A SURVEY OF OPTIMAL POWER FLOW METHODS

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ABSTRACT

The objective of an Optimal Power Flow (OPF) algorithm is to find steady state operation point which minimizes generation cost, loss etc. or maximizes social welfare, loadability etc. while maintaining an acceptable system performance in terms of limits on generators' real and reactive powers, line flow limits, output of various compensating devices etc. Traditionally, classical optimization methods were used to effectively solve OPF. But more recently due to incorporation of FACTS devices and deregulation of a power sector, the traditional concepts and practices of power systems are superimposed by an economic market management. So OPF have become complex. In recent years, Artificial Intelligence (AI) methods have been emerged which can solve highly complex OPF problems. The purpose of this paper is to present a comprehensive survey of various optimization methods used to solve OPF problems.

Keywords: FACTS (Flexible A.C. Transmission system) devices, Optimal Power Flow (OPF), Power System Deregulation.

1. INTRODUCTION

A first comprehensive survey regarding optimal power dispatch was given by H.H.Happ [1] and subsequently an IEEE working group [2] presented bibliography survey of major economic-security functions in 1981. Thereafter in 1985, Carpentair [3] presented a survey and classified the OPF algorithms based on their solution methodology. In 1990, Chowdhury [4] did a survey on economic dispatch methods. In 1999, J.A.Momoh *et al.* [5] presented a review of some selected OPF techniques. In this paper, a review of following optimization methods has been presented. (1)Linear Programming (LP) method, (2) Newton-Raphson (NR) method, (3)Quadratic Programming (QP) method, (4)Nonlinear Programming (NLP) method, (5)Interior Point (IP) method and (6) Artificial Intelligence (AI) methods.

2. OPTIMAL POWER FLOW FORMULATION

OPF is formulated mathematically as a general constrained optimization problem.

Minimize a function $F(u,x)$ (1)

Subject to $h(u,x) = 0$ (2)

and $g(u,x) \geq 0$ (3)

Where, u is the set of controllable quantities in the system and x is the set of dependent variables. F(u,x) is an objective function which is scalar. Equality constraints (2) are derived from conventional power balance equation. Inequality constraints (3) are the limits on control variables u and the operating limit on the other variables of the system.

3. LINEAR PROGRAMMING (LP) METHOD

Linear programming formulation requires linearization of objective function as well as constraints with nonnegative variables.

T.S.Chung *et al.* [6] presented recursive linear programming based approach for minimizing line losses and finding the optimal capacitor allocation in a distribution system. Cost-benefit calculation is carried out for 14-bus system and this method does not require any matrix inversion, thus saves computational time and memory space.

E.Lobato *et al.* [7] proposed LP based OPF for minimization of transmission losses and Generator reactive margins of the Spanish power system. The discrete nature of shunt reactors and capacitors is modeled by integer variables. It linearizes both the objective function and the constraints in each iteration and it is better than one which linearizes only objective function once.

F. Lima *et al.* [8] used Mixed Integer Linear Programming to conduct design study on the combinatorial optimal placement of Thyristor Controlled Phase Shifter Transformers ($TCPST_s$) in large-scale power systems. It finds the number, network location and settings of phase shifters that maximize system loadability under the DC load flow model, subject to limits on the installation investment or total number of $TCPST_s$. Computation time is significantly lower than those of other published comparable cases.

4. NEWTON-RAPHSON (NR) METHOD

The necessary conditions of optimality referred to as the Kuhn-Tucker conditions are obtained in this method.

S.Chen *et al.* [9] proposed a new algorithm based on Newton-Raphson (NR) method with sensitivity factors incorporated to solve emission dispatch in real-time. The Jacobian matrix and the B-coefficients have been developed in terms of the generalized generation shift distribution factor. So the penalty factor and the incremental losses are easily obtained. Execution time is lesser than that of the conventional one.

