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Optimal power flow solutions using differential evolution algorithm integrated with effective constraint handling techniques

Partha P. Biswas[a,*], P.N. Suganthan[a], R. Mallipeddi[b,*], Gehan A.J. Amaratunga[c]

[a] *School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore*
[b] *Kyungpook National University, Daegu, South Korea*
[c] *Department of Engineering, University of Cambridge, UK*

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ABSTRACT

Optimal power flow (OPF) is a highly non-linear complex optimization problem where the steady state parameters of an electrical network need to be determined for its economical and efficient operation. The complexity of the problem escalates with ubiquitous presence of constraints in the problem. Solving OPF remains a popular but challenging task among power system researchers. In last couple of decades, numerous evolutionary algorithms (EAs) have been applied to find optimal solutions with different objectives of OPF. However, the search method adopted by EAs is unconstrained. An extensively used methodology to discard infeasible solutions found during the search process is the static penalty function approach. The process requires appropriate selection of penalty coefficients decided largely by tedious trial and error method. This paper presents performance evaluation of proper constraint handling (CH) techniques — superiority of feasibly solutions (SF), self-adaptive penalty (SP) and an ensemble of these two constraint handling techniques (ECHT) with differential evolution (DE) being the basic search algorithm, on the problem of OPF. The methods are tested on standard IEEE 30, IEEE 57 and IEEE 118-bus systems for several OPF objectives such as cost, emission, power loss, voltage stability etc. Single objective and weighted sum multi-objective cases of OPF are studied under the scope of this literature. Simulation results are analyzed and compared with most recent studies on the problem.

1. Introduction

Since its inception more than half a century ago, the optimal power flow (OPF) remains a widely cultivated topic among power system research communities across the globe due to the intriguing multi-faceted challenges it poses. The OPF is formulated as single or multi-objective problem of minimizing fuel cost, emission, transmission loss, voltage deviation etc. with constraints to be satisfied on generator capability, line capacity, bus voltage and power flow balance. Output of OPF program helps to determine the optimal operating state of a power system and the corresponding settings of control variables for economic and secure operation (Cai et al., 2008). Major control variables refer to the generated real power and generator bus voltages of the network. The latter controls the reactive power flow which is further compensated by adding capacitor banks of appropriate ratings to the network feeding usually the inductive loads. Voltage vectors of load buses and complex power flows in the lines determined during the process of optimization represent the system optimal operating state that would result in single or multiple objectives of the network being largely fulfilled. In summary, OPF involves intricate calculations with multiple variables and finding optimal solution while satisfying all constraints simultaneously is the most difficult part one encounters.

In earlier days, in use were classical numerical optimization methods which suffered from convexity, assumption of continuity and normally employed a gradient based search that converged to local optima. Revolution in numerical optimization introduced several evolutionary algorithms and techniques in last few decades. Most of these methods can successfully overcome the problem of premature convergence and are able to explore the search space in pursuit of global optima. OPF problem has seen application of numerous such evolutionary algorithms. A few standard objectives of OPF were optimized in Abaci and Yamacli (2016) for IEEE bus systems using differential search algorithm (DSA), an effective algorithm for real-valued numerical optimization problems. Daryani et al. (2016) improved standard group

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* Corresponding authors.
E-mail addresses: parthapr001@e.ntu.edu.sg (P.P. Biswas), epnsugan@ntu.edu.sg (P.N. Suganthan), mallipeddi.ram@gmail.com (R. Mallipeddi), gaja1@hermes.cam.ac.uk (G.A.J. Amaratunga).

