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# **Applications of Simulated Annealing-Based Approaches to Electric Power Systems**

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Additional information is available at the end of the chapter

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## **1. Introduction**

In the last decade, many heuristic methods have evolved for solving optimization problems that were previously difficult or impossible to solve. These methods include simulated annealing (SA), tabu search (TS), genetic algorithm (GA), differential evolution (DE), evolutionary programming (EP), evolutionary strategy (ES), ant colony optimization (ACO), and particle swarm optimization (PSO). This chapter reviews papers in international journals that present the SA-based methods for electric power system applications.

The numerical simulation of physical phenomena has become a major issue in the design phase or optimization of many systems. The complexity of the phenomena demands that multi-scale and multi-physical aspects are considered. In recent years, many researchers are concerned with the development, study, and implementation of efficient numerical methods that can be used in applications in engineering, natural and other sciences. They also focus on numerical methods for solving highly complex and CPU-time problems using high-performance computing. For the advancement of computing schemes that improve the efficiency and even optimize calculation processes, researchers must be able to generate novel systematic methods for solving multi-physical problems. The applications of SA-based methods for electric power systems are surveyed.

This chapter reviews various SA-based methods (including SA and other meta-heuristics methods) for the planning, operation, and optimization of power systems, including relevant recent and historical developments. Relevant publications in international journals that cover a broad range of applications of SA methods to solving power system problems are reviewed. As is well known among power engineers, many kinds of combinatorial optimization problems arise in the planning and operation of power systems. The generation and transmission expansion planning, generator maintenance scheduling and unit commitment, reactive power planning, load forecasting and economic dispatch, and distribution systems planning and operation are typical problems.

Since finding the global optimal solution to a problem is difficult because of the vast numbers of combinations of tentative solutions, many approximation algorithms have been developed to find acceptable near-optimal solutions over several decades. In the 1960's to 1970's, many mathematical programming methods were proposed and discussed. In the early 1980's, the expert system was introduced to solve such problems. However, it was not very effective in the most complex problems. In the early 1990's, the artificial neural network (ANN), or the simulation of the brains as a living entity, was revived in the field of artificial intelligence by the calculation speeds of contemporary computers. The ANN can solve combinatorial optimization problems and load forecasting problems extremely rapidly although the size of such problems that could be solved is limited. At that time, other methods for solving combinatorial optimization problems attracted the attention of many researchers. These methods skillfully simulate physical phenomena, natural evolution, and mathematical heuristics, and yield good results when applied to the combinatorial optimization problems. These methods are referred to as “modern heuristic approaches” or “meta-heuristic approaches”.

Many applications of modern heuristic approaches to power systems have been proposed in the past 20 years, especially in generation and transmission expansion planning, generator maintenance scheduling and unit commitment, reactive power planning, load forecasting and economic dispatch, distribution systems planning and operation, and other applications. In this chapter, articles that have been published on the use of SA, TS, GA, DE, EP, ES, and combinations thereof in relation to power systems are systematically reviewed. These articles were published in international journals and cover a broad range of SA-based methods. A total of 81 journal papers are listed in the references.

This chapter provides a broad and relatively technical treatment of important topics at a level suitable for advanced students and for researchers with a background in electric power systems or in engineering optimization applications. It will review key areas of electric power system planning, operation, and optimization in a citation-rich format that is similar to that used by leading review journals.

The rest of this chapter is organized as follows.

- Formulation of Power System Optimization Problems
- Generation and Transmission Expansion Planning
- Generator Maintenance Scheduling and Unit Commitment
- Reactive Power Planning
- Load Forecasting and Economic Dispatch
- Distribution Systems Planning and Operation
- Other Applications
- Conclusion

## 2. Formulation of power system optimization problems

Many optimization problems in power system planning, control, and operation can be formulated mathematically as follows:

$$\text{Minimize } f(x) \quad (1)$$

$$\text{subject to } g_i(x) = 0, i = 1, 2, \dots, I$$

$$h_j(x) \geq 0, j = 1, 2, \dots, J$$

where  $x^T = [x_1, x_2, \dots, x_N]$  and the elements of  $x$  are the decision variables that are to be determined. The constrained optimization problem that is described by (1) can be transformed to an unconstrained optimization problem using the penalty method. With the equality constraints represented as inequality constraints, the unconstrained optimization problem can be formulated as:

$$\text{Minimize } f(x) + p \sum \Theta[h_i(x)] \quad (2)$$

where  $p$  is the penalty coefficient and  $\Theta$  is the penalty function. When  $f(x)$  is multi-modal, SA can be used to find the global optimal values of the decision variables  $x$  that are described in (2). Let  $x_d$  be a dependent parameter in a constrained problem that is randomly selected at any stage in the optimization process. The constrained problem can thus be formulated as

$$\text{Minimize } f(x', x_d) \quad (3)$$

$$\text{subject to } h_j(x) \geq 0, j = 1, 2, \dots, J$$

where  $x'$  is  $x$  excluding  $x_d$ . In minimizing the objective function in (3), the values of the non-dependent parameters in  $x'$  are firstly determined in each iteration of the optimization process. When the values of the parameters in  $x'$  are known,  $x_d$  can be determined by applying the relationship between the dependent and non-dependent parameters:

$$x_d = g'(x') \quad (4)$$

This chapter reviews SA-based optimization methods for solving the constrained optimization problem that is formulated as (3) and (4).

