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A RESEARCH ON EVOLUTIONARY COMPUTATION TECHNIQUES IN OPTIMAL POWER FLOW SOLUTION

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Abstract- Optimal Power Flow (OPF) problem is basically a network analysis challenge and the main objective of this challenge is to plan and to predict the undesirable situations that may arise by adding various assumptions to the account. This challenge can be solved using well-known numerical approaches, however these include derivatives and the solution of them is relatively difficult. Large number of variety of constraints and non-linearity of mathematical models OPF poses a big challenge for the mathematicians as well as for engineers in obtaining optimum solutions. However, the Evolutionary Computation (EC) based optimization algorithms provide more easy solutions for OPF at present. In this study, the most used EC based algorithms and their applications on OPF are reviewed and also some unused EC based algorithms for OPF are also presented.

Keywords: Optimal Power Flow, Evolutionary computation, Optimization.

I. INTRODUCTION

The OPF problem is a well-known problem in the field of power systems engineering where active, reactive production and load values are taken into account when calculating voltage, angle and load values of all bus bars in the system and also to calculate the active and reactive load flows in the system at the same time. The power flow problem involves a system of nonlinear equations. Therefore, an iterative algorithm must be used to solve the load flow problem.

An optimal power flow is basically a network analysis challenge and the main objective of this problem is to plan and to predict the unwanted situations that may arise by adding various assumptions to the account. As an example, if a transmission line to be maintained is deactivated, the remaining lines in the system are an analysis of whether the required loads can carry the working capacities beyond.

The OPF problem is initially motivated by the need for engineers to plan different network configurations needed to serve an expected load. Later, it became an operational problem for engineers and operators because they had to track the network in real time.

Today, the OPF problem is widely accepted as a fundamental problem for power system analysis and there are many advanced algorithms or power flow programs available to solve this problem. Power systems are complex systems that are spread over a wide area and can be affected by many disturbances such as various electrostatic and electromagnetic effects which occur under different conditions and also the disruptive effects of electronic semiconductor elements. This leads to an increase in technical losses during the operation of power systems, and a decrease in efficiency in the production, transmission and distribution of electrical energy.

Optimization is the means by which a system finds the best quality of existing designs. Therefore, optimization of power systems is required to plan the power systems, providing the necessary efficiency during the production, transmission and distribution of the energy and to reduce the total costs to a minimum. Therefore, optimization methods for power systems can be applied to achieve the desired level of optimization.

The problem of optimal power flow first emerged in 1962 and is an important optimization problem that has increased day by day. Many classical methods have been used to solve this problem. Examples of these methods are non-linear programming, quadratic programming, Newton based methods and linear programming. However, these methods have problems such as starting point and easy local minimum switching. Heuristic methods are used to remove such problems. The most important advantage of heuristic methods is that they can obtain optimum solutions near global maximum and global minimum, unlike classical methods.

Evolutionary Computation (EC) based methods at this point are able to provide the best and most appropriate solutions in less time for these problems since it is difficult to deal with classical algorithms. EC based algorithms are quite different from classical methods since they are population-based optimization methods. In this method, there is no need to distinguish between cost functions and constraint functions as in classical methods.

The EC is started by resetting the solutions and then random solutions are produced. All solutions are measured and a selectivity criterion is applied to find the best solution. It is able to familiarize easily to alter and produce good solutions due to global optimum. For this reason, EC based algorithms are needed and efficient for OPF problems.

II. OPTIMAL POWER FLOW PROBLEM

The classical methods that are effectively used to solve the OPF problems are based on the mathematical programming approach and the purpose is to solve OPF problems at various dimensions to meet the properties of the constraint functions. Mathematical expressions must be simplified to solve large-scale power system problems. Such problems have poor convergence and can be stuck to the local optimum. At the same time, the number of variables in the power system is very expensive in terms of calculation.

