Particle Swarm Optimization Variants for Solving Reactive Power Reserve Optimization Problem: Review and Comparative Analysis

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Abstract: **Power systems involve numerous nonlinear optimization problems that play a crucial role in ensuring efficient and reliable operation. Traditional analytical methods often struggle with slow convergence and computational complexity, especially in high-dimensional spaces. In contrast, swarm intelligence-based heuristics offer a promising alternative. Among these, Particle Swarm Optimization (PSO) has emerged as a powerful tool for effectively tackling large-scale nonlinear optimization problems. This paper provides a detailed exposition of the fundamental principles of PSO and its various variants. The discussion encompasses the underlying concepts of PSO, its mechanism, and its application in addressing nonlinear optimization challenges in power systems. Particle Swarm Optimization (PSO) is a nature-inspired optimization algorithm that has gained significant attention due to its efficiency and effectiveness in solving complex optimization problems. This review article provides an in-depth exploration of innovative methodologies and applications of PSO in power systems. The paper covers the fundamental concepts of PSO, discusses innovative variants and hybridizations of the algorithm, and comprehensively reviews its diverse applications in power system optimization. The article concludes with a discussion of challenges, trends, and future research directions in utilizing PSO for power system optimization.**

Keywords: **Particle Swarm Optimization (PSO), Reactive Power, Scout Particle Swarm Optimization (ScPSO), Voltage Control, FACTS devices.**

1. Introduction

The Electric Power Grid is the world's largest man-made machine. Synchronous generators, transformers, transmission lines, switches and relays, active/reactive compensators, and controllers are all part of it. Various control objectives, operational actions, and/or design decisions in such a system necessitate the solution of an optimization issue. The solution to the optimization problem for such a nonlinear non-stationary system with probable noise and uncertainties, as well as numerous design/operational limitations, is far from straightforward. Furthermore, the following difficulties must be addressed:

- The optimization technique used must be acceptable and appropriate for the nature of the problem;
- All parts of the problem must be considered;
- All system restrictions must be correctly addressed;
- A comprehensive yet not too complicated objective function should be defined.

Optimization methods are significant algorithms used in control, classification, communication, and other disciplines. They seek to satisfy the convergence conditions in order to achieve optimal solutions. Convergence must be rapid and successful, especially in online (real-time) applications. It has fallen short in terms of convergence performance over time. To achieve better results, two approaches (new methods or hybridization of some optimization methods) were used concurrently. In this study, the second choice (hybridization) is pursued, and an efficient approach with its operating conditions for benchmark function optimization is investigated [1].

Power system applications often require solving one or multiple optimization problems which are nonlinear. Due to the limitations such as dimensionality constraints and slow convergence as offered by the analytical methods, swarm intelligence-based methods have emerged as a practical optimization problem solution alternate [2]. Optimization is a critical aspect of power system operation and planning to ensure efficient utilization of resources, cost minimization, and optimal performance. Particle Swarm Optimization (PSO), inspired by social behaviour of birds and fish, is a widely used optimization algorithm known for its simplicity and effectiveness in solving various complex optimization problems. This review article aims to provide an overview of innovative methodologies and applications of PSO in the context of power systems. Nonlinear optimization problems are inherent in various aspects of power systems, including economic dispatch, unit commitment, and load forecasting. Analytical methods often struggle with slow convergence and dimensionality issues in these complex scenarios. Swarm intelligence-based heuristics, exemplified by PSO, present a promising approach to efficiently solving these challenges.

2. Fundamentals of Particle Swarm Optimization (PSO)

PSO is founded on the concept of simulating the social behaviour of birds flocking or fish schooling. The algorithm maintains a population of particles, each representing a potential solution, that traverse the solution space in search of optimal solutions. The particles communicate with each other and adapt their positions based on their own best-known positions and the global best-known position of the swarm. Furthermore, PSO employs the swarm intelligence notion, which is a system feature in which the collective behaviours of unsophisticated agents interacting locally with their environment form coherent global functional patterns. It covers the initialization of particle positions and velocities, the interaction among particles through social and cognitive components, and the update mechanism to find optimal solutions. Detailed algorithms for PSO are explained, highlighting the balance between exploration and exploitation.

