Open access • Journal Article • DOI:10.2202/1553-779X.1021

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Published on: 12 Mar 2005 - International Journal of Emerging Electric Power Systems (Walter de Gruyter GmbH)

Topics: Engineering optimization, Probabilistic-based design optimization, Multi-objective optimization, Metaheuristic and Optimization problem

International Journal of Emerging Electric Power Systems

Volume 2, *Issue* 1 | 2005 | *Article* 1021

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Recommended Citation:
Bansal, R. C. Dr. (2005) "Optimization Methods for Electric Power Systems: An Overview," *International Journal of Emerging Electric Power Systems*: Vol. 2: Iss. 1, Article 1021.
DOI: 10.2202/1553-779X.1021

Optimization Methods for Electric Power Systems: An Overview

R. C. Bansal Dr.

Abstract

Power systems optimization problems are very difficult to solve because power systems are very large, complex, geographically widely distributed and are influenced by many unexpected events. It is therefore necessary to employ most efficient optimization methods to take full advantages in simplifying the formulation and implementation of the problem. This article presents an overview of important mathematical optimization and artificial intelligence (AI) techniques used in power optimization problems. Applications of hybrid AI techniques have also been discussed in this article.

KEYWORDS: Power systems optimization, linear programming, expert systems, fuzzy systems, artificial neural network

1 Introduction

Mathematical optimization (algorithmic) methods have been used over the years for many power systems planning, operation, and control problems. Mathematical formulations of real-world problems are derived under certain assumptions and even with these assumptions, the solution of large-scale power systems is not simple. On the other hand, there are many uncertainties in power system problems because power systems are large, complex, and geographically widely distributed. More recently deregulation of power utilities has introduced new issues into the existing problems. It is desirable that solution of power system problems should be optimum globally, but solution searched by mathematical optimization is normally optimum locally. These facts make it difficult to deal effectively with many power system problems through strict mathematical formulation alone.

Therefore, artificial intelligence (AI) techniques which promise a global optimum or nearly so, such as expert systems (ES), artificial neural network (ANN), genetic algorithm (GA), fuzzy logic have emerged in recent years in power systems as a complement tool to mathematical approaches. The real beginning of AI is often quoted as 1958 [1]. Various optimization techniques have been applied to solve the power systems problem and large number of papers has been published in this area since 1950. Review on various power systems problems has been presented by Kothari et al. [2-4], Momoh et al. [5,6], Sachdev et al. [7], Happ [8], Quintanna et al. [9], Gonen et al. [10], Rahman [11], Huneault [12] and IEEE Committee [13,14]. This article presents an overview of important mathematical optimization and AI (e.g. ES, fuzzy logic, ANN, GA, ant colony search (ACS), tabu search (TS)) techniques used in power optimization problems. Applications of hybrid AI techniques in power systems have also been discussed in this article.

2 Mathematical Optimization Methods

An optimization problem is a mathematical model where main objective is to minimize undesirable things (e.g. cost, energy loss, errors, etc.) or maximize desirable things (e.g. profit, quality, efficiency, etc.), subject to some constraints. The main advantages of algorithmic methods include:

- Optimality is mathematically rigorous in some algorithms.
- Problems can be formulated to take advantage of the existing sparsity techniques applicable to large-scale power systems.
- There are a wide range of mature mathematical programming technologies, such as linear programming (LP)/interior point (IP) method and quadratic programming (QP), nonlinear programming (NLP), decomposition technique, integer and mixed integer programming, dynamic programming (DP), etc.

Following Section briefly discusses about the important mathematical optimization techniques used in power systems problems:

2.1 Linear and Quadratic Programming

When the objective function and constraints are linear, this gives the LP [15-17]. LP methods basically fall into two categories: simplex and IP methods [18-25]. These methods can handle problems with thousands of variables and constraints even using inexpensive computers. Main advantage of simplex method is its high computational efficiency. Main disadvantage is that number of iterations grows exponentially with problem size. This disadvantage can be overcome by IP methods. IP methods do not step from one corner point to the next in the manner of simplex algorithm, but rather stay within the interior of the constrained region and progressively move to the optimal point. A variety of IP algorithms have been applied to a number of power system problems, e.g. economic dispatch, reactive power optimization, power system optimization, etc. Both the simplex and IP methods can be extended to a linear and quadratic objective function when constraints are linear. Such methods are called QP [26-27]. LP has been used in various power systems applications, including power systems optimal power flow [16], load flow [17], reactive power planning [28], active and reactive power dispatch [29, 30].

