UNIVERSITI PUTRA MALAYSIA

OPTIMAL POWER FLOW BASED ON FUZZY LINEAR PROGRAMMING AND MODIFIED JAYA ALGORITHMS

WARID SAYEL WARID ALZIHAYMEE

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By

WARID SAYEL WARID ALZIHAYMEE

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

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DEDICATION

This thesis is dedicated to my parents and my wife for their love and support. Without you, none of this would have been possible.

Warid S. Warid
March 2017

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the Degree of Doctor of Philosophy

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Chairman : Associate Professor Hashim Hizam, PhD
Faculty : Engineering

Optimal power flow (OPF) solution is a crucial tool in electric power networks operation. Recently, several factors, including the deregulated electricity markets, electricity consumption growth, the growing role of decision makers, and the increasing exploitation of distributed generation (DG), affect the operation strategies of many meshed power networks. These new conditions have raised the intricacy of OPF problems and necessitate a reliable optimization algorithm that can tackle economic and security concerns.

A set of modified and novel optimization algorithms are proposed in this thesis to deal with different single and multi-objective OPF problems. A new formulation for the multi-objective optimal power flow (MOOPF) problem that considers DG is introduced. The proposed algorithms have been examined and validated using the IEEE 30-bus and IEEE 118-bus test systems.

The first proposed approach is a multi-objective fuzzy linear programming optimization (MFLP) algorithm to solve the MOOPF problem. The results indicate that a unique and optimum solution with an excellent satisfaction for the extreme targets can be achieved. Secondly, the application and modification of a Jaya algorithm to deal with different OPF problems is presented. The main advantage of this algorithm is that no algorithm-particular controlling parameters are required for this algorithm. Two versions of the Jaya algorithm namely, the basic Jaya algorithm and novel quasi-oppositional Jaya (QOJaya) algorithm are proposed to solve different single objective OPF problems. In the proposed novel QOJaya algorithm, an intelligence strategy, namely, quasi-oppositional based learning (QOBL) is incorporated into the basic Jaya algorithm to enhance its convergence speed and solution optimality. For each considered case, results demonstrate that Jaya algorithm can produce a global optimum solution with rapid convergence. Meanwhile, the proposed QOJaya algorithm produces better results than the basic Jaya method in terms of solution optimality and convergence speed. In addition, two novel Jaya-based methods namely, the modified Jaya (MJaya) algorithm and quasi-oppositional modified Jaya (QOMJaya) algorithm are proposed to solve different MOOPF problems. In this work, a considerable contribution has been made in terms of modifying Jaya algorithm for handling MOOPF problems. Results show the applicability, potential, and efficacy of the proposed MJaya and QOMJaya algorithms in solving MOOPF problems.

Finally, two novel hybrid optimization algorithms namely, FLP-QOJaya algorithm for single objective OPF problems and MFLP-QOMJaya algorithm for MOOPF problems are proposed. For all single objective OPF cases, results demonstrate that the FLP-QOJaya algorithm outperforms the proposed Jaya and QOJaya algorithms in terms of solution quality, convergence speed and execution time. For multi-objective OPF problems, results show the supremacy of the proposed MFLP-QOMJaya over the proposed MJaya and QOMJaya algorithms in terms of producing superior Pareto optimal solutions and finer best compromise solutions.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Doktor Falsafah

ALIRAN KUASA OPTIMUM BERDASARKAN ALGORITMA PENGATURCARAAN LINEAR SAMAR DAN JAYA YANG DIUBAH SUAI

Oleh

WARID SAYEL WARID ALZIHAYMEE

Julai 2017

Pengerusi : Profesor Madya Hashim Hizam, PhD
Fakulti : Kejuruteraan

Penyelesaian bagi aliran kuasa optimum (OPF) merupakan perkara penting dalam operasi rangkaian kuasa elektrik. Baru-baru ini, beberapa faktor, termasuk pemasaran tenaga elektrik yang tidak dikawal selia, peningkatan penggunaan elektrik, peningkatan peranan pembuat keputusan dan eksploitasi penjanaan teragih (DG) yang meningkat, memberikan kesan kepada strategi operasi banyak rangkaian tenaga elektrik. Keadaan baharu ini telah menambah kerumitan masalah OPF dan memerlukan algoritma pengoptimuman yang boleh dipercayai untuk menangani kebimbangan ekonomi serta keselamatan.