K.L.Lo *et al.* [10] proposed two Newton-like load flow methods, the Fixed Newton method and the modification of the right-hand-side vector method for line outage simulation that is a part of contingency analysis. These two methods are compared with the Newton-based full AC load flow method and the fast decoupled load flow to show their better convergence characteristics.

X. Tong *et al.* [11] presented the semismooth Newton-type algorithms for solving OPF problems. It treated general inequality constraints and bounded constraints separately. By introducing a diagonal matrix and the nonlinear complementarity function, the KKT system of the OPF is transformed equivalently to a system of nonsmooth bounded constrained equations. The number of variables is less compared to other method. The method saves computing cost.

5. QUADRATIC PROGRAMMING (QP) METHOD

It is a special form of nonlinear programming whose objective function is quadratic and constraints are linear.

J.A.Momoh [12] presented an extension of basic Kuhn-Tucker conditions and employing a generalized Quadratic-Based model for OPF. The conditions for feasibility, convergence and optimality are included in the construction of the OPF algorithm. It is also capable of using hierarchical structures to include multiple objective functions and selectable constraints. The generalized algorithm using sensitivity of objective functions with optimal adjustments in the constraints yields a global optimal solution. Computational memory and execution time required have been reduced.

N. Grudinin [13] proposed a reactive power optimization model that was based on Successive Quadratic Programming (SQP) methods. Six optimization methods were used to test the IEEE 30 bus and 278 bus systems. It is found that the developed SQP methods provide more fast and reliable optimization in comparison with the usual SLP method.

G.P.Granelli *et al.* [14] proposed Security-constrained economic dispatch using dual sequential quadratic programming. A dual feasible starting point is achieved by relaxing transmission limits and then constraint violations are enforced using the dual quadratic algorithm. It is compared with SQP method of NAG routine. It presents limited computation time and sufficiently good accuracy.

X.Lin *et al.* [15] integrated cost analysis and voltage stability analysis using an OPF formulation for competitive market, which was solved using sequential quadratic programming. Optimum reactive power dispatch are obtained under various voltage stability margin requirements in both normal and outage conditions for IEEE 14-bus test system.

A.Berizzi *et al.* [16] presented Security–Constrained Optimal Power Flow (SCOPF) to determine optimal setting and operation mode of UPFC and TCPAR. The solution of the OPF is obtained by the use of the HP (Han-Powell) algorithm. It is an efficient method that solves nonlinear problems with nonlinear constraints through the solution of successive quadratic problems with linear constraints. It is applied to CIGRE 63-bus system and Italian EHV network. A global solution is achieved, even adopting different starting points.

6. NONLINEAR PROGRAMMING (NLP) METHOD

Nonlinear programming (NLP) deals with problems involving nonlinear objective and/or constraint functions.

J.A.Momoh *et al.* [17] proposed a new nonlinear convex network flow programming (NLCNFP) model and algorithm for solving the security-constrained multi-area economic dispatch (MAED) problem. It is solved by using a combined method of quadratic programming and network flow programming. The tie-line security and transfer constraints in each area are considered. An analysis of a buying and selling contract in a multiarea environment is also proposed. This method has been tested on four interconnected power systems. It is feasible and effective.

D.Pudjianto *et al.* [18] used LP and NLP based reactive OPF for allocating (auctioning) reactive power among competing generators in a deregulated environment. It was concluded that the overall cost associated with the system reactive requirement calculated by LP method was reasonably accurate, but the generator's individual commitment may vary considerably. Whereas, NLP offers a faster computation speed and accuracy for the solution but the convergence could not be guaranteed for every condition.

G.L.Torres *et al.* [19] J.Z.Zhu [25] suggested the methods to calculate the price of reactive power support service in a multi-area power system. The methods are cost-benefit analysis (CBA) and nonlinear convex network flow programming. By using multiple cost-benefit indices, the reactive power support benefits with respect to power delivery increases of tie lines are computed.