2.2 Nonlinear Programming

When the objective function or the constraints are nonlinear, it forms NLP. The difference between the NLP and LP is analogous to the difference between a set of solving nonlinear equations and a set of solving linear equations. In most of the NLP methods, the approach is to start from an initial guess and to determine a 'descent direction' in which objective function decreases in case of minimization problem. A large number of NLP methods are available, distinguishable by their definition and step length. Quasi-Newton [31], which attempts to build up an approximation to Hessian matrix, can exhibit powerful convergence. Drawback of this method is that matrix processing is required. If the coefficients of Hessian matrix are available analytically, Newton method [32] can be applied. Some of the most successful mathematical methods in use today are based on applying QP to solve a local approximation to a non-linear problem. IP methods originally developed for LP can be applicable to QP and NLP problem. NLP has been applied to various areas of power systems [5] e.g. optimal power flow [33], hydrothermal scheduling [34], etc.

2.3 Integer and Mixed-Integer Programming

For many optimization problems (e.g. ON status =1, and OFF status =0), some of the independent variables can take only integer values; such problem is called integer programming. When some of the variables are continuous, the problem is called mixed integer programming. Mainly two approaches i.e. 'branch and

DOI: 10.2202/1553-779X.1021

bound', and 'cutting plane methods', have been used to solve integer problems using mathematical programming techniques [31]. It is possible to solve problem of hundreds of variables using integer and mixed integer programming. The size and complexity of integer and mixed-integer programmes that can be solved in practice depends upon the structure of the problem. Decomposition technique to decompose continuous problem into integer/mixed integer programming has been used in [35-40]. Integer/mixed integer programming has been applied to various areas of power systems e.g. optimal reactive power planning [41], power systems planning [42, 43], unit commitment [44], generation scheduling [45], etc.

2.4 Dynamic Programming

DP based on the principle of optimality states that a sub-policy of an optimal policy must in itself be an optimal sub-policy. For example, for a problem of n generators with possible s output level each, exhaustive enumeration would require s^n possible combinations to be examined, where as DP would examine fewer than n^2s^2 combinations. DP is a very powerful technique, where it is applicable, but suffers from the curse of dimensionality [46]**,** (In the above example for n=100, s= 200, $n^2s^2 = 4 X 10^8$). DP has been applied to various areas of power systems e.g. reactive power control [47], transmission planning [48], unit commitment [49], etc.

3 Artificial Intelligence Techniques

Despite the successes of the algorithmic approaches described in the previous section, there remains a large class of problems that elude complete solution in a conventional setting. These problems require:

- Use of knowledge bases to store human knowledge.
- Operator judgment particularly in practical solutions.
- Experience gained over a period of time.
- Characterization by network uncertainty, load variations, etc.

This section presents the overview of AI techniques (ES, ANN, fuzzy systems, EC, ant colony search, tabu search, etc.) for power systems problems.

3.1 Expert System

ES was first broadly researched by Feigenbaum et al. in the early 1970s [50, 51]. ES is a knowledge-based or rule based system, which uses the knowledge and interface procedure to solve problems that are difficult enough to require human expertise for their solution. Main advantages of ES [52] are: (i) It is permanent and consistent; (ii) Can be easily transferred or reproduced; (iii) Can be easily documented. Main disadvantage of ES is that it suffers from a knowledge bottleneck by having inability to learn or adapt to new situations. The level of maturity of applications varies from software prototype to practical systems in use in the power industry environment. The knowledge engineering techniques started with simplistic rule based techniques and extended to more advanced techniques such as object-oriented design, qualitative reasoning, verification and validation methods, natural languages, multi-agent systems.

For the past twenty years, a great deal of ES applications have been developed to help plan, analyze, manage, control and operate various aspects of power generation, transmission and distributions systems. A survey of ES applications in power system is presented in [53-56]. Lu et al. [57, 58] have done considerable work on the applications of ES in power systems. A recent survey presented in [59] indicates that ES has been applied to various areas of power systems, including: power system planning, alarm processing, fault diagnosis, power system protection, power system restoration and reactive power/voltage control.

3.2 Artificial Neural Network

The starting point of ANN was the training algorithm proposed by Hebb in 1949, which demonstrated how a network of neurons could exhibit learning behaviour [60]. ANN are mainly categorized by their architecture (number of layers), topology (connectivity pattern, feed forward or recurrent etc.), and learning regime. Most of the applications of ANN in the power systems use multi-layer feed forward network. The main advantages of ANN are [61-64]: (i) It is fast; (ii) Possesses learning ability; (iii) Adapts to the data; (iv) Robust; (v) Appropriate for non-linear modelling. These advantages suggest the use of ANN for voltage security monitoring and control. Though the neural network training is generally computationally expensive, it takes negligible time to evaluate voltage stability once the network has been trained. Despite the advantages, some disadvantages of the ANN are: (i) Large dimensionality; (ii) Selection of the optimum configuration; (iii) The choice of training methodology; (iv) The 'black-box' representation of ANN – they lack explanation capabilities and so decisions are not audible; (v) The fact that results are always generated even if the input data are unreasonable.