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search optimization algorithm with adaptation to develop adaptive group search optimization (AGSO) to perform study on OPF. Chaib et al. (2016) applied backtracking search optimization algorithm (BSA) to perform OPF calculation with multi-fuel options and valve-point effect in thermal generators. Improved colliding bodies optimization (ICBO) algorithm (Bouchekara et al., 2016b) increased the number of colliding bodies in each iteration to enhance performance of the algorithm when applied to the problem of OPF. Mohamed et al. (2017) applied moth swarm algorithm (MSA) on numerous objectives of OPF for various bus systems to exhibit fast execution time and quick convergence of the algorithm. Chaos theory was incorporated in artificial bee colony to form chaotic artificial bee colony (CABC) in Ayan et al. (2015) and security constrained OPF was solved. Agent based gravitational search algorithm (GSA), where masses of agents play vital roles in guiding the search process, was adopted in Bhowmik and Chakraborty (2015) to solve OPF. To enhance exploration capability and population diversity of biogeography based optimization algorithm (BBO), adaptive real coded BBO (ARCBBO) was suggested in Kumar and Premalatha (2015) and applied to OPF problem. Dynamic adjustment of control parameters in adaptive partitioning flower pollination algorithm (APFPA) (Mahdad and Srairi, 2016) showed higher convergence speed and better accuracy than FPA for OPF solutions. In fuzzy harmony search algorithm (FHSA) (Pandiarajan and Babulal, 2016), effect of fuzzy based automatic adjustment of pitch adjustment rate and bandwidth of harmony search algorithm was studied in applying to the problem of OPF. Fuzzy based adaptive configuration of particle swarm optimization was established in Naderi et al. (2017) to solve a sub-problem of OPF. In solving OPF, Levy mutation strategy for teaching–learning based optimization (LTLBO) (Ghasemi et al., 2015) introduced a Levy mutation operator to enhance exploration at early search stages. Krill herd algorithm (KHA) (Roy and Paul, 2015) and its variant stud krill herd algorithm (SKH) (Pulluri et al., 2017, 2016) have also been popular in finding OPF solutions. Grenade explosion method (GEM) (Bouchekara et al., 2016a), glowworm swarm optimization (GSO) (Reddy and Rathnam, 2016) and Gbest guided artificial bee colony (GABC) (Roy and Jadhav, 2015) have also shown promising results for OPF as reported in respective literatures. Modified imperialist competitive algorithm (MICA) and teaching–learning algorithm (TLA) were hybridized (MICA-TLA) in Ghasemi et al. (2014) to improve local search and convergence of original ICA algorithm in finding OPF solutions. Multi-objective formulation and solution of OPF are found in Shaheen et al. (2016, 2017), Sedighizadeh et al. (2011) and Niknam et al. (2012). Our study focuses on single and weighted-sum multi-objective optimization cases of OPF. As evident from the literature review, either basic or the improved version of an algorithm was tried for real-parameter optimization problem of OPF. Each of the methods has its own strengths and weaknesses, and as depicted in No Free Lunch theorem (Wolpert and Macready, 1997), no single optimization method is capable of solving all types of real-world problems in an effective manner. Differential evolution (DE) and its variants are found to be among the top performing algorithms for single objective real parameter optimization as reflected in the results of CEC competitions (Liang et al., 2006; Li et al., 2008; Liang et al., 2013; Chen et al., 2014). We adopt DE as the basic search algorithm for optimization of OPF objectives. On the aspect constraint handling in OPF, literature (Daryani et al., 2016) defined security objective entwining a couple of inequality constraints as one of the multiple objectives to be minimized. Rest all literatures adopted either static penalty function approach or straight-away discarded the population members that led to constraint violation. As mentioned beforehand, penalty function approach is sensitive to selection of penalty coefficient. Small penalty coefficient over-explores the infeasible region, thus delaying the process of finding feasible solutions, and may prematurely converge to an infeasible solution. On the other hand, large penalty coefficient may not explore the infeasible region properly, thereby resulting in untimely convergence (Mallipeddi et al., 2012). In second approach, removal of infeasible population members would result in restricted scope of exploration and exploitation by the algorithm during the search process.

System security constraints gained importance in determining maximum loading limits of selected networks in some literatures using genetic algorithm (GA) (Acharjee, 2012), fuzzy logic (Mallick et al., 2013) and chaotic PSO (Acharjee et al., 2011). In optimal reactive power flow problem, voltage security constraint is considered in Rabiee and Parniani (2013). However, state-of-the-art constraint handling (CH) techniques in OPF problem remain largely untested. In present study, superiority of feasible solutions (SF), self-adaptive penalty (SP) methods and an ensemble of these two constraint handling techniques (ECHT) are applied to OPF problem with differential evolution (DE) (Storn and Price, 1997) as the basic search algorithm. Performance of these CH techniques is assessed, results are statistically compared and analyzed in detail. It is worthwhile to note that OPF problem has both equality and inequality constraints. Equality constraints are the power balance equations where both active and reactive power generated in the network must be equal to the demand and losses in the network. Convergence of power flow to a solution ensures that the power balance equations are automatically satisfied. Inequality constraints on slack generator power, reactive power output of the generators, bus voltage limits and line capacities need special attention. SF and SP methods of constraint handling work differently on their own way in handling inequality constraints. The motivation behind ECHT is to assess performance of both the constraint handling techniques by the combinatorial algorithm (i.e. ECHT) as one technique might work better than the other on some problems but not on all problems. Instead of user finding the superior performer out of the two for a particular problem, ECHT takes the burden to apply both the techniques and output close to, if not the best results obtained by one of the constituting techniques. The constraint handling (CH) methods are all successfully implemented in OPF problem on standard IEEE 30, IEEE 57 and IEEE 118-bus systems in our research presented in this paper. Generation cost, emission, real power loss and voltage stability of the network are all individually (as single objective) optimized. Study cases with multi-fuel options for the generators and valve-point loading effect are also considered. Although the study cases mostly consider all continuous variables, handling of discrete variables is also discussed and a study-case results with discrete variables are appended to the result section. Weighted sum approach is adopted in multi-objective optimization for selected study cases of both 30-bus and 57-bus systems. Simulation results are compared and critically investigated against constraint violation with most recent studies on optimal power flow (OPF) found in the literatures. A summary of contributions of this work can be listed pointwise as below:

- Applying CH techniques, superiority of feasible solutions (SF) and self-adaptive penalty (SP) individually to handle constraints while optimizing various objectives of OPF using differential evolution (DE).
- Applying ensemble method of CH techniques (ECHT) with SF and SP to handle constraints while optimizing various objectives of OPF using DE.
- Statistically compare the results and analyze the performance of SF-DE, SP-DE and ECHT-DE.
- Comparison of results of current study with most recent studies on OPF with similar experimental set-up.
- Critical analysis of results especially against constraint violation.

The organization of rest of the paper is done in following way. Section 2 includes a review of mathematical model including applicable constraints pertaining to OPF in the network. In Section 3, objectives and case studies performed for all the bus test systems are explained with useful numerical values. Description and application of constraint handling (CH) techniques are elaborated in Section 4. Section 5 discusses the simulation results and comparison followed by concluding remarks in Section 6.