Kennedy and Eberhart presented Particle Swarm Optimization in 1995. As stated in the original publication, sociobiologists believe that a school of fish or flock of birds moving in a group "can benefit from the experience of all other members." In other words, if a bird is flying around randomly looking for food, all of the birds in the flock can share their discoveries and help the entire flock get the best hunt.

Fig. 1: Particle Swarm Optimisation (PSO) Photo by Don DeBold [3]

2.1 Swarm Intelligence Principles

The Five essential principles can be used to characterize swarm intelligence.

- **Proximity Principle:** The population should be able to do basic spatial and temporal computations.
- **Quality Principle:** The people should be able to respond to environmental quality variables.
- **Diverse Response Principle:** States that the people should not direct its activity through excessively restricted channels.
- **Stability Principle:** The population's way of conduct should not change every time the environment changes.
- **Adaptability Principle:** The population should be able to change its behaviour mode when the computational cost is worth it.

Particle Swarm Optimization is a swarm based algorithm inspired by the foraging behaviours of birds. During the imitation of foraging behaviours, PSO utilizes the velocity and position phenomena for the update of its particles. Additionally, the previous particle information is used in general back propagation processes [4]. In this manner, a continuous progression towards the global optimum point is provided. The flowchart of PSO is shown in Fig. 2 [4, 5].

$$x_i(t+1) \leftarrow x_i(t) + v_i(t) \quad (1)$$

$$v_i(t+1) \leftarrow \omega v_i(t) + c_1 r_1\big(pbest_i(t) - x_i(t)\big) + c_2 r_2(gbest(t)) - x_i(t)) \quad (2)$$

In the Eqs. (1) and (2), xi (t) is the position of particle i at time t, vi (t) is the velocity of particle i at time t, pbesti (t) is the best position found by particle itself so far, gbest(t) is the best position found by the whole swarm so far, ω is an inertia weight scaling the previous time step velocity, c1 and c2 are two acceleration coefficients that scale the influence of the best personal position of the particle (pbesti (t)) and the best global position (gbest(t)), and r1 and r2 are random variables within the range of 0 and 1[7].

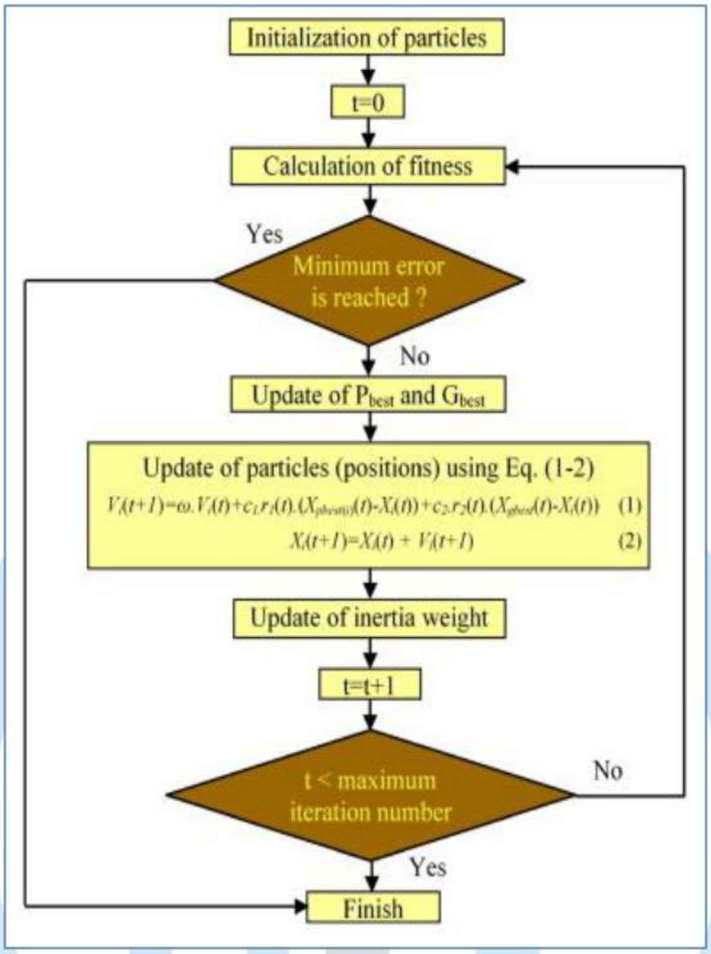

Fig. 1: Flowchart of PSO algorithm [4, 5]