Vankayala et al. [65] have presented a bibliographical survey of neural network and their applications to power systems. Neural network has been mainly used in following areas of power systems:

- Planning (long term load forecasting [66, 67], capacitor placement/voltage control [68-72])
- Operation (economic dispatch/unit commitment [73-79], short-term load forecasting [80-90], fault diagnosis [91-95], load flow [96], static and dynamic security assessment [97-100], hydro scheduling [101-104], transient stability [105-114])
- Analysis (power system stabilizer [115-117]).

3.3 Fuzzy Logic

Fuzzy logic was developed by Zadeh in 1964 to address uncertainty and imprecision which widely exist in the engineering problems and it was first introduced in 1979 for solving power system problems. Fuzzy set theory can be considered as a generalization of the classical set theory. In classical set theory an element of the universe either belongs to or does not belong to the set. Thus the degree of association of an element is crisp. In a fuzzy set theory the association of an element can be continuously varying. Mathematically, a fuzzy set is a mapping (known as membership function) from the universe of discourse to the closed interval [0,1]. The membership function is usually designed by taking into consideration the requirement and constraints of the problem. Fuzzy logic implements human experiences and preferences via membership functions and fuzzy rules. Due to the use of fuzzy variables, the system can be made understandable to a non-expert operator. In this way, fuzzy logic can be used as a general methodology to incorporate knowledge, heuristics or theory into controllers and decision makers.

The advantages of fuzzy theory are (i) More accurately represents the operational constraints of power systems; (ii) Fuzzified constraints are softer than traditional constraints [118, 119]. A detailed introduction to fuzzy logic and their applications in power systems has been presented in [120-122]. Momoh et al. [123] have presented the overview and literature survey of fuzzy set theory application in power systems. A recent survey presented in [124] shows that fuzzy set theory has been applied mainly in voltage and reactive power control, load forecasting, fault diagnosis, power system protection/relaying, stability, and power system control, etc.

3.4 Evolutionary Computation

EC is based on the Darwin's principle of 'survival of the fittest strategy'. An evolutionary algorithm begins by initializing a population of candidate solutions to a problem [132]. New solutions are then created by randomly varying those of the initial population. All solutions are measured with respect to how well they address the task. Finally, a selection criterion is applied to weed out those solutions, which are below par. The process is iterated using the selected set of solutions until a specific criterion is met. The advantages of EC are adaptability to change and ability to generate good enough solutions but it needs to be understood in relation to computing requirements and convergence properties. EC can be subdivided into GA, evolution strategies, evolutionary programming (EP), genetic programming, classified systems and simulated annealing (SA).

The first work in the field of Evolutionary Computation (EC) was reported by Fraser in 1957 [125] to study the aspects of genetic system using a computer. After some time a number of evolutionary inspired optimization techniques were developed, i.e. by Friedman in 1959 [126], Blendsoe in 1961 [127] and Bremermann in 1962 [128]. EC was presented by Fogel et al. in 1966 [129]. The rejection of EC work by AI community was responsible for widespread skepticism faced by more schema-friendly GA of late 1960s and mid 1970s. GA was later popularized by Holland in 1975 [130], and Goldberg in 1989 [131].

Over 95% of all the papers published in power systems are based on GA [52]. Other popular technique for power system applications is SA. GA and SA have been receiving increasing amounts of attention due to their versatile optimization capabilities for both continuous and discrete optimization problems. Both are motivated by so-called nature's wisdom: GA are loosely based on the concept of natural selection and evolution; while SA originated in the annealing process found in the thermodynamics and metallurgies. A recent extensive literature survey on EC applications in power systems presented in [133].

3.4.1 Genetic Algorithm

GA is a global search technique based on mechanics of natural selection and genetics. It is a general-purpose optimization algorithm that is distinguished from conventional optimization techniques by the use of concepts of population genetics to guide the optimization search. Instead of point-to-point search, GA searches from population to population. The advantages of GA over traditional techniques are:

i) It needs only rough information of the objective function and places no restriction such as differentiability and convexity on the objective function.

ii) The method works with a set of solutions from one generation to the next, and not a single solution, thus making it less likely to converge on local minima.

iii) The solutions developed are randomly based on the probability rate of the genetic operators such as mutation and crossover; the initial solutions thus would not dictate the search direction of GA.