A.K.Sharma [20] had proposed a method to determine optimal number and location of TCSC using Mixed Integer Nonlinear Programming (MINLP) approach in the deregulated electricity markets. The system loadability has been determined in a hybrid market model utilizing the secure transaction matrix.

7. INTERIOR POINT (IP) METHOD

Karmarkar proposed a new method in 1984 for solving large-scale linear programming problems very efficiently. It is known as an interior method since it finds improved search directions strictly in the interior of the feasible space.

Sergio Granville [21] presented application of an Interior Point Method to the optimal reactive power dispatch problem. It is based on the primal-dual logarithmic barrier method as described by Monteiro and Adler. The algorithm was applied on large power systems and it converged in 40 iterations. CPU time was 398.9 seconds. The proposed method has the following advantages: number of iterations is not very sensitive to network size or number of control variables, numerical robustness, hot starting capability, no active set identification difficulties and effectiveness in dealing with optimal reactive allocation and loss reduction problems in large scale and ill-conditioned networks.

Whei-Min Lin *et al.* [22] presented the use of Predictor-Corrector Interior-Point Nonlinear Programming (PCIPNLP) algorithm to solve social welfare maximization problem incorporating FACTS devices in a deregulated market structure. FACTS can ease the difficulties caused by transmission congestion. The advantage of the method is the inequality–constraint handling capabilities. Active set identification for handling various upper and lower limits is not required. A strictly feasible starting point is not mandatory.

Ding Xiaoying *et al.* [23] presented an Interior Point Branch and Cut Method (IPBCM) to solve decoupled OPF problem. The Modern Interior Point Algorithm (MIPA) is used to solve Active Power Suboptimal Problem (APSOP) and use IPBCM to iteratively solve linearizations of Reactive Power Suboptimal Problem (RPSOP). The advantages of the proposed method are: The variables and constraints of RPSOP are lesser than that of original OPF problem, which will enhance the calculation speed. However, the proposed algorithm fails in dealing with degenerate problem.

Wei Yan *et al.* [24] presented the solution of the Optimal Reactive Power Flow (ORPF) problem by the Predictor Corrector Primal Dual Interior Point Method (PCPDIPM). A new optimal reactive power flow model in rectangular form is proposed. The Hessian matrices in this model are constants and need to be evaluated only once in the entire optimal process. Total calculation time needed for the proposed method is always shorter than that for the conventional model for the seven test cases.

8. ARTIFICIAL INTELLIGENCE (AI) METHODS

It is the science of making intelligent computer program.

8.1. ARTIFICIAL NEURAL NETWORK (ANN)

ANN is an interconnected group of artificial neurons that uses a mathematical model or computational model for information processing based on a connectionist approach to computation.

Chowdhury [25] had suggested concept of Integrated Security Constrained Optimal Dispatch (ISCOD) which could solve the OPF problem when it was constrained by both static and dynamic security. ISCOD utilized the diagnostic and decision making capabilities of Knowledge Base System (KBS), massive parallel lisms and learning features of an ANN along with conventional power system network solution methodologies to provide real-time control and optimization. The KBS and the ANN are used in different configuration for adding the dispatch or in making control decisions.

N.I.Santoso *et al.* [26] presented a two-stage Artificial Neural Network to control in real time the multi tap capacitors installed on a distribution system for a nonconforming load profile such that the system losses are minimized. The required input data are directly obtained from on-line measurements which include the active and reactive line power flows, voltage magnitudes and the current capacitor settings at certain buses. Inequality constraint consists of limits on capacitor rating. The application of the proposed capacitor control will be limited by the computation time required for the learning process which in turn depends on the number of conforming load groups and capacitors installed rather than the number of system buses.

8.2. FUZZY LOGIC (FL) METHOD

It is derived from fuzzy set theory dealing with reasoning that is approximate rather than precisely deduced from classical predicate logic.

