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Efficiency improvements in meta-heuristic algorithms to solve the optimal power flow problem

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ABSTRACT

This paper presents three efficient approaches for solving the Optimal Power Flow (OPF) problem using the meta-heuristic algorithms. Mathematically, OPF is formulated as non-linear equality and inequality constrained optimization problem. The main drawback of meta-heuristic algorithm based OPF is the excessive execution time required due to the large number of load flows/power flows needed in the solution process. The proposed efficient approaches uses the concept of incremental power flow model based on sensitivities, and lower, upper bounds of objective function values. By using these approaches, the number of load flows/power flows to be performed are substantially, resulting in the solution speed up. The original advantages of meta-heuristic algorithms, such as ability to handle complex non-linearities, discontinuities in the objective function, discrete variables handling, and multi-objective optimization, are still available in the proposed efficient approaches. The proposed OPF formulation includes the active and reactive power generation limits, Valve Point Loading (VPL) effects and Prohibited Operating Zones (POZs) of generating units. The effectiveness of proposed approaches are examined on the IEEE 30, 118 and 300 bus test systems, and the simulation results confirm the efficiency and superiority of the proposed approaches over the other meta-heuristic algorithms. The proposed efficient approaches are generic enough to use with any type of meta-heuristic algorithm based OPF.

Introduction

The Optimal Power Flow (OPF) is an important tool to the power system operator for planning and operation studies. OPF is a large scale non-convex and non-linear optimization problem, that is complicated in practical applications in the presence of large number of discrete variables. The aim of OPF is to give the optimal settings of power system by optimizing an objective function while satisfying the equality and inequality constraints [1]. The AC-OPF is the heart of power markets, and it is solved in some form every year for system planning, every day for day-ahead markets, every hour, and even every 5 min.

OPF formulation was firstly developed by Dommel and Tinny [2] and then this problem has been handled by several researchers. OPF is a major extension to the conventional dispatch calculation. It can respect the system static security constraints, and can schedule active and reactive power [3]. Ref. [4] presents various challenges to the OPF problem from the user's perspective; planning perspective; extended applications of OPF; OPF application in deregulated electricity market; challenges to on-line OPF implementation; and control applications of OPF in Energy Management System (EMS). With the advances in computing power and solution algorithms, we can model more of the constraints and remove unnecessary constraints and approximations that were previously required to determine a solution in reasonable time. One example is non-linear voltage magnitude constraints that are modeled as linear thermal proxy constraints. In this paper, we refer to the full AC-OPF as an OPF that simultaneously optimizes both active and reactive power. Today, after 50 years the OPF problem was formulated, we still do not have a robust, fast solution method for the full AC-OPF. Determining a good solution method for full AC-OPF could potentially save tens of billions of dollars annually [5].

In many countries, power systems are operated under highly stressed conditions due to the continuous increase in load demand. Therefore, the utility companies are facing many problems like increase in total operating cost, real power losses, transmission line over loading, load voltage deviation, voltage instability problems [6,7]. To handle such issues, power system operators/utility companies require OPF methodology as fundamental tool for planning, operation and control of power system network. In the literature there are several conventional methods such as Newton based

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Nomenclature

$a_i,\ b_i,\ c_i$	fuel/generation cost coefficients of ith generating unit
$E_i,\ E_j$	complex bus voltages of generating units and load demands
u	vector of control/independent variables
x	vector of state/dependent variables
$f(x,u)$	objective function
$g(x,u)$	set of equality constraints
$h(x,u)$	set of inequality constraints
P_{Gi}	active power generation of ith generator
V_{Gi}	voltage magnitude of ith generator
T_i	tap settings of ith transformer
Q_{Ci}	VAR compensation of ith shunt capacitor
N_G	total number of generators in the system
N_T	number of regulating transformers
N_C	number of shunt VAR compensators
N_{zi}	number of prohibited operating zones of ith generator
P_{G1}	active power generation of slack generator
V_{Li}	voltage magnitude of ith load/demand bus
Q_{Gi}	reactive power output of ith generating unit
N_L	number of load/demand buses
nl	number of transmission lines
S_{ij}	MVA flow between bus i and bus j
S_{ij}^{max}	thermal limit of the line connected between bus i and bus j
P_{Gi}^0	initial power generation of ith generator
$P_{Di},\ Q_{Di}$	load active and reactive power
P_{loss}	real power losses in the system
$P_{Gi,k}^l,\ P_{Gi,k}^u$	lower and upper bounds of kth prohibited operating zone of generator i
ΔP_{Gi}	change in power generation of ith generator
$R_{Gi}^{up},\ R_{Gi}^{down}$	ramp up and ramp down limits of generating units in MW/h
$P_{Gi}^{max},\ P_{Gi}^{min}$	maximum and minimum generation capacities in MW s
$V_{Gi}^{max},\ V_{Gi}^{min}$	maximum and minimum limits of generator bus voltage magnitudes
$T_i^{max},\ T_i^{min}$	maximum and minimum limits of transformer tap settings
$B_{sh,i}^{max},\ B_{sh,i}^{min}$	maximum and minimum values of bus shunt susceptances
P_{ij}^{max}	power flow limit of line connected between buses i and j
ΔX	dependent voltages and angles changes
J	Jacobian matrix in Newton–Raphson load flow
P_{loss}^0	power loss of 'best-fit' chromosome/particle
ΔP_{loss}	change in power loss for the selected chromosome/particle from 'best-fit' chromosome/particle