In PSO, the solution space of the problem is formulated as a search space. Each position in the search space is a potential solution of the problem. Particles cooperate to find the best position (best solution) in the search space (solution space). Each particle moves according to its velocity.

2.2 Scout Particle Swarm Optimization Algorithm (ScPSO)

Particles are updated using velocity and position in the PSO algorithm. ABC use employed bee and bystander bee phases to do this. Nonetheless, in ABC, the scout bee phase regenerates worthless particles that cannot enhance their individual best placements. As previously stated, this process is controlled by the parameter limit. These particles are unable to retrieve their Pbest value. Particles in Standard PSO are updated without diversity, and their deficiencies are not managed [4, 5] It is evident that PSO requires a control parameter to boost its convergence capabilities, but this parameter must not dramatically increase its convergence time. As a result, it appears to be a sensible idea to incorporate the scout bee phase into the Standard PSO algorithm. ScPSO is created by incorporating the scout bee phase into PSO [4, 5]. All processes (excluding limit) in ScPSO are the same as in the PSO algorithm. The flowchart of ScPSO algorithm is shown in Fig. 3[4, 5]. The Particle Swarm Optimization Algorithm used in different wireless communication system for optimization of results [6, 7, 8].

The nonlinear optimization problems in power systems are multifaceted and often high-dimensional. PSO's ability to efficiently explore solution spaces makes it a valuable tool. This section outlines the adaptation of PSO to address economic dispatch, unit commitment, load forecasting, and other nonlinear optimization problems in power systems. Case studies showcasing successful applications of PSO in these domains are presented.

3. Innovative Methodologies and Variants

This section delves into innovative variations and methodologies of PSO. These include adaptive PSO, chaotic PSO, quantum-behaved PSO, and multi-objective PSO, among others. Each variant introduces unique characteristics that enhance the algorithm's performance and applicability to diverse optimization problems. Various enhancements and modifications have been proposed to adapt PSO to different optimization scenarios. This section delves into these variants, including adaptive PSO, chaotic PSO, quantum-behaved PSO, and multi-objective PSO. Each variant's distinctive features, mechanisms, and advantages are discussed, illustrating how they address specific challenges.

Various methods exist in the literature that addresses the optimization problem under different conditions. In its simplest form, this problem can be expressed as follows. Find the minimum1 of an objective function $f(\underline{x}): A \rightarrow R$

Subject to: $g_i(\underline{x}) = 0, \quad \text{for } i = 1, \dots\dots, k$ (3)

$h_j(\underline{x}) \leq 0, \quad \text{for } j = 1, \dots\dots., m.$ (4)

Different optimization methods are classified based on the type of the search space $A \subseteq R^n$ and the bijective (cost) Function f. Fan and Shi [14] demonstrated that a suitable dynamically changing can increase the performance of the PSO method. Abido [15, 16] has also proposed a maximum velocity offered by to achieve consistent velocity across all dimensions.

$v_{max} = (x_{max} - x_{min})/N$ (5)

Where N is the number of intervals in the k^{th} dimension selected by the user and x_{max}, x_{min} are maximum and minimum values found so far by the particles.