The classical OPF is a load flow challenge and must be calculated to reduce the real power generation or the cost of losses while meeting the operating limits on the functions of some variables. If this challenge is taken into account as a minimization dilemma by limitations, it is able to define as [1, 2]: $f(x, u)$ is aim function, $g(x, u) = 0$ is load flow equality, $h(x, u) \leq 0$ is safety limit values (inequalities), x is state variables vector and u is control variables vector.

State variable is an active output power of the swing bar, peak amplitude of the load bars V_L, and reactive output power of the generator bars Q_g.

$$X_T = \left[P_{swing}, V_L, Q_g \right] \quad (1)$$

Control variables are active output power of P_g, generator bar V_g, tap setting values of transformers T, and values of shunt capacities Q_c.

$$U_T = \left[P_g, V_g, T, Q_c \right] \quad (2)$$

To deliver optimal actual power, the aim function f is the whole cost of production like results:

$$\min f = \sum_{i=1}^{N_G} \left(a_i + b_i P_{gi} + c_i P_{gi}^2 \right) \quad (3)$$

where, N_G is generator number in the system, P_{gi} is ith generator real power generation and a_i, b_i, c_i are ith generator fuel cost coefficients.

$$Q_{gi} - Q_{di} - \sum_{j=1}^{N} |V_i||V_j||V_{ij}| \sin\left(\delta_i - \delta_j - \delta_{ij} \right) = 0 \quad (4)$$

$$P_{gi} - P_{di} - \sum_{j=1}^{N} |V_i||V_j||V_{ij}| \cos\left(\delta_i - \delta_j - \delta_{ij} \right) = 0 \quad (5)$$

Minimum limits and maximum limits on the real and reactive powers:

$$P_{gi}^{\min} \leq P_{gi} \leq P_{gi}^{\max}\ ,\ Q_{gi}^{\min} \leq Q_{gi} \leq Q_{gi}^{\max} \quad (6)$$

Minimum limits and maximum limits of the transformer's step ratio (t) and phase shift (α) are:

$$t_{ij}^{\min} \leq t_{ij} \leq t_{ij}^{\max}\ ,\ \alpha_{ij}^{\min} \leq \alpha_{ij} \leq \alpha_{ij}^{\max} \quad (7)$$

Maximum limit of real power flow P_{ij}:

$$\left| P_{ij} \right| \leq P_{ij}^{\max} \quad (8)$$

Minimum limits and maximum limits of bus voltages:

$$V_i^{\min} \leq V_i \leq V_i^{\max} \quad (9)$$

Minimum limits and maximum limits of shunt FACTSs issues:

$$x^{\min} \leq x_{FACTS} \leq x^{\max} \quad (10)$$

A variety of extended OPF versions has been reported so far. Some of them are as follows:

- Static OPF: This type of problem optimizes optimal flow under various constraints at a certain time of interest. In other words, it can only handle a single load level at a particular time [3].
- Dynamic OPF: This type is an extended version of the static OPF and determines the optimal operating point over a time horizon. In fact, it covers multiple time periods [4, 5].
- Transient stability-constrained OPF: This problem considers static and dynamic constraints of the power network during the optimization process simultaneously [6]. Under this condition, the system can withstand severe contingencies [7].
- Security-constrained OPF: This is another extended version of the OPF which involves constraints arising from the operation of the system under a set of postulated contingencies.
- Deterministic OPF: This widely used type does not consider stochastic factors.
- Stochastic OPF: This type considers uncertainties in power system parameters [8-10]. In fact, it regards the uncertainty as a part of the constraints and objective models. Hence, uncertain factors affect the optimization process as well as the final OPF results [11].
- Probabilistic OPF: It estimates the probability distribution functions of dependent variables based on the probability distributions of loads and other uncertain factors through using Monte-Carlo Simulation [12], Cumulant method [13], Point Estimate Method (PEM) [14], customized Gaussian mixture model [15], and etc. In this type of OPF, the uncertain factors do not affect the final results [11].
- AC OPF: This is associated with the AC power networks and is based on the natural power flow characteristics of the system [16]. Consequently, the results obtained by this type of OPF are more accurate [17, 18].
- DC OPF: This type does not consider the reactive power and transmission losses [16].
- Mixed AC/DC OPF: It is associated with OPF in both AC and DC grids [19, 20].

