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Optimal Power Flow Methods – A Survey

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ABSTRACT:The main objective of power system is provision of efficient and reliable power supply at minimal cost and line losses, hence the need for monitoring, analysis and control of power system to meet the load demand without violation of equality and inequality constraints. The optimal power flow (OPF) provides a means of achieving the optimal state of control variables through minimization of desired set objectives, provided relevant constraints are satisfied. The artificial intelligence methods are gradually replacing the traditional methods used in solving OPF problems due to steady growth in complexity as a result of incorporation of FACTS devices and renewable energy sources into power system networks. This paper presents a simplified classification of modern OPF methods in which the applied algorithm, objective functions, validation systems used in solving various OPF problems, year of publication and the authors' reference number is tabulated. This survey will be helpful to researchers and system operators interested in improvement of established OPF methodologies and the establishment of knowledge gaps in the area of optimal power flow for further research work.

KEYWORDS: Optimal Power Flow, Economic Dispatch, Flexible Alternating Current Transmission System (FACTS), Objective Function, Metaheuristic Algorithm, System Constraints.

I. INTRODUCTION

H. H. Happ [1] presented the first comprehensive survey on optimal power, which was followed by the IEEE working group that presented bibliography review on main economic-security functions in 1981 [2]. The major task of Optimal Power Flow is to ascertain the best or the safest operating point (control variables) for certain objective functions while satisfying the system equality and inequality constraints [3]. OPF problems have been given much attention by researchers since its introduction as network constrained economic dispatch. OPF has the ability to optimize objective function without violation of the system operating constraints. OPF can be described as a means by which one or more objectives are optimized which have resulted to the developments of computation and optimization theories in the power system [4].

About 70% of world energy production is based on thermal power plants hence the need for fuel optimization owing to the rapid increase in energy demand [5]. The common objectives of OPF can be classified as active and reactive power objectives. The active power objectives include economic dispatch such as minimization of generating fuel cost and line losses, environmental dispatch and maximum power transfer while the reactive power objectives involve minimization of MVAR loss. However, majority of OPF research dwell on the minimization of cost of operation while some researchers focus on minimization of active power losses [6], electricity market deregulation [7], voltage stability index [8] and incorporation of FACTS devices [9], [10].

1.1 Optimal Power Flow Challenges

The demand for OPF solution has been on the increase for the purpose of state evaluation and recommendations for control measures, for both line and off line studies since 1960s when OPF was first published. The desire to solve OPF problems of deregulated and vertically integrated industries have been a great challenge in trying to evaluate existing capabilities and potentials.

Some of the common challenges facing OPF include:

a. Mathematicians and engineers faced a major drawback in trying to obtain optimal solutions due to many constraints as a result of non-linear mathematical models
b. Practicability and sensitivity for online applications, poor response time, external modelling and environmental transfer.

c. Deregulated electricity market model requirement, real time processing and selection of appropriate costing.
d. Local and global control measures which threatens voltage stability.
e. Operational scope and planning for the purpose of accommodating new generation facilities and resource allocations.

1.2 Major Advantages of Modern OPF Methods

It is difficult to find an exact advantage among OPF methods as a result of variation in problem formulations and models as well as algorithms. However, the common advantages of the reviewed OPF methods include:

a. Handles various qualitative constraints
b. Multiple optimal solutions can be found in single simulation run
c. Suitable in solving multi-objective optimization problems
d. Global optimum solution can be found
e. Suitable for both small and large-scale systems
f. Rapid convergence to the optimum solution
g. Rarely suffer from stagnation or trapped in local minima solution

II. OPTIMAL POWER FLOW FORMULATION

The solution of Optimal Power Flow (OPF) problem is targeted at optimal enhancement of an objective function through adjustment of power control variables, while satisfying several equality and inequality constraints. According to R. P. Singh et al [11], the optimal power flow problem can be mathematically represented as equations (1) - (3).

$$\mathrm{Min}\,F(x,u) \qquad (1)$$

Subjected to

$$g(x,u) = 0 \qquad (2)$$

$$h_{\min} \leq h(x,u) \leq h_{\max} \qquad (3)$$

where, F is the objective function, x is a vector quantity representing the dependent variables (state vector), u is the vector quantity of independent variables (control variables), g is the equality constraints and h is the operating constraints.