Miranda *et al.* [27] gave a fuzzy model to represent uncertainty in loads and generation as fuzzy numbers. While uncertain injections were dealt with D.C. fuzzy power flow model. System optimal operation was calculated with Dantzing-Wolfe decomposition technique and dual simplex method. Among the results, fuzzy cost value for system operation and possibility distribution of branch power flows and power generation were obtained.

V.C.Ramesh *et al.* [28] presented a Fuzzy Logic approach for the contingency constrained OPF problem formulated in a decomposed form that allows for post-contingency corrective rescheduling. Linear membership function is used. The formulation treats the minimization of both the base case (pre-contingency) operating cost and of the post-contingency correction times as conflicting but fuzzy goals. The proposed approach can yield Pareto curves that can guide the system operator regarding the tradeoff between cost and security against contingencies. However, choice of a suitable metric for measuring correction time is unclear.

N.P.Padhy [29] presented an efficient hybrid model for congestion management analysis for both real and reactive power transaction under deregulated Fuzzy environment of power system. The proposed model determines the optimal bilateral or multilateral transaction and their corresponding load curtailment in two stages. In the first stage classical gradient descent OPF algorithm has been used to determine the set of feasible curtailment strategies for different amount of real and reactive power transactions. In second stage, fuzzy decision opinion matrix has been used to select the optimal transaction strategy.

8.3. GENETIC ALGORITHM (GA) METHOD

It belongs to the category of random search algorithms which simulate the evolution process based on the theory of survival of the fittest.

Walters *et al.* [30] applied a Genetic Algorithm (GA) to solve an economic dispatch problem for valve point discontinuities.

Po-H.Chen *et al.* [31] proposed a new genetic algorithm for solving the Economic Dispatch (ED) problem in large-scale systems. A new encoding method is developed in which the chromosome contains only an encoding of the normalized system incremental cost. So the total number of bits of chromosome is entirely independent of the number of units. The approach can take network losses, ramp rate limits and prohibited zone avoidance into account. It is faster than lambda – iteration method in large systems.

T.S.Chung *et al.* [32] presented a Hybrid Genetic Algorithm (GA) method to solve OPF incorporating FACTS devices. GA is integrated with conventional OPF to select the best control parameters to minimize the total generation fuel cost and keep the power flows within the security limits. TCPS and TCSC are modeled. The proposed method was applied on modified IEEE 14 bus system and it converged in a few iterations.

L.J.Cai *et al.* [33] proposed optimal choice and allocation of FACTS devices in multi-machine power systems using genetic algorithm. The objective is to achieve the power system economic generation allocation and dispatch in deregulated electricity market. The locations of the FACTS devices, their types and ratings are optimized simultaneously. UPFC, TCSC, TCPST and SVC are modeled and their investment costs are also considered.

8.4. MISCELLANEOUS AI METHODS

Chowdhury *et al.* [34] proposed Expert System (ES) which was used in combination with a transmission constrained economic dispatch to provide real time security. The strategy for combining the ES with an economic dispatch which identifies the constraint violations in bus voltage magnitudes and in line flows, as well as the set of optimal generations. The ES then determines the best possible control measure using rules on voltage and line flow control. The purpose of the expert system is to expeditiously remediate voltage and branch over load problems.

H.Mori *et al.* [35] presented a Parallel Tabu Search (PTS) based method for determining optimal allocation of FACTS devices in competitive power systems. Available Transfer Capability (ATC) was maximized with the FACTS devices. UPFC was modeled and concept of incremental load rate was used. The proposed method was compared with Simulated Annealing, GA and Tabu Search methods. It is 1.95 and 2.68 times faster than TS and GA respectively. It is not affected by the initial conditions and gave higher quality solutions.

8.5. EVOLUTIONARY PROGRAMMING (EP)

It is a subset of evolutionary computation, a generic population based metaheuristic optimization algorithm.

P.Somasundaram *et al.* [36] proposed an algorithm for solving security constrained optimal power flow problem through the application of EP. The controllable system quantities in the base-case state are optimized to minimize some defined objective function subject to the base-case operating constraints as well as the contingency-case security constraints. Fitness function converges smoothly without any oscillations.