III. EVOLUTIONARY COMPUTATION

Evolutionary Computation is a problem solving methods based on the principle of biologic progression, such as genetic inheritance and natural selection that are often used to create optimization procedures and methodologies to solve problems on computers. This algorithm has many advantages over classical optimization methods. While classical optimization methods contribute to the solution of small-sized problems, EC based algorithms are widely used in large-scale problems [21].

Adaptation to mathematical formulation changes in classical optimization methods is rather difficult, but in the EC based algorithm the parameters can be easily modified and adapted. Similarly, while there is a need to understand mathematical expressions in classical optimization methods, there is no need to understand such expressions in EC based algorithms. In terms of probing solution search, EC based algorithms are easier to solve than many alternative points, while starting from a single point to search for classical methods. As a further advantage, no assumptions need to be made in EC based algorithms while classical methods use a number of additional data such as derivatives of objective function.

Evolutionary Computations have a number of components, procedures or operators that must be specified in order to a particular EC. The most important components indicated as below.

• Representation (definition, individuals),
• Evolution Function (or fitness function),
• Population,
• Parent Selection Mechanism,
• Variation Operators, Recombination and Mutation,
• Survivor Selection Mechanism (replacement).

At the beginning of the computation a number of individuals (the population) are randomly initialized. The objective function is then evaluated for these individuals. The first/initial generation is produced. If the optimization criteria are not met the creation of a new generation starts. Individuals are selected according to their fitness for the production of offspring. Parents are recombined to produce offspring. All offspring will be mutated with a certain probability. The fitness of the offspring is then computed. The offspring are inserted into the population replacing the parents, producing a new generation. This cycle is performed until the optimization criteria are reached.

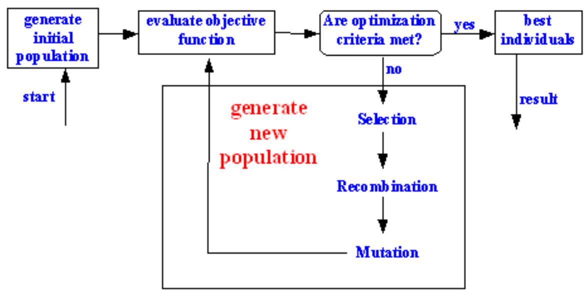

Figure 1. Structure of EC

• Selection: Selection determines which individuals are chosen for mating (recombination) and how many offspring each selected individual produces.
• Recombination: Recombination produces new individuals in combining the information contained in the parents (parents-mating population).
• Mutation: After recombination every offspring undergoes mutation. Offspring variables are mutated by small perturbations (size of mutation step), with low probability.
• Reproduction: If less offspring is produced than the size of the original population the offspring have to be reinserted into the old population.

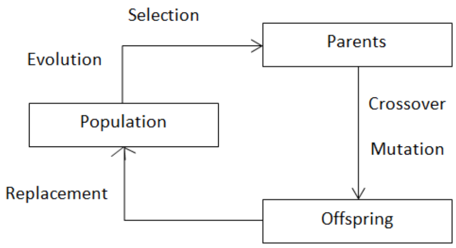

Figure 2. Evolutionary cycle

Evolutionary Computations have some advantages and disadvantages as below.

Advantages:
• No presumptions for problem space,
• Widely applicable,
• Low development and application costs,
• Easy to incorporate other methods,
• Solutions are interpretable,
• Can be run interactively, accommodate user proposed solutions,
• Provide many alternative solutions.

Disadvantages:
• No guarantee for optimal solution within finite time
• Weak theoretical basis,
• May need parameter tuning,
• Often computationally expensive, i.e. slow.

