devices is presented in [221]. The results show that the combined search method approach can provide better solutions and requires less CPU time than the genetic algorithm, SA, or TS alone. The flowchart of an example of the combination of gravitational search algorithms and PSO methods is shown in Fig. 26. As can be seen, the hybrid algorithm starts from a random initialization, and at the end, it satisfies the criteria of speed and position of the final criterion. Fig. 27 shows the system speed deviation response under small disturbances in heavy load conditions for an energy system. As can be seen, the hybrid controller is very effective against the new conditions and provides more stable performance compared to the other two controllers, particle swarm optimization and gravitational search algorithms [222].

9. CONCLUSION

The problem of finding the shortest path is an optimization problem, which is sometimes very difficult to solve, and sometimes very time-consuming. Power systems are subject to repeated extreme oscillations that may cause generator shaft fatigue and failure. The PSS is an effective device, which damps the low-frequency oscillations LFO of the electrical power system by generating supplementary damping control signals for the excitation system. The use of techniques based on artificial intelligence has covered a wide range of applications related to the design and tuning of control parameters of electric power systems.

In this survey paper, more than 200 research articles on the application of meta-heuristic methods in the design of PSS parameters have been studied and analyzed, in order to provide a good summary for researchers interested and eager to optimize PSS parameters to reduce power system oscillations fluctuation damping. Meta-heuristic methods, often characterized as population-based, stochastic, and non-greedy, constitute a diverse array of approaches. The majority of these methods employ a static objective function to address

Table 1. ***Summary of advantages and disadvantages of meta-heuristic methods studied.***

Optimization technique			Disadvantages	Advantages
evolutionary algorithms		Harmony search optimization	The possibility of stagnation in the convergence performance in the final iterations	Easy implementation Less adjustable parameters Fast convergence
		Genetic algorithm	The possibility of having a high cost in implementation Difficulty understanding the algorithm Difficulty debugging Difficulty of optimization.	Finding solutions to problems that are difficult to solve with traditional methods Solving problems with multiple objectives or constraints
bio-heuristic algorithms	based on imitation	Particle swarm optimization	Convenience collapse in high-dimensional space to local optima Having a low convergence rate in the iterative process Showing low-quality results with complex and large datasets	Having fewer parameters to adjust Obtaining the best solution from particle interaction
		Bat algorithm	Obtaining population-based solutions and local search-based algorithms Comfortable trapping in local minima Lack of high accuracy	Obtaining population-based solutions and local search-based algorithms
		Bacterial foraging optimization	The chemotactic step size is constant. The connection between bacteria is weak.	Reduce user-defined parameters Fast convergence
	Based on sign	Ant colony optimization	Low convergence speed and solution accuracy when dealing with a large amount of data	Continuously running the algorithm and adapting to changes in real-time Having good performance in solving discrete problems Good stability
		Cuckoo search optimization	Slow convergence	Being efficient in the global search Balanced mixing Suitability for solving continuous problems and multi-objective problems
		Bee colony	Insufficient population diversity Weak developing capacity Premature convergence in the later search period The accuracy of the optimal value cannot meet the requirements sometimes	Strong robustness Fast convergence High flexibility
trajectory-based algorithms		Simulated annealing algorithm	More repetition is required than conventional spring fitters Slow cooling to apply design rules	Easy implementation It is possible to find the global optimum even after finding the local minimum

Tabu Search	Balancing search intensity and variety A pioneer in the systematic exploration of memory functions in search processes Used to find optimal and near-optimal solutions for a wide variety of classical and practical problems	The semi-deterministic nature of the algorithm Use a flexible memory of search history to avoid getting stuck in local optima

optimization challenges. In reviewing various meta-heuristic techniques for adjusting PSS parameters, it becomes evident that the utilization of bio-inspired techniques presents a notable advantage- the availability of different solutions after each run. Fuzzy logic is more effective than other methods in non-linear problems. Also, the integration of the above method with other methods helps to determine the optimal parameters of PSS. Table 1 summarizes the advantages and disadvantages of the studied meta-heuristic methods.

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