The dependent variables (x) in power system can be represented in terms of vector of independent variables (u) as equation (4).

$$U^T = [P_{G1} \ldots P_{GNG}, V_{G1} \ldots V_{GNG}, Q_{C1} \ldots Q_{CNC}, T_1 \ldots T_{NT}] \qquad (4)$$

where P_G is the real power output of generators, P_{G1} is the slack bus power, V_G is the generator voltage at PV buses, T as transformer tap settings, NT as number of taps changing transformers, NC as number of VAR compensators, and Q_C is the injected reactive power of shunt compensator.

The equality constraints refer to the set of non-linear power flow equations that govern the operation of power system which is represented in equation (5) and (6).

$$P_{Gi} - P_{Di} - \sum_{j=1}^{N} |V_i||V_j|\,|Y_{ij}|\cos(\theta_{ij} - \delta_i + \delta_j) = 0 \qquad (5)$$

$$P_{Gi} - P_{Di} + \sum_{j=1}^{N} |V_i||V_j|\,|Y_{ij}|\mathrm{Sin}(\theta_{ij} - \delta_i + \delta_j) = 0 \qquad (6)$$

where the real and reactive output power injected at bus i is P_{Gi} and Q_{Gi} respectively, P_{Di} and Q_{Di} as the load demand at the same bus respectively, and the bus admittance matrix elements as $|Y_{ij}|$.

The inequality constraints refer to set of constraints that represent the system operational and security limits such as the bounds on the following:

(i) The generators active power output:

$$P_{Gi}^{min} \leq P_{Gi} \leq P_{Gi}^{max} \quad i = 1, 2, \ldots, NG \qquad (7)$$

(ii) Generators bus voltages:

$$V_{Gi}^{min} \leq V_{Gi} \leq V_{Gi}^{max} \quad i = 1, 2, \ldots, NG \qquad (8)$$

(iii) Generators reactive power output:

$$Q_{Gi}^{min} \leq Q_{Gi} \leq V_{Gi}^{max} \quad i = 1, 2, \ldots, NG \qquad (9)$$

(iv) Transformer tap settings:

$$\mathrm{T_i^{min}} \leq \mathrm{T_i} \leq \mathrm{T_i^{min}} \quad \mathrm{i = 1, 2, \ldots, NT} \qquad (10)$$

(v) Shunt VAR compensator:

$$\mathrm{Q_{ci}^{min}} \leq \mathrm{Q_{ci}} \leq \mathrm{Q_{ci}^{max}} \quad \mathrm{i = 1, 2, \ldots, NC} \qquad (11)$$

(vi) Apparent power flow in transmission lines:

$$\mathrm{S_{Li}} \leq \mathrm{S_{Li}^{min}} \quad \mathrm{i = 1, 2, \ldots, NTL} \qquad (12)$$

(vii) Voltage magnitude of load buses:

$$\mathrm{V_{Li}^{min}} \leq \mathrm{V_{Li}} \leq \mathrm{V_{Li}^{max}} \quad \mathrm{i = 1, 2, \ldots, NPQ} \qquad (13)$$

III. OPTIMAL POWER FLOW METHODS

OPF problems are multimodal, non-linear or non-convex, hence the application of conventional methods in solving OPF problems does not guarantee a global solution. The development of numerous heuristic optimization techniques in solving OPF problems is to take care of challenges faced by conventional methods. Under this section is the detailed survey presentation of the applications of nondeterministic (heuristic) optimization methods for OPF.

According to [3], the classification of the heuristic optimization algorithms for OPF problems is based on inspiration methods as follows:

3.1 Swarm and Bio-inspired Optimization Techniques

Thebio-inspired and nature-inspired optimization techniques are inspired to mimic the style of movement and searching behaviour of swarms of animals and birds in quest for food sources. Some of the nature-inspired techniques that have been used in solving OPF problems is presented in Table 1.

Table 1: Some of the literature review in respect of bio and nature-inspired algorithms for OPF problem