Adaptation to mathematical formulation changes in classical optimization methods is rather difficult, but in the EC based algorithm the parameters can be easily modified and adapted. Similarly, while there is a need to understand mathematical expressions in classical optimization methods, there is no need to understand such expressions in EC based algorithms.

In terms of probing solution search, EC based algorithms are easier to solve than many alternative points, while starting from a single point to search for classical methods. As a further advantage, no assumptions need to be made in EC based algorithms while classical methods use a number of additional data such as derivatives of the objective function.

Most used EC based optimization algorithms used in literature for OPF problem can be listed as follows:
• Particle Swarm Optimization Algorithm
• Artificial Bee Colony Algorithm
• Electromagnetism - Like Algorithm
• Cuckoo Search Optimization Algorithm
• Flower Pollination Optimization Algorithm
• Harmony Search Optimization Algorithm
• Bat Optimization Algorithm
• Fire fly Optimization Algorithm
• Social Spider Optimization Algorithm
• Collective Animal Behavior Algorithm
• Colonel Selection Optimization Algorithm
• Cultural Optimization Algorithm
• Genetic Expressing Programming
• Genetic Optimization Algorithm
• Genetic Programming
• Evolutionary Programming
• Evolutionary Strategy

- Differential Evolution Optimization Algorithm
- Differential Search Optimization Algorithm
- Grammatical Evolution Optimization Algorithm
- Learning Classifier Optimization Algorithm
- Gene Expression Programming
- Non-dominated Sorting Genetic Algorithm
- Strength Pareto Evolutionary Algorithm

On the other hand, EC based algorithms are distinguished in two parts: the swarm intelligence based algorithms and evolutionary algorithms.

Both algorithms serve the same purpose to solve optimization problems. Certainly there are some differences between these two techniques and these differences can be explained as follows.

An evolutionary algorithm imitates the evolutionary process of a segment of individuals with the aim of developing the best possible solution to the optimization problem at hand. Swarm intelligence is the collective behavior of systems that are centripetal, self-organizing, natural or artificial. This concept is being studied on artificial intelligence.

IV. OPF SOLUTIONS WITH EC

Table 1 is a comparative table of literature review. The algorithms used in the literature are explained. The descriptions of the application of these algorithms, the test systems are given and also compared these algorithms.