Major disadvantage of GA method is that it requires tremendously high time. Alander [134] has presented a bibliography of genetic algorithm in power systems. Following are the major applications of GA in power systems:

- Planning (transmission expansion planning [135-140], capacitor placement [141-142])
- Operation (voltage/reactive power control [143-145], unit commitment/economic dispatch [146-154], hydrothermal scheduling [155-157]).

3.4.2 Simulated Annealing

SA technique based on thermodynamics were originally inspired by the formation of crystals in solids during cooling. The advantages of SA are its general applicability to deal with arbitrary systems and cost functions, its ability to refine optimal solution, and its simplicity of implementation even for complex problems. The major drawback of SA is repeated annealing. This method cannot tell whether it has found optimal solution. Some other method (e.g. branch and bound) is required to do this. SA has been used in various power system applications e.g. transmission expansion planning [158, 159], unit commitment [160-162], maintenance scheduling [163], etc.

3.5 Ant Colony Search

Dorigo introduced the ACS system first time in 1992 [164]. ACS techniques take inspiration from the behavior of real ant colonies and are used to solve function or combinational problems. ACS algorithms to some extent mimic the behavior of real ants. The main characteristics of ACS are positive feedback for recovery of good solutions, distributed computation, which avoids premature convergence, and the use of a constructive greedy heuristic to find acceptable solutions in the early stages of the search process. Poor computational of the ACS is the main drawback of this technique. ACS technique has been mainly used in finding the shortest route for transmission network [165, 166].

3.6 Tabu Search

TS is an iterative improvement procedure that starts from some initial solution and attempts to determine a better solution in the manner of a 'greatest descent neighborhood' search algorithm. Basic components of TS are the moves, tabu list and aspiration level. TS is a metahuristic search to solve global optimization problem, based on multi-level memory management and response exploration [167-170]. TS has been used in various power system applications, e.g. transmission planning [171], optimal capacitor placement [172-174], unit commitment [175], hydrothermal scheduling [176], fault diagnosis/alarm processing [177, 178], reactive power planning [179], etc.

4 Hybrid AI Techniques

The real life power system problems may neither fit the assumptions of a single AI technique nor be effectively solved by the strengths and capabilities of single technique. One approach to deal with these complex real world problems is to integrate the two or more techniques in order to combine their strengths and overcome each other's weaknesses to generate hybrid solutions [52]. With the benefits offered by hybrid AI techniques, their applications to power systems have been increasing rapidly. Table 1 lists the different hybrid AI techniques, which have been applied to various power systems problems.

Table 1: Applications of hybrid AI techniques in power systems problems

Hybrid AI techniques	Application area/power system problems
Fuzzy neural network systems	Generation and distribution [180], relaying [181], fault diagnosis [182], load forecasting [183, 184], reactive power control [185, 186], generator maintenance scheduling [187]
Fuzzy genetic systems	Stability [188], Power systems control [189, 190], economic dispatch [191]
Fuzzy expert systems	Power system planning [192]
Fuzzy/ neural/expert/genetic systems	Load forecasting [193, 194], generation expansion planning [195], power system stabilizer [196]
Simulated annealing with fuzzy/genetic/expert systems	Reactive power planning [197], generator maintenance scheduling [198-200]

5 Conclusions

This article has shed some light on the important mathematical optimization and AI techniques used in power system applications. Various hybrid AI techniques used in power systems have also been discussed. In the light of the overview presented in this article, the following are the significant points of conclusions.

Despite remarkable advances in mathematical optimization techniques, conventional mathematical methods have yet to achieve fast and reliable real time applications in power system applications. Considerable efforts are required to avoid mathematical traps such as ill-conditioning and convergence difficulties.

AI relies heavily on good problem description and extensive domain knowledge. ES, which is a knowledge-based system, suffers from a knowledge bottleneck by having an inability to learn or to adapt to new situations. Knowledge-based system can enhance the capabilities of a power system, whereas ANN can acquire knowledge through adaptive training and generalization. ANN, fuzzy, and ES suffer from the same requirement of expert user in their design and implementation. They also suffer from a lack of the formal model theory and mathematical rigors and so are vulnerable to the experts' depth of knowledge in problem definition. Fuzzy theory with its of realistic description of power system problems and ANN with its promise of adaptive training and generalization deserves scope for further study. GA, by contrast, access deep knowledge of systems problem by well-established models. GA has much more potential in power systems analysis and are also latest entry into the

AI fields and are getting most of the current attention. GA needs to be understood in relation to the computation requirements and convergence properties. The application of hybrid systems in power system problems is a novel development, which represents a definite future trend in power systems research.

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