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A Survey of Particle Swarm Optimization Applications in Electric Power Systems

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***Abstract*—Particle swarm optimization (PSO) has received increased attention in many research fields recently. This paper presents a comprehensive coverage of different PSO applications in solving optimization problems in the area of electric power systems. It highlights the PSO key features and advantages over other various optimization algorithms. Furthermore, recent trends with regard to PSO development in this area are explored. This paper also discusses PSO possible future applications in the area of electric power systems and its potential theoretical studies.**

***Index Terms*—Particle swarm optimization (PSO), power system control, power system operations.**

I. Introduction

OPTIMIZATION problems are widely encountered in various fields of science and technology. Sometimes such problems can be very complex due to the actual and practical nature of the objective function or the model constraints. Traditionally, optimization methods involved derivative-based techniques such as those summarized in [1]–[3]. These techniques are robust and have proven their effectiveness in handling many classes of optimization problems. However, such techniques can encounter difficulties such as getting trapped in local minima, increasing computational complexity, and not being applicable to certain classes of objective functions. This led to the need of developing a new class of solution methods that can overcome these shortcomings. Heuristic optimization techniques are fast growing tools that can overcome most of the limitations found in derivative-based techniques.

Kennedy and Eberhart first introduced particle swarm optimization (PSO) in 1995 as a new heuristic method [4], [5]. The original objective of their research was to mathematically simulate the social behavior of bird flocks and fish schools. As their research progressed, they discovered that with some modifications, their social behavior model can also serve as a powerful optimizer. The first version of PSO was intended to handle only nonlinear continuous optimization problems. However, many advances in PSO development elevated its capabilities to handle a wide class of complex engineering and science optimization problems. Summaries of recent advances in these areas are presented in [6] and [7] and will not be addressed in this paper due to space limitations.

Different variants of the PSO algorithm were proposed but the most standard one is the global version of PSO (Gbest model) introduced by Shi and Eberhart [8], where the whole population is considered as a single neighborhood throughout the optimization process. A key attractive feature of the PSO approach is its simplicity as it involves only two model equations. In PSO, the coordinates of each particle represent a possible solution associated with two vectors, the position (x_i) and velocity (v_i) vectors. In N-dimensional search space, $X_i = [x_{i1}, x_{i2}, \ldots, x_{iN}]$ and $V_i = [v_{i1}, v_{i2}, \ldots, v_{iN}]$ are the two vectors associated with each particle i. A swarm consists of a number of particles "or possible solutions" that proceed (fly) through the feasible solution space to explore optimal solutions. Each particle updates its position based on its own best exploration, best swarm overall experience, and its previous velocity vector according to the following model:

$$v_i^{k+1} = wv_i^k + \mathrm{c}_1\mathrm{r}_1\left(\mathrm{pbest}_\mathrm{i}^\mathrm{k} - x_i^k\right) + \mathrm{c}_2\mathrm{r}_2\left(\mathrm{gbest}^\mathrm{k} - x_i^k\right) \tag{1}$$

$$x_i^{k+1} = x_i^k + v_i^{k+1} \tag{2}$$

where

c_1 and c_2	are two positive constants;
r_1 and r_2	are two randomly generated numbers with a range of [0,1];
w	is the inertia weight;
$\mathrm{pbest}_\mathrm{i}^\mathrm{k}$	is the best position particle i achieved based on its own experience; $\mathrm{pbest}_\mathrm{i}^\mathrm{k} = [x_{i1}^{pbest}, x_{i2}^{pbest}, \ldots, x_{iN}^{pbest}]$;
$\mathrm{gbest}^\mathrm{k}$	is the best particle position based on overall swarm's experience; $\mathrm{gbest}^\mathrm{k} = [x_1^{gbest}, x_2^{gbest}, \ldots, x_N^{gbest}]$;
k	is the iteration index.