Table 1. EC based optimization algorithms used for OPF problem

Ref.	Publication Name	Publication Date	Used Algorithms	Compared Algorithms
[22]	Improved Genetic Algorithms for Optimal Power Flow Under both Normal And Contingent Operations States	1997	Improved Genetic Algorithm	Gradient Based Conventional Method
[23]	Optimal Power Flow Using Particle Swarm Optimization	2001	PSO Algorithm	Evolutionary Programming Genetic Algorithm
[24]	Optimal Power Flow Using Tabu Search Algorithm	2001	Tabu Search Algorithms	Evolutionary Programming Nonlinear Programming
[25]	Optimal Power Flow of the Algerian Electrical Network using an Ant Colony Optimization Method	2005	Ant Colony Optimization Algorithm	Genetic Algorithm
[26]	Modified Differential Evolution Algorithm For Optimal Power Flow With Non-Smooth Cost Functions	2007	Improved Differential Evolution Optimization Algorithm	Genetic Algorithm Evolutionary Programming PSO Algorithm Simulated Annealing Tabu Search Opt. Algorithm Differential Evolution Opt. Algorithm
[27]	Optimal Power Flow Using Differential Evolution Algorithm	2008	Differential Evolution Optimization Algorithm	-
[28]	An Improved Particle Swarm Optimization Algorithm for Optimal Power Flow	2009	Improved Particle Swarm Optimization Algorithm	PSO Algorithm Genetic Algorithm
[29]	Optimal Power Flow By A Fuzzy Based Hybrid Particle Swarm Optimization Approach	2009	Fuzzy Based Hybrid PSO	PSO Algorithm (Local Random Search) Evolution Programming
[30]	Particle Swarm Optimization Applied To Optimal Power Flow Solution	2009	Particle Swarm Optimization Algorithms	Matpower
[31]	A Solution to the Optimal Power Flow Using Artificial Bee Colony Algorithm	2010	ABC Algorithm	PSO Algorithm Genetic Algorithm
[32]	Application Of Biogeography-Based Optimisation To Solve Different Optimal Power Flow Problems	2011	Biogeography-Based Optimisation Algorithm	Particle Swarm Optimization Genetic Algorithms Evolutionary Programming Differential Evolution Gradient Method
[33]	Application of Particle Swarm Optimization To Optimal Power Systems	2011	Particle Swarm Optimization Algorithm (Using Loss Minimization)	Interior Point Algorithm
[34]	Optimal Power Flow Using Gravitational Search Algorithm	2011	Gravitational Search Algorithm	Other Methods in Literature
[35]	A Solution to Multi-Objective Optimal Power Flow using Hybrid Cultural-based Bees Algorithm	2012	Cultural-Based Bees Optimization Algorithm	Artificial Bee Colony Algorithm Particle Swarm Optimization Genetic Algorithm
[36]	Optimal Power Flow with Emission Controlled Using Firefly Algorithm	2013	Firefly Optimization Algorithm	Genetic Algorithm PSO Algorithm
[37]	Temperature Dependent Optimal Power Flow Using GBest - Guided Artificial Bee Colony Algorithm	2014	GBest - Guided ABC Optimization Algorithm	Gravitational Search Algorithms
[38]	Optimal Power Flow using Glowworm Swarm Optimization	2015	Glowworm Swarm Optimization Algorithm PSO Algorithm	Glowworm Swarm Optimization PSO
[39]	Optimal Power Flow Using Moth Swarm Algorithm	2016	Moth Swarm Algorithms	Modified Particle Swarm Optimization Modified Differential Evolution Moth Flame Optimization Flower Pollination Algorithm

These algorithms have been successfully applied to the OPF challenge and the more optimal solutions have been obtained due to their fast and accurate convergence abilities. On the other hand, it is considered that there are still some unused EC based optimization algorithms for OPF problem in literature. They are listed in Table 2 for unused in OPF problem.

Table 2. Some unused EC based optimization algorithms for OPF

Population-based incremental learning
Tabu search Continuous Optimization
Firework algorithm
Generative Algorithms
Hybrid Differential Evolution Algorithm With Adaptive Crossover Mechanism
Raindrop optimization
Swine flow Optimization Algorithm
Bayesian Optimization Algorithms
Charged system search Optimization Algorithm
Continuous scatter search Optimization Algorithm
The Wind Driven Optimization algorithm
Lloyd's Algorithm
Huffman Algorithm
Active-Set Algorithm
Random Search Algorithm
Alternating Conditional Expectation algorithm
Normalized Normal Constraint algorithm
Binary Bat Algorithm
Global Neighborhood Algorithm
Vortex Algorithm
Jaya Algorithm
Hill Climbing Optimization Algorithm
Adaptive Random Search Optimization Algorithm
Stochastic Hill Climbing Optimization Algorithm
Iterated Local Search Optimization Algorithm
Guided Local Search Optimization Algorithm
Variable Neighborhood Search Optimization Algorithm
Greedy randomized adaptive search Optimization Algorithm
Scatter Search Optimization Algorithm
Learning Classifier Optimization Algorithm
Non-dominated Sorting Genetic Optimization Algorithm
Extremal Optimization Algorithm
Univariate Marginal Distribution Optimization Algorithm
Cross-Entropy Optimization Algorithm
Negative Selection Optimization Algorithm
Immune Network Optimization Algorithm
Dendritic Cell Optimization Algorithm
Perceptron Learning Algorithm
Self-Organizing Map Algorithm