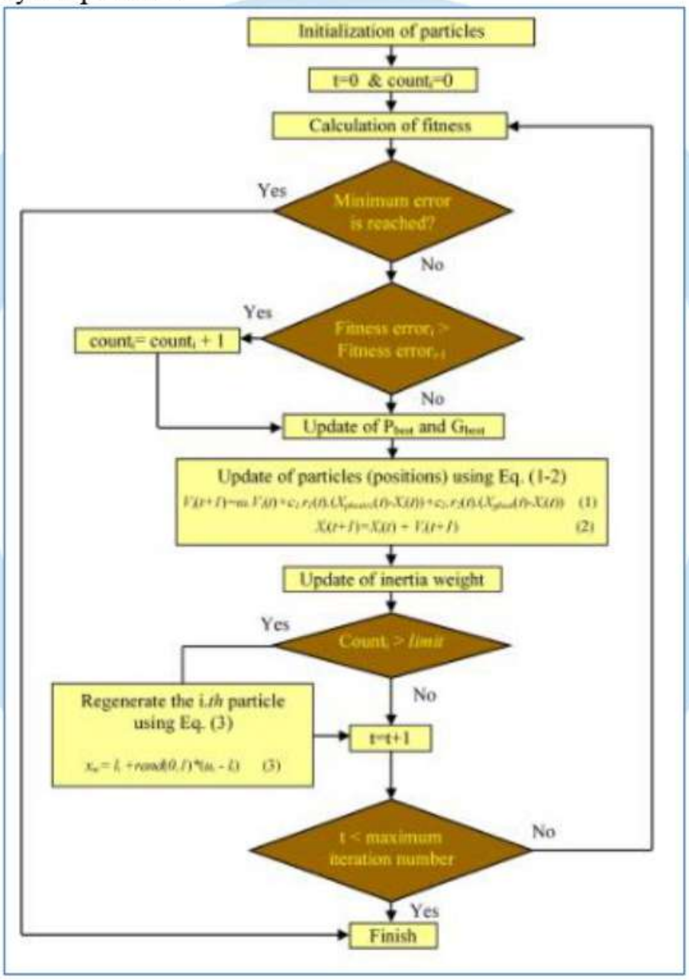

Fig.3: Flowchart of ScPSO algorithm[4, 5]

4. Literature Review on PSO with Applications to Power Systems

This section provides an overview of PSO technique applications to power system challenges. Table 1 outlines the applications where PSO has been utilized to solve optimization problems, as well as the type of PSO used and the significant papers linked with the application [16-22]. This section covers topics discussed by Al Rashidi and El-Hawari, as well as some new ones. Furthermore, technical details are provided for each application to allow the reader to do similar experiments and address issues with similar features.

Table 1: Application of PSO Technique to Power Systems by Technical Areas

Area Name	PSO types
Reactive power and voltage control	Conventional PSO, Integer PSO, Adaptive PSO
Economic Dispatch	Conventional PSO, Evolutionary Programming PSO (EPSO)
Power System Reliability and Security	Conventional PSO, Binary PSO
Generation Expansion Problem	Conventional PSO, Stretching PSO (SPSO), Composite PSO (C-PSO)
State Estimation	Conventional PSO, Hybrid PSO (GA-PSO)
Load Flow and Optimal Power Flow	Conventional PSO, Hybrid PSO (GA-PSO), Vector Evaluated PSO (VEPSO), PSO with Passive Congregation (PSOPC), Dissipative PSO (DPSO)
Power System Identification and Control	
- Controller Tuning	Conventional PSO
- System Identification and Intelligent Control	Conventional PSO, Hybrid PSO (GA-PSO)
Electric Machinery	Conventional PSO
Capacitor Placement	Conventional PSO, Integer PSO
Generator Maintenance Scheduling	Conventional PSO, Evolutionary Programming PSO (EPSO)
Short-Term Load Forecasting	Conventional PSO

Over the last decade, the field of Knowledge Discovery in Databases (KDD) has emerged to solve this difficulty. Data mining is an important aspect of the KDD process. Data mining is the process of extracting meaningful patterns or mining knowledge from huge amounts of data using proper algorithms, tools, and methodologies. Clustering is a well-known and significant data mining task [8].

Clustering means the process of partitioning an unlabelled dataset into groups of similar objects. Each group, called a cluster, consists of objects that are similar to each other with respect to a certain similarity measure and which are dissimilar to objects of other groups. The applications of cluster analysis have been used in a wide range of different areas, including artificial intelligence, bioinformatics, biology, computer vision, data compression, image analysis, information retrieval, machine learning, marketing, medicine, pattern recognition, spatial database analysis, statistics, recommendation systems and web mining [9].