### 3. Generation and transmission expansion planning

Generation expansion planning (GEP) problems are important in planning activities to determine what generating units should be constructed and when such units should come on line over a long-term planning horizon. The major objectives of GEP are to minimize the total investment and operating costs of the generating units, while meeting capacity constraints, energy constraints, operating constraints, and the reliability criteria. The GEP problem is equivalent to finding a set of optimal decision vectors over a planning horizon that minimize the investment and operating costs under various constraints. Therefore, GEP is a highly constrained, nonlinear, discrete optimization problem.

GEP for a power system is challenging because the large-scale, long-term, nonlinear and discrete nature of generation units. Many emerging techniques (including expert systems,

fuzzy logic, neural networks, analytic hierarchy process, network flow, decomposition methods, SA and GA) have been used in GEP. These emerging optimization techniques and their potential use in challenging GEP in the future competitive environment of the power industry have been reviewed, and some useful information and resources for future GEP were provided (Zhu & Chow, 1997).

Meta-heuristic techniques, such as GA, DE, EP, ES, ACO, PSO, TS, SA, and hybrid approaches have been used in GEP and compared (Kannan et al., 2005). The original GEP problem has been modified using the virtual mapping procedure and the penalty factor method to improve the efficiency of these meta-heuristic techniques. Further, intelligent initial population generation has been introduced to reduce computational time. The GEP problem considered synthetic test systems for 6-year, 14-year, and 24-year planning horizons and five types of candidate units. The results obtained using these proposed techniques were compared and validated against conventional dynamic programming, and the effectiveness of each of the proposed methods was verified.

A novel GEP model was proposed (Kannan et al., 2007) for developing countries in a partially deregulated environment, in which both utilities and independent power producers (IPPs) participate in the generation market. In this model, the utility purchases electric power from the IPPs and sells it to the consumer. The utility maximizes its profit and ensures profits for all of the participating IPPs. Additionally, the utility checks under/over investment and considers system security, national security (fuel-mix ratio), social welfare and reliability simultaneously. The budget constraints of the utility are considered in the expansion plan. Meta-heuristic methods, such as GA, DE, EP, ES, PSO, TS, SA, and the hybrid approaches have been used to solve the restructured GEP problem, and the performances of each was evaluated and validated against the dynamic programming method for a synthetic test system with five types of candidate plant for the utility and three types of candidate plant for IPPs, with a 6-year planning horizon. The effectiveness of the proposed modifications and techniques has been demonstrated.

Transmission expansion planning (TEP) involves determining when and where new circuits must be installed, as well as the number that must be installed, to ensure that the power system will meet customer's demand with sufficient quality over a long planning horizon, while minimizing investment, operating, and interruption costs. TEP in a deregulated environment is highly complex. The possibility of generation planning and demand-side management as substitutes for transmission expansion must be considered when candidates for transmission expansions are generated. The deregulation of a power system produces new objectives in expansion planning such as the minimization of congestion cost. The optimized TEP considers such primary objectives as network investment cost, congestion cost, reliability, and environmental impact, subject to the relevant technical constraints.

The SA method was proposed for solving long-term TEP problems which are hard, large-scale combinatorial problems (Romero et al., 1996). The proposed approach has been compared with a more conventional optimization technique that is based on mathematical

decomposition with an implicit zero-one enumeration procedure. Tests have been performed on three systems. Two smaller systems for which optimal solutions are known have been used to tune the main parameters of the SA process. The SA method has then been applied to a larger example system for which no optimal solutions are known. Therefore, an entire family of interesting solutions have been obtained a cost of approximately 7% less than those of the best solutions for the example system.

A parallel SA (PSA) algorithm for solving the long-term TEP problem was proposed (Gallego et al., 1997). A strategy that does not affect the basic convergence properties of the sequential SA have been implemented and tested. They studied the conditions under which the PSA is most efficient and tested the PSA on three example networks: a small 6-bus network and two complex real-life networks. Excellent results were reported in the test. In addition to reducing computing times, the proposed PSA algorithm greatly improved solution quality when applied to the largest of the test networks.

Three families of non-convex optimization approaches for solving the TEP: SA, GA, and TS, were compared and an integrated view of these methodologies was proposed (Gallego et al., 1998a). Test results obtained using large-scale, real-life networks verified that the presented hybrid approach greatly outperformed those obtained using any individual approach.

An extended GA was proposed to solve the optimal TEP (Gallego et al., 1998b). They improved the GA in two main ways: the initial population was obtained by conventional optimization based methods, and the mutation approach was used in the SA. Test results revealed excellent performance for a difficult large-scale real-life problem, and demonstrated a substantial reduction in investment cost relative to earlier solutions that were obtained by conventional optimization methods and SA.

A parallel TS was proposed to solve the TEP (Gallego et al., 2000). The presented method is a third-generation TS procedure with many advanced features. It exhibits the features of many other approaches, such as heuristic search, SA and GA. In all studied test cases, new generation and load sites can be connected to an existing main network, and these connections may require more than one line and the addition of a transformer, making the problem harder to solve in the sense that more combinations must be considered.

#### **4. Generator maintenance scheduling and unit commitment**

The proper generator maintenance scheduling (GMS) in a power system is very important to its economic and reliable operation. To prevent premature aging and the failure of generators in a power system, which would cause unplanned and costly power outages, preventive maintenance must be performed at regular intervals. The generator maintenance in a power system involves scheduling and executing actual maintenance work. The GMS must be solved in the planning of the secure and reliable operation of a power system, primarily because other short- and long-term planning activities, including unit commitment, generation dispatch, import/export of power and GEP are directly influenced by related decisions. Modern power systems have become larger as the demand for



electricity has considerably increased, increasing the number of generators, reducing reserve margins, and making the GMS problem even more complex.