programming technique [8], Linear programming method [9] and recently Interior Point Method (IPM) [10] to solve the OPF problem. The solution of OPF problem in the rectangular form by an IPM for non-linear programming is proposed in [11]. In [12], a non-linear complementarity method is proposed for solving the non-linear OPF problem. Ref. [13] presents a method for non-linear systems optimization based on a modified barrier function by the introduction of a safety barrier parameter into the IPM. The OPF solution based on the mathematical programming techniques are not guaranteed to converge to the global optimum of general non-convex OPF problem, and discrete variables. Gradient based techniques quickly converge to an optimum solution, but are not efficient for discontinuous or non-differentiable problems [14].

Even though, many works are still conducted in the fled of conventional methods, progressively meta-heuristic/evolutionary algorithms are becoming a serious and a reliable alternative for solving the OPF problem. The meta-heuristic algorithms differ from the classical search and optimization algorithm [14] in many ways. Classical search algorithms use a single solution updates in every iteration, and mainly use some deterministic transition rules for approaching the optimum solution. Such algorithms start from a random guess solution, and based on some pre-specified transition rule, the algorithm suggests a search direction which is arrived at by considering the local information. A unidirectional search is performed along the search direction, to find a best solution. The best solution becomes new solution, and the search is continued for a number of times. Some examples of meta-heuristic algorithms used for solving the OPF problem are: Genetic Algorithm (GA) [15], Evolutionary Programming (EP) [16], Particle Swarm Optimization (PSO) [17], Differential Evolution (DE) [18], Tabu Search (TS) [19], Biogeography based Optimization (BBO) [20], Simulated Annealing (SA) [21], etc. An evolving ant direction PSO algorithm is presented in [22] for solving the OPF problem with non-convex and non-smooth generator cost characteristics. In [23], Shuffle Frog Leaping Algorithm (SFLA) and SA is proposed for solving the OPF problem with non-smooth and non-convex generator cost characteristics, which is an optimization problem with many local optima.

Ref. [24] presents an energy saving dispatch strategy, based upon the OPF model, considering complex constraints, like Prohibited Operating Zones (POZs), Valve Point Loading (VPL) effects of generating units and the carbon tax of a power grid. In [25], the Teaching Learning Based Optimization (TLBO) algorithm is used for solving the OPF problem. Ref. [26] solves the OPF problem based on TLBO algorithm with Lévy mutation operator. An efficient Modified Differential Evolution (MDE) algorithm is used to solve the OPF problem with non-convex and non-smooth generator fuel cost curves is proposed in [27]. Modifications in mutation rule are suggested to original DE algorithm, that improve its rate of convergence with a better solution quality. A comprehensive Security Constrained Optimal Power Flow (SCOPF) model including more non-linear characteristics of the generating units and security constraints of power system is solved using DE algorithm is proposed in [28]. An improved group search optimization algorithm is proposed in Ref. [29] for solving the OPF problem considering VPL effects.

All evolutionary/meta-heuristic algorithms perform a separate load flow for every chromosome/particle. This may be utilized for the objective function evaluation or/and constraint feasibility check. Penalties are added as per the extent of infeasibility. This exercise is repeated for every chromosome/particle. Therefore, the total number of power flows to be run is enormous. This is the main reason for excessive computational burden in these evolutionary algorithms. Other parts of the algorithm need comparatively insignificant time.

It has been recognized that meta-heuristic algorithms perform much better, if we can make use of the domain specific knowledge of problem at hand in the computational process. In view of the above, this paper explores a possibility of reducing the computational burden by performing much lesser load flows. This is possible because the effects of control changes on the network are not likely to be too large. In that case, it should be possible to use