The challenge of clustering high-dimensional data has emerged in recent years. Clustering high-dimensional data is the cluster analysis of data with anywhere from a few dozen to many thousands of dimensions. Such high-dimensional data spaces are often encountered in areas such as medicine, biology, bioinformatics, and the clustering of text documents, where, if a word-frequency vector is used, the number of dimensions equals the size of the dictionary. However, high-dimensional data poses different challenges for clustering algorithms that require specialized solutions. In particular, in high-dimensional data, traditional similarity measures, as used in conventional clustering algorithms, are usually not meaningful [10].

Almost all research on specialized approaches to clustering high dimensional data is relatively new. Recently, some surveys have given overviews of some approaches. In the survey by [11] the problem is introduced in a very illustrative way and some approaches are sketched out. In [9] the survey took a more systematic approach to the problem and focused on the different tasks and sub-problems (axis-parallel, pattern-based, and arbitrarily-oriented clustering).

Common approaches for high dimensional cluster analysis either employ dimension reduction at a data pre-processing step or iteratively carry out dimension reduction and clustering. In particular, dimension reduction based on variable selection aims at identifying a subspace spanned by a small set of variables that include most of the relevant variables that generate the nature data clusters and excludes most irrelevant variables [11]. Variable selection in clustering has been approached from different perspectives: density-based methods such as [12], model-based methods such as [11] and criterion-based methods such as [13].

5. REACTIVE POWER AND VOLTAGE CONTROL

In general, an electric power network is susceptible to abrupt changes in configuration as lines and loads are turned on and off. One of the most critical operational duties of utilities in such a dynamic system is keeping the voltage within a permitted range for consumers. To do this, power utility operators can program the synchronous generators, transformer tap settings, FACTS devices, and shunt reactors to provide the appropriate amount of reactive power to keep the bus voltages at the correct level. Reactive power and voltage control, or volt/var control (VVC), is an online control approach for accomplishing this. The fundamental function of OPRF is to keep bus voltage magnitudes within operating limits [20]. This is especially important in PV-heavy distribution grids, because cloud covering can obscure certain grid sections, rendering typical grid-wide control methods ineffective [20]. Key elements for addressing climate change, enhancing energy efficiency, and gaining access to contemporary energy services are included among others in the United Nations 2030 Agenda for Sustainable Development [22]. Essentially, any VVC method must maintain voltage security so that the system conditions do not deteriorate to the point of voltage collapse. There are several traditional ways for analysing voltage contingency analysis in the literature [17]. VVC can be expressed in general as follows:

Minimize $\sum$ Loss (6)

Subject to the following constraints:

• Voltage at each node must lie within its permissible range.
• Power flow of each branch must be lower than the maximum allowable.
• Transformer tap positions must be within the available range of steps.
• Generator reactive powers must lie within their permissible range.

In addition to the above constraints, VVC can be formulated to keep the voltage security of the power system. In light of the foregoing, this work describes a Scout Particle Swarm Optimization (ScPSO) algorithm for improving distribution system reliability. The best improvements for a distribution system's failure rate and repair time are assessed. The changes are in relation to the minimizing of a penalty cost function. The cost function has been minimized while taking into account the various indices. Statistical analysis is also available. The Introduction to Reliability Indices. Customer and Energy based indices are as follows:

System average interruption frequency index (SAIFI):

$$\mathrm{SAIFI} = \frac{\sum \lambda_{sys,} N_i}{\sum N_i} \tag{7}$$

Most important energy based indices is average energy not supplied (AENS) which is given as follows.

$$\mathrm{AENS} = \frac{\sum L_i U_{sys,i}}{\sum N_i} \tag{8}$$

Where L_i is average load connected at i^{th} load point.