The objective of GMS is to plan preventive maintenance scheduling for generators based on load forecasts. The purpose is to minimize the operating cost, maximize the profit or minimize the power shortage annually. Many constraints must be considered, including the system load, the maintenance window of each generator, maintenance resources (including human resources, machinery, equipment, and others), and the estimated power output. Therefore, GMS is a mixed-integer programming problem, in which a combination of 0s and 1s specifies whether a generator unit is undergoing maintenance, subject to some equality and inequality constraints. Before deregulation of the electric power industry, system reliability and loss of load probability were two major objectives of the GMS problem. After deregulation, however, maximizing profit is the driving interest of an IPP. Hence, the profitability of power plants is the objective function for the GMS problem.

The thermal power plant GMS problem has been formulated as a mixed-integer programming problem and solved efficiently using the SA (Sato & Nara, 1991). The GA, SA and TS methods have been used together to solve the large-scale, long-term GMS problem (Kim et al., 1997). This combined solution algorithm has the advantages of the individual algorithms and supports a reasonable combination of local and global searches. The method considers the maintenance class and many consecutive years scheduling. Several real-scale numerical examples demonstrate the effectiveness of the proposed method.

The application of meta-heuristic approaches, such as GA, SA and their hybrid for GMS in power systems was proposed (Dahal & Chakpitak, 2007). The presented paper mainly focuses on the application of GA/SA and GA/SA/heuristic hybrid approaches. The GA/SA hybrid used the probabilistic acceptance criterion of SA in the GA framework. The GA/SA/heuristic hybrid used heuristic methods with the GA/SA hybrid to seed the initial population. The authors formulated the GMS as an integer programming problem using a reliability-based objective function and typical problem constraints. They discussed the implementation and performance of the meta-heuristic methods and their hybrid in a test case. The obtained results are promising and reveal that the hybrid methods are less sensitive to variations in the parameters of the technique and are effective alternatives to other methods for performing GMS.

The main objective of unit commitment (UC) is how to schedule the on/off status of the generators to minimize the production cost of electricity. A typical UC problem is combinatorial and involves a large set of physical, operating and contractual constraints, making the problem difficult to solve. The SA method was originally proposed to solve the UC problem (Zhuang & Galiana, 1990). It is highly flexible in handling UC constraints, and numerical results on test systems of up to 100 units were reported.

A short-term hydrothermal UC based on the SA method was proposed (Wong & Wong, 1994a). In the algorithm, the power balance constraint, total water discharge constraint, reservoir volume limits and constraints on the operational limits of the hydrothermal

generator and the thermal generator are fully considered. The relative operational capacities of the hydroplant and the thermal plant are also considered. A coarse-grained parallel SA algorithm was presented for short-term hydrothermal UC (Wong & Wong, 1994b). The design of the algorithm considers load balancing, processor synchronization reduction, communication overhead reduction and memory contention elimination. The test results were compared with those obtained using a sequential algorithm and the results revealed that the proposed method provides an almost linear reduction in computation time. Two parallel SA concepts, speculative computation and serial subset, were proposed to the UC (Annakkage et al., 1995). A combined scheme in which speculative computation is used in the initial phase and the serial subset is used in the final phase. The test results revealed that the proposed parallel schemes greatly improved the computing performance of SA.

A hybrid GA/SA method was developed to the UC (Wong & Wong, 1995). The proposed method can typically provide feasible schedules in the solution process. The hybrid method can handle the nonconvexity of the UC. The authors subsequently provided a new formulation for short-term UC with a take-or-pay fuel contract (Wong & Wong, 1996) and a used a fuzzy set approach to help to find schedules that yield, as closely as possible, the take-or-pay fuel consumption. They extended the formulation to cover the economic dispatch problem when fuel consumption exceeds the agreed amount in the take-or-pay contract, and the extended formulation was combined with the GA and SA algorithms for determining the UC.

A new formulation for short-term multiple-fuel-constrained UC was presented (Wong & Wong, 1997). In the formulation, the power balance constraint, operating limits of the generators, fuel availability factors of the generators, efficiency factors of the fuels and the supply limits of the fuels are fully considered. They combined the new formulation with GA, SA and hybrid GA/SA methods to establish new algorithms. They demonstrated the new algorithms by using them to determine the most economical generation schedule for 25 generators in a local power system and the schedule of the system for four fuels.

An enhanced SA was adopted to solve the UC by applying mechanisms to ensure that the generated candidate solutions are feasible and satisfy all of the constraints (Wong, 1998). The performance of the enhanced SA was demonstrated and compared with that of conventional methods. The UC was divided into two subproblems: a combinatorial optimization problem and a nonlinear programming problem (Mantawy et al., 1998). They solved the former using the SA and the latter using a quadratic programming routine. Numerical results revealed an improvement in the cost associated with the solutions.

A new algorithm based on integrating GA, TS and SA methods to solve the UC was presented (Mantawy et al., 1999). The core of the proposed algorithm is based on GA. TS is used to generate new population members in the reproduction phase of the GA. The SA is used to accelerate the convergence of the GA by applying the SA test for all the population members. Numerical results showed the superiority of the solutions thus obtained over those obtained using GA, TS and SA methods, and two exact algorithms.