W.Ongsakul *et al.* [37] proposed Evolutionary Programming (EP) to determine the optimal allocation of FACTS devices for maximizing the total transfer capability (TTC) of power transactions between source and sink areas in deregulated power system. EP simultaneously searches for FACTS locations, FACTS parameters, real power generations except slack bus in source area, real power loads in sink area and generation bus voltages.

P.Attaviriyanupap *et al.* [38] presented a new bidding strategy for a day-ahead energy and reserve markets based on an EP. The optimal bidding parameters for both markets are determined by solving an optimization problem that takes unit commitment constraints such as generating limits and unit minimum up/down time constraints into account. The proposed algorithm is developed from the view point of a generation company wishing to maximize a profit as a participant in the deregulated power and reserve markets. Separate power and reserve markets are considered, both are operated by clearing price auction system.

T.Jayabarathi *et al.* [39] proposed the application of Classical Evolutionary Programming (EP), Fast EP and Improved FEP methods to solve all kinds of economic dispatch problems such as ED of generators with prohibited operating zones (POZ), ED of generators with piecewise quadratic cost function (PQCF), combined economic-environmental dispatch (CEED) and multi-area economic dispatch (MAED). The constraints considered are the power balance, generating capacity, prohibited operating zones, area power balance, generation limits and tieline limits constraints.

8.6. ANT COLONY OPTIMIZATION (ACO)

It is based on the ideas of ant foraging by pheromone communication to make path.

I.K.Yu *et al.* [40] presented a novel co-operative agents approach, Ant Colony Search Algorithm (ACSA)-based scheme, for solving a short-term generation scheduling problem of thermal power systems. The state transition rule, global and local updating rules are also introduced to ensure the optimal solution. Once all the ants have completed their tours, a global pheromone-updating rule is then applied and the process is iterated until the stop condition is satisfied. The feasibility of the algorithm in large systems with more complicated constraints is yet to be investigated.

Libao Shi *et al.* [41] presented ant colony optimization algorithm with random perturbation behavior (RPACO) based on combination of general ant colony optimization and stochastic mechanism is developed for the solution of optimal unit commitment (UC) with probabilistic spinning reserve determination. Total production fuel costs, start-up costs of units in stage t, the penalty cost imposed when any of constraints are violated and the total accumulated cost from stage 0 to stage t. are included in objective function. The security function approach is also applied to evaluate the desired level of system security.

R.Meziane *et al.* [42] used ACO to solve the allocation problem involving the selection of electrical devices and the appropriate levels of redundancy to maximize system reliability of series-parallel topology, under performance and cost constraints. A universal moment generating function (UMGF) approach is used by the ACO to determine the optimal electrical power network topology.

8.7. PARTICLE SWARM OPTIMIZATION (PSO)

It is based on the ideas of social behavior of organisms such as animal flocking and fish schooling.

H.Yoshida *et al.* [43] proposed a Particle Swarm Optimization (PSO) for reactive power and Voltage/VAR Control (VVC) considering voltage security assessment. It determines an on-line VVC strategy with continuous and discrete control variables such as AVR operating values of generators, tap positions of OLTC of transformers and the number of reactive power compensation equipment.

Jong-Bae Park *et al.* [44] suggested a Modified Particle Swarm Optimization (MPSO) for economic dispatch with nonsmooth cost functions. A position adjustment strategy is proposed to provide the solutions satisfying the inequality constraints. The equality constraint is resolved by reducing the degree of freedom by one at random. Dynamic search-space reduction strategy is devised to accelerate the process. The results obtained from the proposed method are compared with those obtained by GA, TS, EP, MHNN, AHNN and NM methods. It has shown superiority to the conventional methods.