PSO is a population-based evolutionary technique that has many key advantages over other optimization techniques like:

- It is a derivative-free algorithm unlike many conventional techniques.
- It has the flexibility to be integrated with other optimization techniques to form hybrid tools.
- It is less sensitive to the nature of the objective function, i.e., convexity or continuity.
- It has less parameters to adjust unlike many other competing evolutionary techniques.
- It has the ability to escape local minima.
- It is easy to implement and program with basic mathematical and logic operations.
- It can handle objective functions with stochastic nature, like in the case of representing one of the optimization variables as random.
- It does not require a good initial solution to start its iteration process.

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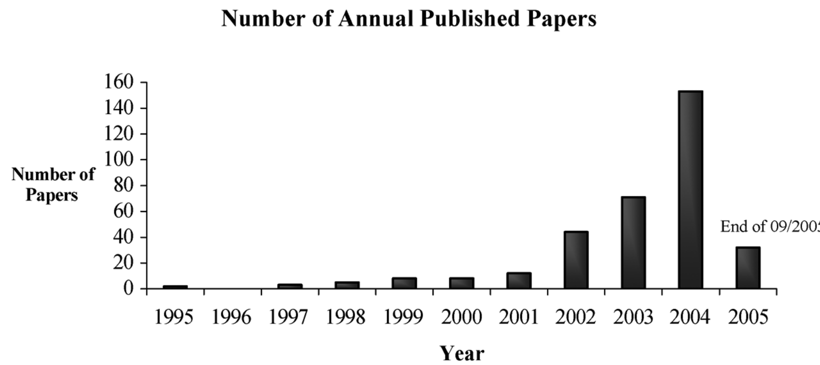

Fig. 1. Number of PSO related published papers each year in all research fields.

The PSO algorithm can be best described in general as follows:

1) For each particle, the position and velocity vectors will be randomly initialized with the same size as the problem dimension.
2) Measure the fitness of each particle (pbest) and store the particle with the best fitness (gbest) value.
3) Update velocity and position vectors according to (1) and (2) for each particle.
4) Repeat steps 2–3 until a termination criterion is satisfied.

In addition to traditional gradient-based optimization algorithms, there are many other heuristic techniques that compete with PSO such as genetic algorithm, simulated annealing, evolutionary programming, and most recently ant colony optimization. In general, most of these techniques can be used to solve various optimization problems, just like in the case of PSO. However, such competing techniques tend to have major drawbacks such as the following:

- More parameter tuning is required.
- They require extensive computational time.
- Heavily involved programming skills are required to develop and modify competing algorithm to suit different classes of optimization problems.
- Some techniques require binary conversion instead of working with direct real valued variables.

On the other hand, some advantages of aforementioned algorithms over PSO are the following:

- The availability of commercial versions of some algorithms like Matlab (genetic algorithm) and Excel premium solver (evolutionary programming).
- The extensive collection of books and research literatures, especially in the case of genetic algorithm and evolutionary programming, which cover these competing methods.

Despite the simplicity of the PSO concept and implementation, its superiority is proven when compared with other techniques in many different application areas [9]–[13].

Other heuristic techniques that belong to the same category are summarized in [14]. These techniques have been gaining more popularity mainly because of their robustness, simplicity, and their ability to deal with more exact models instead of making intolerable approximations. The major drawbacks of PSO are the lack of solid mathematical background and failure to assure global optimal solution. PSO has been proven to perform well in many standard benchmark optimization problems used by researchers to validate new global optimization techniques [15]–[18]. Reference [16] is an excellent reference that analyzed and studied the PSO promising convergence characteristics. In [16], Clerc and Kennedy successfully established some mathematical foundation to explain the behavior of a simplified PSO model in its search for an optimal solution. However, further analysis is needed to explain other issues of the PSO, like the social influence aspect of the algorithm and generalized rules in how to tune its parameters to suit different optimization problems. In [16], the authors emphasized the need for further future studies by stating "Several kinds of coefficient adjustments are suggested in the present paper, but we have barely scratched the surface and plenty of experiments should be prompted by these findings." Fig. 1 shows the increasing growth in various research papers with regard to PSO (based on IEEE/IEE databases).