An extended mean field annealing neural network (NN) approach was presented to short-term UC (Liang et al., 2000). The annealing NN provides the high solution quality of the SA with the rapid convergence of the NN. Test results confirmed that their approach was very effective in finding the optimum solution to the UC. An approach combining the feedforward NN and the SA method was presented to solve UC (Nayak & Sharma, 2000). The NN is used to determine the discrete variables that correspond to the state of each unit at various times. The SA is used to generate the continuous variables that correspond to the power output of each unit and the production cost. A set of load profiles as inputs and the corresponding UC schedules as outputs that satisfy the minimum up–down times, spinning reserve and crew constraints were used to train the NN. The experimental results demonstrate that the proposed approach can solve the UC in a reduced computational time.

A combined SA and TS approach was used to solve the UC (Purushothama et al., 2003). In their stochastic extended neighborhood algorithm, SA is the main stochastic algorithm, and TS is used to perform an extended neighborhood search and thus locally improve the solution obtained by SA. The neighborhood search uses local domain-knowledge, resulting in rapid convergence of the SA. The results obtained for many example systems illustrate the potential of the hybrid approach. The SA with local search hybrid algorithm was proposed to solve the UC (Purushothama & Jenkins, 2003). The hybrid algorithm is robust and provides faster convergence than earlier algorithms. The results verified its potential for solving the UC.

A scheduling method for representing the thermal stress of turbine shafts as ramp rate constraints in the UC (Li & Shahidehpour, 2003). In the UC, thermal stress over the elastic limit is used to calculate the ramping cost. Determination of the contribution of the thermal stress to the generation cost requires that a set of solution that includes thermal stress at the end of each time step be calculated; this requirement establishes a complex problem that cannot be solved using an ordinary optimization method. An improved SA was used to determine the optimal trajectory of each generating unit, and they elucidated the economics of frequently ramping up/down of low-cost generating units in relation to the cost of replacing their turbine rotors with a shorter life span. The results demonstrated the effectiveness of the proposed method.

A new SA combined with a dynamic economic dispatch method was designed to solve the short-term UC (Simopoulos et al., 2006a). SA was used to schedule the generating units, while a dynamic economic dispatch method, incorporating the ramp rate constraints, was used to solve the UC. The ramp rates are considered by performing either a backward or a forward sequence of conventional economic dispatches with modified limits on the generating units. The proposed algorithm is relatively fast and provides feasible near-optimal solutions. A new method for the incorporation of the unit unavailability and the uncertainty of the load forecast in the solution of the short-term UC solved by the SA was presented in (Simopoulos et al., 2006b). The required spinning reserve capacity was conducted by imposing reliability constraints, based on the expected unserved energy and the loss of load probability indices. Numerical simulations demonstrated the efficiency of the proposed method.

An absolutely stochastic SA method was proposed to UC (Saber et al., 2007) and fuzzy UC using the absolutely stochastic SA was presented (Saber et al., 2006). In both papers, all of the solutions that involved high and low costs, are associated with acceptance probabilities and an early jump from one local minimum to another, enabling more local minima to be found and compared in a particular time or number of iterations. The number of bits to be flipped is determined by the appropriate control of parameter. Excess units with a system-dependent probability distribution handle constraints efficiently. The sensitivity of the distribution parameters is satisfactory. To reduce the number of required economic load dispatch calculations, a sign bit vector was introduced. Numerical results indicate an improvement in the cost and time required to find a solution relative to those using the proposed algorithms. Besides, An EP based SA was proposed to the short-term UC (Christober Asir Rajan & Mohan, 2007) and the UC using SA embedded EP approach was presented to hydro-thermal UC (Christober Asir Rajan, 2011). Numerical results are used to compare the costs of the solutions and computation times obtained when the proposed approaches and conventional methods are used to determine the optimal UC.

## 5. Reactive power planning

Reactive power planning, or Var planning seeks to optimize the allocation of reactive power sources in a power system, based on location and size. The objectives of Var planning are to minimize the cost of new reactive power supplies. The many variants of this objective involve the cost of real power losses or the cost of fuel. Furthermore, such technical indices as deviation from a given voltage schedule or the security margin may be used as objectives for optimization. The installation of reactive power sources also releases system capacity and improves the voltage level.

The Var planning greatly influences the secure and economic operation of electric power systems. SA was used to contingency-constrained optimal Var planning in large-scale power systems (Hsiao et al., 1993). Their problem formulation considered practical aspects of Var sources, load constraints, and the operating constraints at different load levels. The proposed SA determines the locations of installed Var sources, the types and sizes of Var sources to be installed, and the settings of Var sources at different loading conditions. Test results confirm that the proposed approach is suitable for large-scale power systems applications.

SA based computer package for multi-objective, Var planning in large-scale power systems was proposed (Hsiao et al., 1994). Optimal Var planning is reformulated as a constrained, multi-objective, nondifferentiable optimization problem. The new formulation considers four objective functions that are related to investment in the system, its operating efficiency, its security and the system service quality. Their new formulation also considered load, operating constraints and contingency constraints. The problem formulation allows both the objective functions and the equality and inequality constraints to be nondifferentiable, making the problem formulation more realistic. The package uses a two-stage solution algorithm that is based on an extended SA and the  $\epsilon$ -constraint method. The first-stage of

the solution algorithm uses an extended SA to find a global, noninferior solution. The primary objective function and the trade-off tolerances are then used to transform the constrained multi-objective optimization problem into a single-objective optimization problem with more constraints by applying the  $\epsilon$ -constraint method. The second-stage uses the SA to obtain the global optimal solution.