Cui-Ru Wang *et al.* [45] presented a Modified Particle Swarm Optimization (MPSO) algorithm to solve economic dispatch problem. In the new algorithm, particles not only studies from itself and the best one but also from other individuals. By this enhanced study behavior, the opportunity to find the global optimum is increased and the influence of the initial position of the particles is decreased. The particle also adjusts its velocity according to two extremes. One is the best position of its own and the other is not always the best one of the group, but selected randomly from the group.

J.G.Vlachogiannis *et al.* [46] formulated the contributions of generators to the power flows in transmission lines as a multiobjective optimization problem and calculated using a Parallel Vector Evaluated Particle Swarm Optimization (VEPSO) algorithm. VEPSO accounts for nonlinear characteristics of the generators and lines. The contributions of generators are modeled as positions of agents in swarms. Generator constraints such as prohibited operating zones and line thermal limits are considered. It can obtain precise solutions compared to analytical methods.

M.Saravanan *et al.* [47] proposed the application of Particle Swarm Optimization to find the optimal location, settings, type and number of FACTS devices to minimize their cost of installation and to improve system loadability for single and multi-type FACTS devices. While finding the optimal location, the thermal limit for the lines and voltage limit for the buses are taken as constraints. TCSC, UPFC and SVC were considered.

9. SUMMARY OF THE PAPER

The following table shows the suitable methods for solving the various optimization problems of Electrical Engineering.

Objective function to be optimized	Suitable method(s)	Reason to use that method
Economic dispatch	LP, NR	Fast methods
Economic dispatch with non-smooth cost function	AI	Non-linear problem
Economic – Emission dispatch	Fuzzy	Suitable for conflicting objectives
Reactive power optimization	NLP, QP,IP,AI	Accurate methods
Optimal location of FACTS device	AI	Multiobjective nonlinear problem
Social welfare	QP, AI	---Do---
Congestion management	AI	---Do----
Security constrained	NLP, IP	Stable convergence

OPF		

10. CONCLUSION

In this paper an attempt has been made to review various optimization methods used to solve OPF problems. Even though, excellent advancements have been made in classical methods, they suffer with the following disadvantages: In most cases, mathematical formulations have to be simplified to get the solutions because of the extremely limited capability to solve real-world large-scale power system problems. They are weak in handling qualitative constraints. They have poor convergence, may get stuck at local optimum, they can find only a single optimized solution in a single simulation run, they become too slow if number of variables are large and they are computationally expensive for solution of a large system.

Whereas, the major advantage of the AI methods is that they are relatively versatile for handling various qualitative constraints. AI methods can find multiple optimal solutions in single simulation run. So they are quite suitable in solving multi-objective optimization problems. In most cases, they can find the global optimum solution. The main advantages of ANN are: Possesses learning ability, fast, appropriate for non-linear modeling, etc. whereas, large dimensionality and the choice of training methodology are some disadvantages of ANN. The advantages of Fuzzy method are: Accurately represents the operational constraints and fuzzified constraints are softer than traditional constraints. The advantages of GA methods are: It only uses the values of the objective function and less likely to get trapped at a local optimum. Higher computational time is its disadvantage. The advantages of EP are adaptability to change, ability to generate good enough solutions and rapid convergence. ACO and PSO are the latest entry in the field of optimization. The main advantages of ACO are positive feedback for recovery of good solutions, distributed computation, which avoids premature convergence. It has been mainly used in finding the shortest route in transmission network, short-term generation scheduling and optimal unit commitment. PSO can be used to solve complex optimization problems, which are non-linear, non-differentiable and multi-model. The main merits of PSO are its fast convergence speed and it can be realized simply for less parameters need adjusting. PSO has been mainly used to solve Bi-objective generation scheduling, optimal reactive power dispatch and to minimize total cost of power generation. Yet, the applications of ACO and PSO to solve Security constrained OPF, Contingency constrained OPF, Congestion management incorporating FACTS devices etc. of a deregulated power system are to be explored out.

Authors strongly believe that this survey article will be very much useful to the researchers for finding out the relevant references as well as the previous work done in the field of OPF methods, So that further research work can be carried out.

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