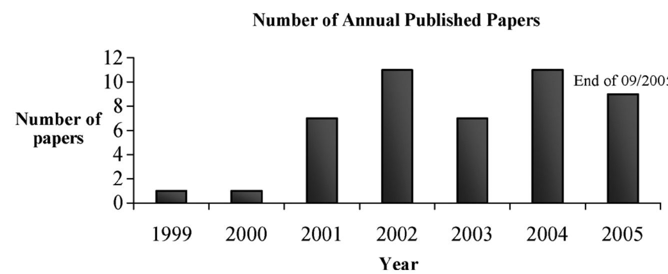

Fig. 2. Number of PSO related published papers each year in power system areas.

The focus of the present paper is to survey and summarize most PSO applications in the area of electric power systems. This work can serve as a good starting point for those interested in learning about the development of PSO and its applications in electric power systems engineering.

II. Areas of PSO Applications in Electric Power Systems

Research in power systems has its share in applying PSO to various optimization problems. Fig. 2 shows the number of published papers in which PSO was applied to different areas of electric power systems (based on IEEE/IEE/Elsevier databases). It clearly indicates its applicability and the fast growing interest in PSO utilization in this research area.

Electric power system optimization problems are fairly diverse and they can be categorized in terms of the objective function characteristics and/or type of constraints. They are commonly referred to as linear, nonlinear, integer, and/or mixed integer constrained optimization problems. Traditionally, a derivative-based optimization technique is utilized to tackle a specific problem based on its formulation which requires differentiability among many other things. However, the PSO technique can be easily adapted to suit various categories of optimization problems with minor modifications. This key attribute makes the PSO a general purpose optimizer that solves a wide range of optimization problems. PSO applications in electric power systems are similar to those in different research fields once a common formulation is established. However, PSO parameter tuning might be different from one application to another.

Reference [19] appears to be the first published paper that applied PSO in the area of electric power systems to minimize the real power losses of an electric power grid. The problem is classified as one of mixed-integer nonlinear optimization because some control variables are continuous while others are discrete. This introductory application was followed by a series of PSO related papers to solve similar problems [20]–[22]. The initial motivation to apply PSO in this research field is mainly due to the complexity of this problem, since power flow calculations that involve solving a system of nonlinear equations, are required to evaluate each solution candidate. The PSO technique demonstrated its effectiveness in solving this difficult optimization problem by improving the solution's accuracy and computation time. The following are the major areas in which PSO was applied.

A. Economic Dispatch

El-Gallad *et al.* [23] and Park *et al.* [12] adapted PSO to solve the traditional economic dispatch problem. In both papers, the objective function was formulated as a combination of piecewise quadratic cost functions with nondifferential regions, instead of adopting a single convex function for each generating unit. This innovation in problem formulation is due to the incorporation of practical operating conditions, like valve-point effects and fuel types. The system constraints included in [23] were system demand and the balance of power, with network losses incorporated and the generating capacity limits. Park *et al.* did not account for transmission line losses in [12] for simplicity. El-Gallad *et al.* added new constraints to the problem formulation in [24] by introducing system spinning reserve and generator prohibited operating zones. In this formulation, they included the same constraints as those used in [23] and considered a single convex cost function.

In [9], a different formulation was proposed by including the generator ramp rate limits in the same problem treated in [24]. In Gaing's work [9], a comparison between PSO and genetic algorithm performance in solving the same economic dispatch problem is made. Gaing introduced a dynamic aspect to the same problem by adding a time-varying system load in addition to accounting for some of the generator operation related restrictions, such as ramping rate limits and prohibited operating zones, while imposing system spinning reserve requirement and line flow as inequality constraints [25]. Victoire and Jeyakumar extended Gaing's research by forming a hybrid optimizer to tackle the same problem [26]. They used sequential quadratic programming to fine-tune the PSO search in finding the optimal solution.

Kumar *et al.* included emission aspects of power dispatching problem [27]. They utilized PSO in solving a multiobjective optimization problem that includes both cost and emission functions. They combined the two objective functions by assigning a single price penalty factor to the emission function to form a single objective function.