A constrained, multi-objective and non-differentiable optimisation for Var planning problem was proposed (Chen & Liu, 1994). The objectives were minimization of active power loss cost, minimization of the cost of investment in Var sources, robustness of the system security margin and minimization of the voltage deviation of the system. The operating constraints, load constraints and expansion constraints of the system were considered. The goal-attainment method, based on SA, for solving general multi-objective optimization problems by assuming that the decision-maker has goals for each of the objective functions was used to solve the problem. The solution methodology involved finding a desirable, global noninferior solution to the problem, even when the objective space is nonconvex.

An interactive satisfying method, a two-level structure, was proposed to solve the multi-objective power system Var planning (Chen & Liu, 1995). The analysis level involved calculation of a possible or set of possible solutions to the multi-objective problem, and the decision level generate noninferior solutions that meet the preferences of the decision makers. In the analysis level, the  $\epsilon$ -constraint method that is based on SA is used to find a global noninferior solution. The proposed method guarantees the solution to be a desirable, global noninferior solution for a general multiobjective Var planning, according to the preferences of the decision makers.

Var planning was presented as a multi-objective optimization problem in terms of maximum system security and minimum operation cost (Jwo et al., 1995). An effective algorithm based on hybrid expert system and SA was proposed to obtain the global optimal solution considering both quality and speed. A weak bus-oriented criterion for identifying candidate buses for Var planning was presented in (Chen, 1996). A voltage collapse proximity indicator was first used to identify weak buses. Then appropriate Var planning for those weak buses increased the system security margin to prevent voltage collapse. The goal attainment method, based on the SA, was applied to solving the multi-objective problem by assuming that the decision-maker has goals for each of the objective functions. The presented method both provides a good final solution and reduces the solution space.

An innovative fast global optimization technique, hybrid partial gradient descent/SA (HPGDSA), for optimal Var planning was presented (Liu et al., 1997). The basic concept of the HPGDSA is that partial gradient descent and SA alternate with each other to reduce the CPU time below that of the conventional SA while the ability to find the global optimal of the SA is retained. A hybrid SA/GA approach was proposed to solve the Var planning (Jwo et al., 1999). That approach found the near-global optimal solution in a finite time. Moreover, the solution time was much less than that of the conventional SA. The proposed method yielded promising results, relative to those obtained using SA, GA and HPGDSA.

Three GA/SA/TS combined algorithms for Var planning were proposed (Liu et al., 2002). Trying reasonably to combine local and global search, they adopt the acceptance probability of SA to improve the convergence of the simple GA, and to apply TS to find more accurate solutions. Test results confirmed that the proposed method is effective to find better solutions than those of existing methods within reasonable time. A projection-based two-layer SA was used to solve the multi-objective optimization problems (Chen & Ke, 2004). The SA yielded a desirable, globally efficient solution to such problems, even when the solution space is nonconvex and the objective functions are nondifferentiable.

A new approach was presented to model and solve Var planning under the static voltage stability constraint (Wang et al., 2011). First, the fuzzy clustering method was used to select new candidate Var source locations. Then, modified Gray code was applied to represent a series of non-uniform Var capacity intervals at different candidate buses. Under the new ordering of the Var capacity intervals, a simplified piecewise linear function that relates the total transfer capability with new Var capacity was derived and applied as a static voltage stability constraint in Var planning. Finally, the optimization problem was solved by an enhanced SA using modified Gray code. The proposed SA adopted a modified definition of neighborhood selection and a novel approach to generating new random solutions. Test results demonstrated that the proposed method is a simple and effective approach for voltage stability-constrained Var planning with contingency considered.

A multi-objective SA was proposed to provide decision support in reactive power compensation (Antunes et al., 2011). Their method computed a set of well-distributed and diversified solutions underlying distinct trade-offs, even for a challenging network. The characteristics of the non-dominated front are relevant information that helps planning engineers select satisfactory compromise solutions that improve the operating conditions of the network.

## 6. Load forecasting and economic dispatch

Accurate forecasting of electricity load has been one of the most important issues in the planning, operation, and control of electric power systems. Recently, following power system privatization and deregulation, the accurate forecasting of electricity load has received increasing attention. An optimal fuzzy inference method for short-term load forecasting was presented (Mori & Kobayashi, 1996). Their proposed method constructs an optimal structure of the simplified fuzzy inference that minimizes model errors and the number of membership functions to capture the nonlinear behavior of short-term loads in the power system. The model was identified by SA and the steepest descent method.

Support vector machines (SVMs) have been successfully used to solve nonlinear regression and time series problems. The SVM with SA approach was proposed to forecast electricity load (Pai & Hong, 2005). They used SA to select the parameters of the SVM model. Empirical results indicate that the proposed model outperforms the autoregressive integrated moving average model and the general regression NN model.

A fuzzy NN combined with a chaos-search GA (CGA) and SA, applied to short-term power-system load forecasting was presented (Liao & Tsao, 2006). They used a fuzzy hyperrectangular composite NN for forecasting the initial load. An integrated CGA and SA method is then used to find the optimal NN parameters. The CGA is effective in global search but ineffective in local search, while the SA is effective in local optimal search. The paper combined the two methods to exploit the advantages of both and to eliminate the known downside of the traditional NN. Their test results demonstrated superior a forecasting accuracy than other commonly used forecasting methods.