5.1 Hybridization Approaches and whale optimization algorithm (WOA)

Hybridizing PSO with other optimization algorithms and techniques can result in improved convergence speed and solution quality. Common hybridizations include combining PSO with genetic algorithms, differential evolution, and fuzzy logic. This section explores the benefits and synergies of these hybrid approaches. The standard whale optimization algorithm (WOA) involves exploitation and exploration operations that are required to be balanced for improved performance. The Whale Optimization Algorithm (WOA) has been introduced a decade later using a distinct hunting performance of humpback whales in the early 2016 [18, 19]. The performances of AFSA and WOA have been compared with few well developed and very prominent bio-inspired techniques like Particle Swarm Optimization (PSO), DE, etc [18, 19].

The primary goal of optimal reactive power planning is to fix the sizes of var compensators while maintaining the system voltage margin. Thus, the authors explored the relevance and effectiveness of evolutionary algorithms in allocating the appropriate size of var sources from a planning standpoint. The paper presented how to tackle the reactive power optimization problem using a hybrid particle swarm optimization (HPSO) optimizer [21].

5.2 Comparative Analysis for Reactive Power Reserve optimization Problem

[1] The authors ***Tawfiq M. Aljohani and et al. [22]*** discussed the Reactive Power Reserve optimization Problem. The Optimal reactive power dispatch (ORPD) is an important problem in power system operation. The economy of grid operation has two main aspects to consider: active (Watt) and reactive (Var) power control problems. The Watt problem concerns regulating and controlling the output of the generation units to reduce the overall costs of production. On the other hand, the Var is considered a more complex problem due to the nature of control variables involved in its operation, where it focuses on different voltage control aspects of the grid components (i.e., tap-changing transformers, reactive compensators, etc.) to reduce the overall grid losses, and improve voltage balance. ORPD is considered a pivotal problem in this manner, which aims to solve highly constrained, non-convex, and nonlinear optimization problems that possess both discrete and continuous control variables to achieve important goals, such as minimizing active power losses and voltage deviations, while improving the voltage stability index of the grid.

[2] The ***Mahmmadsufiyan S. and et al. [23]***. The results for the base-case settings of control variables are denoted by “Base.” The results of multi-objective PF for OC minimization and ERPR maximization considering all the active and reactive control variables are denoted by MOOPF. The objectives of TSOARPD are the operating cost (OC) minimization in stage 1 and voltage stability (VS) maximization in stage 2, whereas the VS is improved by maximizing the system’s reactive power reserve (RPR). In this paper, instead of using multi-objective optimal power Allow, this TSOARPD is used to give more importance to VS when the system is substantially loaded. The authors discussed the detailed procedure of solving POARPD by considering correlation and the increased nonlinearities by giving more importance to VS when the system is heavily loaded.

[3] ***Hanan T. and et al. [24].*** Reactive power compensation is extremely crucial for maintaining the power quality that includes voltage, current, and power system stability [25], and it can be ensured using different techniques, including capacitor-banks, synchronous generators, and, likewise, via the flexible alternating current transmission

system (FACTS) [26, 27]. If there is no reactive power compensation, it may lead to a complete power system collapse [28, 29]. The world has already seen some radical cases of major blackouts, such as Tokyo in 1987 and Italy in 2003. Both of these contingencies resulted in massive economic and social lags [30, 31]. Traditionally, in the past, utilizing a synchronous condenser system was considered a reliable approach, not only for the provision of reactive power but also for the power factor improvement [32].

[4] ***Baseem K. and Pawan S. [33].*** This work presents a comprehensive study of optimal power flows methods with conventional and renewable energy constraints. Additionally, this work presents a progress of optimal power flow solution from its beginning to its present form. Authors classify the optimal power flow methods under different constraints condition of conventional and renewable energy sources. The current and future applications of optimal power flow programs in smart system planning, operations, sensitivity calculation, and control are presented. This study will help the engineers and researchers to optimize power flow with conventional and renewable energy sources.

Applications in Power Systems PSO [34-40] have demonstrated its versatility in addressing a wide range of power system optimization challenges. This section reviews applications such as economic dispatch, unit commitment, load forecasting, reactive power optimization, voltage control, and optimal placement of renewable energy resources. Each application is discussed in terms of problem formulation, PSO implementation, and achieved results [41-45].