B. Reactive Power Control and Power Losses Reduction

In this area, PSO was used to optimize the reactive power flow in the power system network in order to minimize real power system losses. Yoshida *et al.* [19], [20], [22] and Fukuyama *et al.* [21] took the initiative of introducing PSO to reactive power optimization. In their problem formulation, the objective was to find the optimal settings of some control variables that would minimize the total real power losses in a network. The control variables are automatic voltage regulator operating values, transformer tap positions, and a number of reactive power compensation equipment subject to equality and inequality constraints. Based on the nature of the control variables, the problem is classified as a mixed-integer nonlinear optimization problem since some variables are continuous while others are discrete. Mantawy and Al-Ghamdi investigated the same problem using a different test system [28].

Miranda and Fonseco appear to be the first to introduce a hybrid PSO approach in this area [29], [30]. They combined evolutionary strategies with PSO to improve the robustness of the classical PSO. In [31], Zhao *et al.* combined multiagent systems with PSO to solve the same problem. Esmin *et al.* considered shunt capacitor banks as the only type of control variables in their problem formulation [32]. They incorporated the tangent vector technique to identify the critical area of power system network where voltage stability might be in danger. Then, they applied PSO to find the "needed" reactive power compensation. A new hybrid method was introduced by Chuanwen and Bompard as they combined PSO with a linear interior point technique to solve a reactive power optimization problem [33]. In their work, PSO was used as a global optimizer to search the entire solution space, while the linear interior point method acted as a local optimizer to search the space around the optimal solution.

To show the effectiveness of PSO in reactive power control and power losses reduction, it was successfully applied to a practical power system in the province of Heilongjiang in China [13]. This system consists of 151 buses and 220 transmission lines with 71 control variables. A different problem formulation was proposed by Coath *et al.* where they considered reactive power losses minimization as an objective function [34]. They also introduced generator real power outputs as additional control variables. The difference in their problem formulation was mainly due to the inclusion of wind farms as modern integral parts of the power system networks.

C. Optimal Power Flow (OPF)

Abido is credited with introducing PSO to solve the OPF problem [35]. In OPF, the goal is to find the optimal settings of the control variables such that the sum of all generator's cost functions is minimized. The generator real power outputs are considered control variables in addition to the other control variables considered previously in the reactive power optimization problem. PSO was effective in dealing with this complex optimization problem that has various equality and inequality constraints and both continuous and discrete variables. In a different approach to the problem, Zhao *et al.* solved the highly constrained OPF optimization problem by minimizing a nonstationary multiagent assignment penalty function [10]. In this formulation, PSO was used to solve the highly constrained OPF optimization problem in which the penalty values were dynamically modified in accordance with system constraints. In [36], the passive congregation concept was incorporated in PSO to solve the OPF problem. This hybrid technique improved the convergence characteristics over the traditional PSO in solving the same OPF problem.

D. Power System Controller Design

In [37] and [38], PSO was employed to find the optimal settings of power system stabilizer parameters. The problem was formulated as one of min–max optimization of two eigenvalue-based objective functions. Okada *et al.* went along the same lines when they used PSO to optimally design a fixed-structure controller to enhance the stability of power systems [39]. In this work, the authors' goal was to find the global optimal solution of a multimodal optimization problem. PSO was also used in optimizing the feedback controller gains. Al-Musabi *et al.* made use of PSO in finding optimal controller gain values for a load frequency problem of a single area power system [40]. Abdel-Magid and Abido extended PSO usage in this area when they enlarged the control system to two areas [41]. In their work, they considered two types of controllers, namely an integral controller and a proportional plus integral controller. Juang and Lu combined the genetic algorithm with PSO in [42] to perform the same optimization process as in [41] on a fuzzy proportional-integral-controller. Ghoshal augmented the problem by trying to find the optimal proportional-integral-derivative controller gains of a three area power system [43]. He tackled the problem using PSO in addition to other heuristic techniques. Lu and Juang applied PSO to design a fuzzy controller for a thyristor-controlled series capacitor to enhance the transient stability of flexible AC transmission systems [44].