Economic dispatch (ED) is an important daily optimization task in the operation of a power system. Most calculus-based industrial algorithms for solving the ED problem, such as the Lagrangian multiplier method, require the incremental cost curves to be monotonically increasing or piece-wise linear. When the generating units have non-monotonically increasing or non-linear incremental cost curves, the conventional procedure either ignores or flattens out the portions of the incremental cost curves that are not continuous or monotonically increasing. Inaccurate dispatch results are thus obtained. In these cases, accurate dispatch results can only be obtained using more general approaches without restrictions on the shape of fuel cost functions.

SA-based ED was presented to obtain a global or near-global optimum dispatch solution (Wong & Fung, 1993). In the algorithm, the load balance constraint and the operating limit constraints of the generators are fully accounted for. Transmission losses were firstly discounted and subsequently incorporated in the algorithm using the B-matrix loss formula. Test results are obtained by the proposed approach more economically than using the dynamic programming method with a zoom feature.

A combination of the incremental GA and SA was presented to obtain the global or near-global optimum solution for the ED and developed to minimize the memory requirement (Wong & Wong 1994c). They proposed a method for solving the problem of discretization in the encoding of generator loadings. The algorithms include a method for ensuring that the dispatch solutions that are generated by the solution process are feasible and valid. The effects of valve-point loading and ramping characteristics of the generators are considered. The developed algorithms were demonstrated by applying them to a power system, and they were shown to be general and are computationally faster than the earlier SA-based method.

A new multi-objective stochastic search technique for ED was proposed (Das & Patvardhan, 1998). Their heuristic combined a real coded GA and SA. The proposed approach provides the values of various parameters that optimize different objectives, and the best compromise between them in a single run. The test results were compared with those obtained using other methods and the proposed heuristic was found to converge rapidly to better solutions. Additionally, perturbation analysis demonstrated that the solutions that were obtained by the proposed algorithm were truly pareto-optimal, meaning that no objective could be further improved without degrading the others. SA approach was used to solve optimal power flow (OPF) problem that involved both the load flow and the ED (Roa-Sepulveda & Pavez-Lazo, 2003). Test results confirmed the effectiveness of the solution technique.



A parallel TS for determining ramp rate constrained ED for generating units with non-monotonically and monotonically increasing incremental cost functions was proposed (Ongsakul et al., 2004). To parallelize TS efficiently, neighborhood decomposition was performed to balance the computing load, and competitive selection was used to update the best solution reached among subneighborhoods. The proposed approach optimizes the compromises between the experimental speedup and the solution quality for the best performance with different subneighborhood sizes. The proposed approach is potentially viable for online ED because of it provides substantial generator fuel cost savings and the high upper bound on speedup.

A novel multiobjective optimization method for economic emission load dispatch of fixed head hydro plants and thermal plants with nonsmooth fuel cost and emission level functions was presented (Basu, 2005). In this problem, economic and emission objectives were competing. Based on the assumption that the decision-maker has goals for each of the objective functions, the multiobjective problem is converted into a single-objective optimization problem by the goal-attainment method, which is then handled by the SA. The solution method yields a global or near-global noninferior solution that will be close to meeting the decision-maker's requirements. Test results confirmed the applicability and validity of the proposed method.

Dynamic ED determines the optimal operation of units with predicted load demands over a certain period with the objective of minimizing total production cost while the system is operating within its ramp rate limits. SA was proposed to obtain the global or near global optimum dynamic ED (Panigrahi et al., 2006). They incorporated load balance constraints, operating limits, valve point loading, ramp constraints, and network losses into the dynamic ED. Numerical results revealed the performance and applicability of the proposed method.

Since generators have quadratic fuel cost functions, classical techniques ignore or flatten out the portions of the incremental fuel cost curves and so may have difficulty in determining the global optimum solution for non-differentiable fuel cost functions. EP based SA approach was presented to ED in a large-scale power system (Christober Asir Rajan, 2010). The proposed techniques can offer global or near-global optimum dispatch solutions. Test results demonstrate that the proposed integrated approach can provide accurate solutions within reasonable times for any fuel cost functions.

## 7. Distribution systems planning and operation

Network reconfiguration problem was formulated as a constrained, multi-objective and non-differential optimization problem for both loss reduction and load balancing that considers load constraints and operating constraints (Chiang & Jean-Jumeau, 1990a, 1990b). The number of switch-on/switch-off operations that are involved in network reconfiguration was included as a constraint. Then, a two-stage solution method that is based on a modified SA and the  $\varepsilon$ -constraint method for general multi-objective optimization were presented. The proposed approach allows designers to obtain a desirable, global noninferior solution in a reasonable computation time. Given a target number of switch-on/switch-off operations

involved in the network configuration, the solution algorithm can identify the most effective operations. To reduce the required computing time, the researchers studied the idea of approximate calculations and incorporated them into the solution algorithm, in which two efficient load-flow methods were used: one for high temperatures and the other for low temperatures.

A comprehensive approach to strategic planning of Var compensators in a nonsinusoidal distribution system was presented (Chu et al., 1994). The problem was formulated as a nondifferentiable, combinatorial optimization problem to minimize the system costs while meeting various operating constraints and harmonic limits. SA was used to determine the optimal locations, types and sizes, and settings of these Var compensators. Their proposed approach could handle discrete rather than continuous Var compensator values and determine whether the Var compensators were fixed or switchable for different load levels.