Some of these algorithms briefly presented below

- Tabu Search Continuous Optimization: In this algorithm in general, at a local minimum the cue performs to accept some non-cue points from that point to allow the search to search for new areas of the area.
- Bayesian Optimization Algorithms: The Bayesian Optimization Algorithm (BOA) combines the idea of using probabilistic models to guide optimization and the methods for learning and sampling Bayesian networks. To learn an adequate decomposition of the problem, BOA builds a Bayesian network for the set of promising solutions. New candidate solutions are generated by sampling the built network.
- The Wind Driven Optimization Algorithm: Wind-Driven Optimization (WDO) technique is an iterative heuristic global optimization algorithm with application potentials for search area constraints for multi-domain and multi-mode problems.
- Hill Climbing Optimization Algorithm: It is one of the search algorithms used in computer science. It gets the name from the hills in the graph where the search is made. Simply looking at the lowest point in a graph, the movement in the graph is actually similar to the climbing of the hill.
- Perceptron Learning Algorithm: The Perceptron Learning Algorithm is used to predict the outcome of new future data using observed data. The algorithm first takes any vector in space and looks at whether it provides complete separation for all data. If it does, it scrolls the vector and repeats it until it is available for all the data. If it is not available with any vector it will continue forever.
- Self-Organizing Map Algorithm: Kohonen, named for the first time is developed by Finnish scientists map the Kohonen (Kohonen map). The name given to these networks operate in two different ways, like all other artificial neural networks.
- Iterated Local Search Optimization Algorithm: Iterative Local Search (ILS) is a search algorithm that produces a series of solutions generated by an embedded heuristic.
- Extremal Optimization Algorithm: A new heuristic approach that combines the modularity and community fitness and uses extremal optimization algorithm (EO) as an underlying method has been proposed.
- Cross-Entropy Optimization Algorithm: Cross entropy method is used to solve difficult estimation and optimization problems used. The Kullback-Leibler (or cross entropy) is a versatile intuitive tool based on the most downsizing of your work.
- Variable Neighborhood Search Optimization Algorithm: It was discovered in 1997 by Mladenovi'c and Hansen. The main idea of this meta-intuitive is systematic change of neighbors when search regions are used.
- Harmony Search Optimization Algorithm: HS is based on natural musical performance a process that searches for a perfect state of harmony. The harmony in music is analogous to the optimization solution vector, and the musician's improvisations are analogous to local and global search schemes in optimization techniques. The HS algorithm does not require initial values for the decision variables and uses a stochastic random search that is based on the harmony memory considering rate and the pitch adjusting rate [40].
- Binary Bat Optimization Algorithm: BAT search algorithm is an optimization algorithm inspired by the echolocation behavior of natural bats in locating their foods. It is used for solving various optimization problems [41].

V. COMPARISON OF EC BASED ALGORITHMS AND CLASSICAL OPTIMIZATION METHODS

- Adaptation to mathematical formulation changes in classical optimization methods is rather difficult, but in the EC based algorithm the parameters can be easily modified and adapted.
- While there is a need to understand mathematical expressions in classical optimization methods, there is no need to understand such expressions in EC based algorithms.

• In terms of probing solution search, EC based algorithms are easier to solve than many alternative points, while starting from a single point to search for classical methods.

• As a further advantage, no assumptions need to be made in EC based algorithms while classical methods use a number of additional data such as derivatives of the objective function.

VI. CONCLUSION

Equality and inequality limitations of OPF challenge can be expressed like a nonlinear optimization challenge. In this brief review study, EC based algorithms proposed in order to solve OPF have been found to have advantages over other algorithms. It is known that power system problems, which are difficult to express in large scale and algebraically, yield effective results in their solutions. At the same time, it is preferred by researchers according to classical methods, because it requires less algebraic operation and therefore the processing time is short.

In addition, some unused algorithms for OPF problem are also given. Researchers may try these algorithms that have not been used yet, and when comparing and analyzing, it is better for the researchers to compare with the algorithms listed above, in terms of the adequacy of the results.

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