Algorithm	**Objective Function**	**System**	**Year**	**Ref.**
Moth swarm algorithm	Fuel cost, fuel cost with valve effect, emission, voltage stability index, active loss, piecewise cost and voltage deviation	IEEE 30-bus, IEEE 57-bus, IEEE 118-bus	2017	[12]
Moth flame optimization	Fuel cost, active power loss and emission	IEEE 30-bus	2017	[13]
A novel method based on coyote algorithm	real power losses	69 and 119-node distribution systems at two different scenarios	2020	[14]
Coyote optimization algorithm	Total power loss and voltage regulator tap changes at different load levels	IEEE 123-bus unbalanced benchmark system	2020	[15]
Improved coyote optimization algorithm	Total power loss, voltage profile index, PVDGUs capacities and harmonic distortion	IEEE 33 and 69- bus systems.	2020	[16]
Modified coyote algorithm	Active power losses and total cost of thermal generation	Three different IEEE transmission power networks	2019	[17]
Coyote search algorithm	Active power loss	IEEE 57-bus system	2018	[18]
Dragonfly optimization algorithm	Active power loss in transmission lines	IEEE 14 and 30-bus test systems	2018	[19]
Non-dominated sorting dragonfly algorithm	Fuel cost, emission, real power loss, Var power loss, voltage deviation and voltage stability	IEEE 30-bus	2019	[20]
Adaptive partitioning flower pollination	Fuel cost, active power loss & voltage deviation.	IEEE 30-bus, IEEE 57-bus	2016	[21]
Enhanced flower pollination algorithm	Fuel cost, voltage stability improvement, transmission line losses and thermal emission	IEEE 30-bus	2017	[22]
Flower pollination algorithm	Fuel cost and voltage magnitude	IEEE 30-bus,	2018	[23]
Best-guidedartificial beecolony algorithm	Fuel cost	IEEE30-bus, IEEE 57-bus	2016	[24]
Improved krill herd algorithm with novel constraint handling method	Exploration and exploitation abilities and global solution	IEEE 30-bus, IEEE 57-bus and IEEE 118-bus	2018	[25]

Krill Herd Algorithm	Fuel cost of generation, transmission active power losses, emission and combined economic and environmental cost (CEEC).	IEEE 30-bus and IEEE 57-bus	2020	[26]
Cuckoo search algorithm	Real power loss, voltage stability index (VSI) and reactive power loss	Nigerian Distribution network using Ayede 34-bus system	2019	[27]
Artificial bee colony algorithm	Voltage profile, real power loss and voltage stability	Different IEEE buses	2019	[28]
Moth-flame algorithm	Voltage stability index, active power loss and voltage deviation	IEEE 30-bus	2016	[29]
Chicken swarm optimization	Fuel cost and transmission losses	6-unit system and 15-unit test systems	2016	[30]
Bat optimization Algorithm	Fuel cost	IEEE 9, 14, 30 and 57-bus systems	2016	[31]
Improved bat algorithm	Fuel cost and emission	IEEE 57-bus system	2017	[32]
Firefly optimization technique	Total generation cost of fuel	IEEE 30-bus system and 24-bus Nigerian system	2018	[33]
Ant lion optimizer	Optimal reactive power dispatch	IEEE 30-bus, IEEE 118-bus and 300-bus	2017	[34]
New partitioned ant lion algorithm	Total fuel cost of generation, total power loss and total voltage deviation	IEEE 30-bus	2020	[35]
Multi-objective ant lion algorithm	Fuel cost of generation, emission of environmental pollution, active power losses and voltage deviation	IEEE 30-bus, IEEE 57-bus, IEEE 118-bus and	2019	[36]
Social spider optimization algorithm	Fuel cost, power losses and voltage profile	33-bus standard distribution system	2019	[37]
Opposition based social spider optimization	Total cost of generation	Hybrid Renewable Energy Systems	2019	[38]
Particle swarm optimization algorithm	Generation and operational cost	IEEE 30-bus	2017	[39]
Multi-objective grey wolf optimizer algorithm	Emission, fuel cost and active power loss	IEEE-30-bus test	2018	[40]
Moth swarm optimizer	Fuel cost, emission rate, network power loss.	IEEE 30-bus and 57-bus	2020	[41]
Stud krill herd algorithm	Fuel cost, fuel cost with valve effect, emission, voltage stability index and active power loss	IEEE 14-bus, IEEE 30-bus and IEEE 57-bus	2016	[42]
Enhanced ant colony optimization	Fuel cost and emission	IEEE 30-bus, IEEE 118-bus	2016	[43]
Ant colony optimization	Optimal placement of Distributed Generator (DG**)**	11kV piggery feeder of Abuja Electricity Distribution Company, Mina	2017	[44]

The modified flower pollination	Fuel cost, Power loss and voltage deviation	IEEE 30-bus	2017	[45]
Weighted artificial fish swarm algorithm	Voltage profile and network losses	IEEE 30 and 57-bus	2018	[46]
Whale optimization algorithm	Total production cost	IEEE 30, and 118-bus test systems	2018	[47]
Whale optimization algorithm	Voltage profile, fuel cost and severity function, line overload sensitivity index	IEEE 30-bus test system.	2020	[48]
An improved squirrel search algorithm	Convergence and local search ability	Thirty-two benchmark function and CEC 2014 functions	2019	[49]
Squirrel search algorithm	Generation cost and total real power loss	IEEE 30-bus	2020	[50]

3.2 Human-Inspired Optimization Techniques

This class of optimization techniques mimic human behaviour in terms of thinking and decision making. The human-inspired algorithms that have been used to solve OPF problems is presented in Table 2.