[5] ***Bhattacharyya B. and Raj S. [46]*** Reactive power control has become an important aspect for many reasons. Firstly, the need for most efficient operation of power systems has increased with the price of fuel. In many cases power transmitted through older circuit increases day by day, requiring the application of reactive power control measures to restore stability margins. The objective of the reactive power planning problem is to minimize the active power loss and the overall operating cost that includes cost due to energy loss and the investment cost of shunt capacitors installed at weak buses determined either by modal analysis or L-index method [46]. Also, the improvement of voltage stability is addressed along with the effective planning of the reactive power sources.

Table 2: Comparative Analysis for Reactive Power Reserve of PSO

Reference	Year	Objectives	Algorithms	Methodology	Findings
Tawfiq M. Aljohani and et al. [22]	2019	To optimal reactive power dispatch (ORPD) for solving the problem of power system operation.	PSO, ORPD	Focuses on different voltage control aspects of the grid components (i.e., tap-changing transformers, reactive compensators, etc.)	Achieve important goals, such as minimizing active power losses and voltage deviations, while improving the voltage stability index of the grid.
Mahmmadsufiyan S. and et al. [23].	2023	The objectives of TSOARPD are the operating cost (OC) minimization in stage 1 and voltage stability (VS) maximization in stage 2, whereas the VS is improved by maximizing the system's reactive power reserve (RPR).	TSOARPD, PSO.	In this paper, instead of using multi-objective optimal power Allow, this TSOARPD is used to give more importance to VS when the system is substantially loaded	The results of multi-objective PF for OC minimization and ERPR maximization considering all the active and reactive control variables are denoted by MOOPF
Hanan T. and et al. [24].	2022	The core objective of performing a load flow analysis is to conclude voltages along with the real and reactive power of individual bus bars and transformers' parameters in the power grid	Capacitor-banks, Synchronous generators	Multiple aspects were investigated via software simulations to assess the performance of the aforementioned FACTS devices, such as the voltage profile evaluation via the load flow analysis method (LFA)	Power factor improvement.
Baseem K. and Pawan S. [33]	2020	This work presents a comprehensive study of	Power Systems	Optimize power flow with conventional and	Each application is discussed in terms of

		optimal power flows methods with conventional and renewable energy constraints.	PSO	renewable energy sources.	problem formulation, PSO implementation, and achieved results.
Bhattacharyya B. and Raj S. [46]	2017	The objective of the reactive power planning problem is to minimize the active power loss and the overall operating cost that includes cost due to energy loss and the investment cost of shunt capacitors installed at weak buses determined either by modal analysis or L-index method	PSO, GA, DE	Differential Evolution (DE) and Genetic Algorithm (GA)-based optimization	It is observed that modal analysis based detection of weak nodes are more effective than the L-index-based detection. Moreover, the DE-based optimization algorithm gives better result compared to GA-based approach in maximizing reactive power reserves.

5.3 Challenges and Future Directions

While PSO has proven its effectiveness, challenges remain. These challenges include premature convergence, scalability to large systems, and handling complex and non-linear constraints. The article discusses these challenges and outlines potential research directions to overcome them, including the development of more advanced PSO variants and hybrid algorithms. Despite its effectiveness, PSO faces challenges such as premature convergence and parameter tuning. This section explores these challenges and presents potential avenues for future research, including hybridization with other techniques, incorporation of adaptive mechanisms, and addressing scalability issues.

6. CONCLUSION

Particle Swarm Optimization offers an efficient and adaptive approach to solving complex optimization problems in power systems. This review article highlighted the fundamental concepts of PSO, explored innovative methodologies and variants, reviewed its applications in power systems, and discussed challenges and future directions. PSO's ability to handle diverse power system optimization problems makes it a valuable tool in the quest for more sustainable and efficient power systems. In most circumstances, implementing any of the standard analytical optimization procedures may be impossible. PSO, on the other hand, may be an alternative solution. It is a stochastic-based search technique with roots in artificial life, social psychology, engineering, and computer science.

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