A modified SA was presented for network reconfiguration for loss reduction in distribution systems and the switching limitation was considered (Chang & Kuo, 1994). They proposed a set of simplified line flow equations for approximate loss calculation. They then used an efficient perturbation scheme and an initialization procedure to determine a better starting temperature for the SA. The computing time of the SA was greatly reduced without loss of quality of the solution. Additionally, the proposed SA could rapidly provide a global optimal or near-optimal solution to the problem, and numerical results confirmed the effectiveness of the proposed method.

Optimal capacitor placement, replacement and control in large-scale unbalanced, radial or loop distribution networks were formulated in a combinatorial optimization problem with a non-differentiable objective function (Chiang et al., 1995a, 1995b). They solved this problem using SA and the greedy search technique to obtain high-quality of solutions at a high computing speed. The challenge is to determine the optimal locations in which to install (or replace, or remove) capacitors, the types and sizes of the capacitors to be installed (or replaced) and, for each load level, the control schemes for each capacitor in the nodes of a general three-phase unbalanced distribution system, such that a desired objective function is minimized while the load constraints, network constraints and operating constraints at various load levels are satisfied. The objective function incorporated both the cost of energy loss and costs related to capacitor purchase, capacitor installation, capacitor replacement and capacitor removal. Analysis of the computational complexity of the solution algorithm reveals that the algorithm is also effective for large-scale distribution systems as the computational efforts is reasonable.

A new formulation for power system sectionalizing device placement considering outage, maintenance and investments costs was proposed (Billinton & Jonnavithula, 1996). They formulated the problem as a combinatorial constrained optimization problem with a nonlinear, nondifferentiable objective function. The SA was used to determine the number of sectionalizing switches and the locations of the switches. Test results revealed that the proposed approach yielded a global optimal solution to the sectionalizing device placement problem, considering reliability, investment and maintenance costs.

A single comprehensive algorithm for distribution system switch reconfiguration and capacitor control was proposed (Jiang & Baldick, 1996). They used SA to optimize the switch configuration of the distribution system, and a discrete optimization algorithm to find the optimal capacitor control. They evaluated the benefits of the optimal switch configuration and capacitor control, in terms of both reduced loss and decreased voltage bandwidth. A nonlinear constrained, non-differentiable approach for optimal network routing in distribution system planning was presented (Jonnavithula & Billinton, 1996). The main objective was to minimize the total cost, which is the summation of reliability costs, the cost of feeder resistive loss, investment costs and maintenance costs. They used SA to find a global optimum solution to the problem.

SA-based approach for loss minimization by using an automatic switching operation in large-scale distribution systems was presented (Jeon et al., 2002). SA is particularly well suited for a large combinatorial optimization problem since it can avoid local minima by accepting improvements in cost. However, it commonly requires a meaningful cooling schedule and a special strategy, which makes use of the property of distribution systems in finding the optimal solution. This paper expands the cost function by adding the operating conditions of a distribution system, improving the perturbation mechanism with system topology, and using the polynomial-time cooling schedule, which is based on the statistical calculation in the search. Test results validated and confirmed the effectiveness of the proposed approach.

Hybrid SA and TS approach was applied to minimize real power loss in distribution systems (Jeon et al., 2004). SA is very suitable for large combinatorial optimization problems, but the SA requires excessive computing time. TS attempts to determine a better solution in the manner of a greatest-descent algorithm, but it cannot guarantee convergence. The hybrid SA and TS algorithm was applied to improve the computing time and convergence. Numerical examples validated and established the effectiveness of their hybrid approach.

A method for optimal planning of radial distribution networks was solved by a combination of the steepest descent and the SA (Nahman & Peric, 2008). Their objective was to find the complete network of available routes and the optimization goal was to obtain the routes that provide the minimal total annual cost. The solution with minimum capital cost, obtained using the steepest descent approach, was used as the initial solution in SA to obtain the solution with minimum total cost. The costs associated with capital recovery, energy loss and undelivered energy costs were considered.

## 8. The other applications

SA for optimal tearing of networks was presented to divide a power system network model into a number of sub-networks to optimize the use of parallel computer systems for network analysis (Irving & Sterling, 1990). Test results were compared with those obtained using the iterative improvement method, and the proposed SA yielded significantly better solutions.

The placement of a minimal set of phasor measurement units (PMUs) to make the system measurement model observable was presented (Baldwin et al., 1993). A PMU at a bus measures the voltage and all of the current phasors at that bus, requiring extension of the topological observability theory. The minimal PMU set is found using a dual search algorithm, which uses both a modified bisecting search and SA. The former fixes the number of PMUs while the latter seeks a placement set that yields an observable network for a fixed number of PMUs. Test results verified the effectiveness of the proposed approach.

A parallel SA was presented to decompose power systems into subsystems that were with equal numbers of nodes and control variables (Mori & Takeda, 1994). The decomposition of a power system is a difficult discrete combinatorial problem. The researchers' numerical results revealed that the parallel SA yielded better solutions than the conventional SA.

SA was applied to multi-partition an observable power system state estimation network into two or more observable sub-networks (Habiballah & Irving, 1995). The proposed SA was theoretically based on combinatorial optimization, rather than a heuristic derivation. Numerical results demonstrated the effectiveness of the proposed SA.

A novel method for designing power system damping controllers was presented (Chen et al., 1996). They used SA to optimize the controller parameters in the nonlinear optimization problem, and considered the all of the design criteria of the controllers simultaneously. Their proposed method can also be used to design controllers that are robust under a specified set of operating conditions.