Table 2. Some of the literature review in respect of human inspired algorithms for OPF problem

Algorithm	**Objective Function**	**System**	**Year**	**Ref.**
Biogeography-based optimization	Fuel cost, emission, Voltage stability index, Power loss and voltage deviation	IEEE 30-bus, IEEE 57-bus	2015	[51]
League championship algorithm	Fuel cost, voltage profile, real power loss and stability enhancement index	IEEE 30-bus system and 62-bus Indian utility system network	2019	[52]
Imperialist competitive algorithm	power losses, index voltage profile, load balancing index and annual cost saving index	IEEE 33 and 69-buse systems	2017	[53]
Teaching learning-based optimization Algorithm	Power loss and voltage profile	5-bus PJM network	2017	[54]
Teaching-learning based optimization approach	Real power loss and voltage deviation	The IEEE 34-bus system and Ayepe 34-bus RDS	2019	[55]
Novel quasi-oppositional Jaya algorithm	Fuel cost, active power loss and voltage stability	IEEE 30-bus network	2018	[56]
Quasi oppositional teaching-learning based optimization	Active power generation cost	IEEE 30-bus	2016	[57]
Adaptive fuzzy logic controllers	Power system stability and control	Standard IEEE 30-bus test system		[58]
Chaotic immune symbiotic organisms search	Voltage profile improvement	The IEEE 26-bus RTS	2020	[59]
Quasi-reflection-based symbiotic organisms search algorithm	Fuel cost, loss, voltage stability index (VSI), voltage deviation (VD) and combined cost minimization	IEEE 30-bus and IEEE 118 bus test systems	2019	[60]
Symbiotic organism search algorithm	Real power loss	33-bus, 69-bus, 84-bus, and 119-bus	2020	[61]

3.3 Physic-Inspired Optimization Techniques

Physics-inspired algorithms are conceived fromlaws of physics or natural phenomena in space. The physics-inspired optimization methods used for OPF solutions are presented in Table 3.

Table 3: Some of the literature review in respect of physics inspired algorithms for OPF problem

Algorithm	**Objective Function**	**System**	**Year**	**Ref.**
Colliding bodies optimization	Total fuel cost with valve point loading effect and emission profile	IEEE 30-bus	2019	[62]
Improved colliding bodies optimization algorithm	Fuel cost, fuel cost with valve effect, emission, voltage stability index, active power loss, piecewise cost and voltage deviation	IEEE 30-bus, IEEE 57- IEEE 118-bus	2016	[63]
Opposition-based gravitational search algorithm	Fuel cost, transmission loss, the sum of total voltage deviation	Standard 26-bus test system	2015	[64]
Black-hole-based optimization approach	Fuel cost, voltage stability index, active power loss and voltage deviation	30-bus, Algerian 59-bus system	2014	[65]

3.4 Evolutionary-Inspired Optimization Techniques

This class of optimization techniques are product of derivation from mechanics of natural selection and genetics or living organisms. Some of the evolutionary-based optimization techniques that have been applied for OPF problems are presented in Table 4.

Table 4: Some of the literature review in respect of evolutionary-inspired algorithms for OPF problem

Algorithm	**Objective Function**	**System**	**Year**	**Ref.**
Enhanced self-adaptive differential evolution	Fuel cost, emission, voltage stability index, real power loss	IEEE 30-bus, IEEE 57-bus	2017	[66]
Improved evolutionary algorithm	Fuel cost and emission	IEEE 30-bus, IEEE 57-bus	2017	[67]
Differential evolution algorithm	Fuel cost, power loss, voltage stability and emission.	IEEE 30, 57 and 188-bus	2018	[68]
Multi-objective backtracking search algorithm	Fuel cost, voltage improvement, and voltage stability	IEEE 30 bus system	2017	[69]
Differential search algorithm	Fuel cost, emission, Voltage stability index, real power loss and voltage deviation	IEEE 9-bus, IEEE 30-bus IEEE 57-bus	2016	[70]
Genetic algorithm	Generation cost and system losses	IEEE 6-bus, 14 bus and 30-bus system	2019	[71]

3.5 Artificial Neural Networks (ANN) and Fuzzy Logic Approach

Artificial neural networks (ANNs) are computational methods that mimic the operation of living neural networks whereas the fuzzy set theory is a suitable natural tool that represent imprecise relationships. The optimizations methods based on ANNs and fuzzy logic approaches are presented in Table 5.