E. Neural Network Training

Neural networks emerged as a valuable artificial intelligence tool in many areas in electric power systems. El-Gallad *et al.* used PSO to train a neural network for power transformer protection [45]. The objective was to develop a model that would be able to intelligently distinguish between magnetizing inrush current and internal fault current in power transformers. PSO was employed to improve the accuracy and the execution time of the identification process. Hirata *et al.* used PSO to determine the optimal connection weights of a neural network model used to improve stability control of power systems [46]. They formulated the optimization problem as a min–max problem with an objective function that has nondifferential and discontinuous nature. Kassabalidis *et al.* integrated PSO with a neural network to identify the dynamic security border of power systems under a deregulated power system environment [47].

F. Other Electric Power System Areas

In [48] and [49], the performance of PSO was explored in the area of electric power quality by improving the process of feeder reconfiguration. The problem is formulated as a nonlinear optimization problem with nondifferentiable characteristics. Victoire and Jeyakumar combined PSO, sequential-quadratic-programming, and tabu search to form a hybrid technique to tackle the unit commitment combinatorial optimization problem [50]. In the area of short-term load forecasting, Huang *et al.* were able to identify the autoregressive moving with exogenous variable (ARMAX) model using PSO [11]. Slochanal *et al.* and Kannan *et al.* introduced PSO in the area of generation expansion planning in [51] and [52] to solve discrete nonlinear optimization problems. They used it in [51] to maximize the profit of a generating utility subject to certain market conditions and various system constraints. In [52], PSO was employed to minimize the capital and operation cost of the generation expansion planning problem. Also in this area, PSO was utilized in solving the expansion planning problem of a transmission line network [53].

Koay and Srinivasan solved the multiobjective generator maintenance scheduling problem by creating a hybrid technique by means of combining PSO with evolutionary strategies in [54]. In power system reliability studies, PSO was applied to a feeder-switch relocation problem in a radial distribution system [55]. The authors in [55] used PSO to allocate the most appropriate positions to place sectionalized devices in distribution lines. The objective function of this problem is categorized as nonlinear with nondifferentiable characteristics. In [56], applications of PSO in finding optimal operation settings of a system composed of distributed generators and energy storage systems were illustrated. Naka *et al.* and Fukuyama formed hybrid techniques by combining PSO with other heuristic techniques to improve the performance of a distribution of state estimator in [57] and [58], respectively. PSO was later applied to solve a short-term hydroelectric system scheduling problem in [59]. The problems in references [57]–[59] are formulated as continuous nonlinear optimization problems. Yu *et al.* applied PSO to tackle the discrete optimal capacitor placement problem in a noisy environment [60].

III. Conclusion

This paper presents a summary of PSO applications in power systems. It highlights many applications in which PSO was successfully applied, yet it reveals some additional unexplored areas where it can be further employed like protection, restoration, etc. Also, deregulating all major parts of the electric power industry led to the emergence of a new operation philosophy that will reformulate many optimization problems. Another promising research area with regard to PSO is hybridization. Recently, many researchers in power systems attempted to combine the PSO algorithm with other techniques to form hybrid tools. PSO adaptability to be integrated with other deterministic and evolutionary optimization algorithms is expanding. This hybridization extended PSO capabilities and improved its accuracy and computation time. This paper also emphasizes the need for future mathematical investigations of PSO characteristics and behavior in its search for optimal solution. PSO is still in its infancy and further development and research are needed to enhance its overall performance characteristics.

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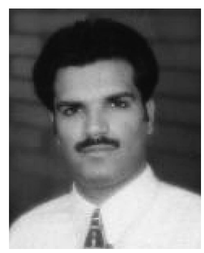

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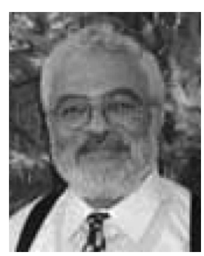

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