Design of output feedback controllers for thyristor controlled series compensators in a meshed power system was proposed (Chen et al., 1998). They used SA to optimize the output feedback gains for the controllers. Conflicting design objectives, such as improvement in the damping of the critical modes, any deterioration of the damping of the noncritical modes and the saturation of the controller actuators, were simultaneously considered. Numerical results verified that the SA can be applied to design robust controllers that satisfy the required performance criteria under many operating conditions.

Feeder imbalance describes a situation in which the magnitudes of the voltages of a three-phase voltage source are not equal, or the phase differences between them are not 120 electrical degrees, or both. Phase balancing make the voltages balanced at each load point of the feeder. Phase balancing optimization is currently attracting more attention in the power industry, especially following deregulation. Nonlinear effects, such as voltage drops and energy losses, make the problem difficult to solve. SA was used as an effective method to solve a power distribution phase balancing problem with its nonlinear effects (Zhu et al., 1999). Test results verified the effectiveness of the proposed approach.

Robust design of multi-machine power system stabilizers (PSS) using SA was proposed (Abido, 2000a). The SA can obtain optimal parameter settings of an extensively used conventional fixed-structure lead-lag PSS. The parameters of the proposed SA-based PSS were optimized to shift simultaneously the system electromechanical modes under different

loading conditions and system configurations to the left in the  $s$ -plane. The incorporation of SA as a derivative-free optimization approach in PSS design greatly reduces the computational burden. Test results demonstrated the effectiveness of the proposed approach under various disturbances and loading conditions for two multimachine power systems.

SA-based approach to PSS and flexible alternating current transmission systems (FACTS) based stabilizer tuning was presented (Abido, 2000b). The problem of designing PSS and FACTS-based stabilizers was formulated as an optimization problem. An eigenvalue-based objective function to increase system damping was proposed, and the SA was used to search for optimal stabilizer parameters. Different control schemes have been proposed and tested on a weakly connected power system under different disturbances, loading conditions, and parameter variations. Nonlinear simulation results indicate the potential usefulness of the SA in the problem of tuning PSS and FACTS-based stabilizer. The effectiveness and robustness of the proposed control schemes under a wide range of loading conditions and system parameter variations have been demonstrated.

A pole placement technique for PSS and thyristor controlled series capacitor (TCSC) based stabilizer using SA was proposed (Abido, 2000c). The design problem is formulated as an optimization problem where SA was used to search for the optimal setting of the design parameters, and considered a pole placement-based objective function to shift the dominant eigenvalues to the left in the  $s$ -plane. Eigenvalue analysis and nonlinear simulation results confirmed the effectiveness and the robustness of the proposed stabilizers and their ability to provide efficient damping of low frequency oscillations.

SA was applied to evaluate harmonics and frequency for power system quality analysis and frequency relaying (Soliman et al., 2004). The sum of the squares of errors is the objective function to be minimized for evaluating the amplitude and phase angle of each harmonic component as well as the fundamental frequency of the voltage signal. The proposed algorithm applied digitized samples of the voltage signal where the power quality is to be measured and the frequency relaying is to be implemented. The proposed SA had an adaptive cooling schedule and used a variable discretization to accelerate the convergence of the original SA. Numerical results revealed that the proposed approach can identify the harmonic spectrum in the signal.

Calculation of the optimum installation angle for the fixed solar-cell panels based on GA and SA was presented (Chen et al., 2005). The incident angle of sunlight strongly affects the output power of a solar-cell panel, and its efficiency can be improved if the solar-cell panel is properly installed at the optimum angle. Both GA and SA with climatic data are utilized to calculate the optimum installation angle of the solar-cell panel at various locations in Taiwan. Experimental results reveal that the best monthly installation angles are very close to those determined by the computer simulation results.

Identifying placement sites for PMUs in a power system based on incomplete observability was presented (Nuqui & Phadke, 2005). They introduced the novel concept of depth of unobservability and explained its effect on the number of PMU placements. They extended



their model to recognize limitations in the availability of communication facilities around the network and thus formulated the constrained placement problem. The SA was further used to solve the pragmatic phased installation of PMUs. Results demonstrated that the proposed SA provides utilities with systematic approach for incrementally placing PMUs, to help manage the impact of their cost.

SA was applied to optimize size of a PV/wind integrated hybrid energy system with battery storage (Ekren & Ekren, 2010). Their SA used a stochastic gradient search to find the global optimization solution that minimized the total cost of the hybrid energy system. The decision variables included PV size, area swept by the wind turbine rotor, and battery capacity. Test results confirmed that SA yielded better results than those obtained from response surface method.

## 9. Conclusions

This chapter reviewed journal papers that have presented the applications of SA-based approaches to electric power systems, especially in generation and transmission expansion planning, generator maintenance scheduling and unit commitment, reactive power planning, load forecasting and economic dispatch, distribution systems planning and operation, and the other applications. The SA-based approaches have the following advantages. They may find a global optimum; they can produce a number of alternative solutions; no mathematical restrictions on the problem formulation exist, and they are relatively easy to program and numerically robust. The purpose of the review of papers and example applications in this chapter is to illustrate the potential application of the SA-based approaches in the optimization of electric power systems, and the advantages of such methods. Recently, these new heuristic tools have been combined with each other and with knowledge to solve extremely challenging problems. Hybrid approaches typically seem both to combine complementary strengths and to overcome the drawbacks of single methods by embedding in them one or more steps that involve different techniques. Developing solutions using such tools provides two major advantages: development time is much shorter than when more traditional approaches are used, and the solutions are very robust.

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