Table 5: Some of the literature review in respect of ANNs and fuzzy approach-inspired algorithms for OPF problem

Algorithm	Objective Function	System	Year	Ref.
Artificial neural network	Fuel cost, maximizethe voltage stabilitymargin	IEEE 30-bus	2003	[72]
Multi-objective fuzzy linear programming approach	Power loss, voltage stability	IEEE 30-busand IEEE 118-bus test systems	2016	[73]
Adaptive fuzzy logic controllers	System stability and power flow control	IEEE 30-bus system	2013	[74]
Hopfield neural network	Minimum deviations in real power generations and loads at buses	IEEE 6-bus	1996	[75]
Fuzzy linear programming	Fuel cost, maximizing the generation reserve	IEEE 5-bus, IEEE 14-bus	2005	[76]

3.6 Hybrid Optimization Techniques

Many hybrid optimization algorithms have been developed to take care of several challenges faced by singular techniques. Some of the hybrid optimization techniques applied in solving OPF problems are presented in Table 6.

Table 6: Some of the literature review in respect of hybrid-inspired algorithms for OPF problem

Algorithm	**Objective Function**	**System**	**Year**	**Ref.**
Hybrid genetic algorithm and particle swarm	Fuel cost, fuel cost with valve effect	IEEE 30 bus	2017	[77]
Moth swarm algorithm and gravitational search algorithm	Fuel cost and power loss	IEEE 30, 57 and 118-bus	2019	[78]
Hybrid cuckoo search algorithm and krill herd algorithm	Fuel costs, active power losses, voltage stability and voltage profile	IEEE 57 and IEEE 118-buses	2019	[79]
Hybrid firefly and particle swarm optimization algorithm	Generation cost, voltage profile improvement, voltage stability, active power loss and reactive power loss	IEEE 30-bus	2020	[80]
Hybrid imperialist competitive and grey wolf algorithm	Twelve different cases of simple and multi-objective OPF problems for modern power systems that involved wind and photovoltaic power generators.	IEEE 30-bus and IEEE 118-bus	2018	[81]
Newton-Raphson (NR) method and grey wolf optimization	Determination of Power flow and	IEEE 14-bus	2019	[82]

	optimal placement of UPFC			
Hybrid differential evolution and harmony search algorithm	Fuel cost, transmission loss and voltage stability index	IEEE 30, 118 and 300-bus	2018	[83]
Differential evolution particle swarm optimization (DEPSO)	Active power losses at fast computation time	IEEE 30, 57 and 118-bus systems	2018	[84]
Hybrid Imperialist competitive and grey wolf algorithm	Fuel cost, emission, voltage deviation, voltage stability active power loss,	IEEE 30-bus and IEEE 118-bus	2018	[85]
Squirrel search algorithm whale optimization (SSAWO)	Flow management (PFM) of a hybrid renewable energy source	Implemented in MATLAB/Simulink environment	2020	[86]
Whale versus genetic optimization algorithms	Production cost	IEEE 48-bus system	2019	[87]
DuponcheliaFovealis optimization (DFO) algorithm and enriched squirrel search optimization (ESSO)	power loss, voltage deviation and voltage stability.	IEEE 30-bus test system	2020	[88]

IV. CONCLUSION

This paper represents a comprehensive literature survey of various optimization methods especially the emerging techniques used in solving OPF problems. Despite brilliant progress made in ensuring improvement of traditional OPF methods characterized by poor convergence, stuck optimal solutions and weakness in handling qualitative constraints, there still exist some drawbacks due to its limitations in solving real-world large-scale power system problems.

The introduction of artificial intelligence methods in solving OPF problems is a deliberate effort by researchers towards addressing weaknesses faced by traditional methods as a result of continuous growth in complexity due to incorporation of FACTS devices and renewable energy sources into power system networks. The comprehensive algorithms, objective functions, testing systems, year of publications and references of all OPF methods reviewed are tabulated. This paper is very much beneficial to researchersin determining appropriate references as well as the state of the art in the field of OPF methods for the purpose of further research work and improvements.

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