Satu set algoritma pengoptimuman yang diubah suai dan baharu dicadangkan dalam tesis ini untuk menangani masalah OPF sama ada dengan satu objektif mahupun dengan pelbagai objektif. Rumusan baharu untuk masalah aliran kuasa optimum pelbagai objektif (MOOPF) yang mengambilkira DG diperkenalkan. Algoritma yang dicadangkan telah diperiksa dan disahkan dengan menggunakan sistem ujian IEEE 30-bus dan IEEE 118-bus.

Pendekatan pertama yang dicadangkan ialah algoritma pengoptimuman pengaturcaraan linear samar pelbagai objektif (MFLP) untuk menyelesaikan masalah MOOPF. Keputusan menunjukkan bahawa penyelesaian yang unik dan optimum dengan kepuasan yang sangat baik untuk sasaran yang tinggi dapat dicapai. Kedua, aplikasi dan pengubahsuaian algoritma Jaya untuk menangani masalah OPF yang berbeza dilaksanakan. Kelebihan utama algoritma ini adalah lantaran ketiadaan parameter kawalan algoritma tertentu yang diperlukan untuk algoritma ini. Dua versi algoritma Jaya ini, iaitu algoritma Jaya asas dan algoritma Jaya kuasi-tentangan (QOJaya) baharu dicadangkan untuk menyelesaikan masalah OPF satu objektif yang berbeza. Dalam algoritma QOJaya baharu yang dicadangkan, strategi kecerdasan,

yakni kuasi-tentangan berasaskan pembelajaran (QOBL) dimasukkan ke dalam algoritma Jaya asas untuk meningkatkan kepantasan penumpuan dan kecepatan penyelesaian. Bagi setiap kes yang dipertimbangkan, keputusan menunjukkan bahawa algoritma Jaya dapat menghasilkan penyelesaian optimum global dengan penumpuan yang pantas. Sementara itu, algoritma QOJaya yang dicadangkan menghasilkan keputusan yang lebih baik daripada kaedah Jaya asas dari segi kecepatan penyelesaian dan kepantasan penumpuan. Di samping itu, dua kaedah baharu berasaskan Jaya, iaitu algoritma Jaya yang diubah suai (MJaya) dan algoritma Jaya kuasi-tentangan yang diubah suai (QOMJaya) dicadangkan untuk menyelesaikan masalah MOOPF yang berbeza. Dalam kajian ini, usaha yang besar telah dibuat dari segi mengubah suai algoritma Jaya untuk menangani masalah MOOPF. Keputusan menunjukkan wujudnya ciri keterterapan, potensi dan keberkesanan MJaya dan algoritma QOMJaya yang dicadangkan dalam penyelesaian masalah MOOPF.

Akhir sekali, dua algoritma pengoptimuman hibrid baharu iaitu algoritma FLP-QOJaya untuk masalah OPF satu objektif dan algoritma MFLP-QOMJaya untuk masalah MOOPF dicadangkan. Untuk semua kes OPF satu objektif, keputusan menunjukkan bahawa algoritma FLP-QOJaya melebihi performa Jaya dan algoritma QOJaya yang dicadangkan dari segi kualiti penyelesaian, kecepatan penumpuan dan masa pelaksanaan. Untuk masalah OPF pelbagai objektif, keputusan menunjukkan keunggulan MFLP-QOMJaya berbanding dengan MJaya dan algoritma QOMJaya yang dicadangkan dari segi penghasilan penyelesaian optimum Pareto yang terbaik dan penyelesaian kesepakatan terbaik yang lebih teliti.

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Warid Sayel Warid
March 2017

I certify that a Thesis Examination Committee has met on 28 July 2017 to conduct the final examination of Warid Sayel Warid Alzihaymee on his thesis entitled "Optimal Power Flow Based on Fuzzy Linear Programming and Modified Jaya Algorithms" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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LIST OF ABBREVIATIONS

ACOPF	AC optimal power flow
CHPED	combined heat and power economic dispatch
DC-OPF	Direct Current optimal power flow
DG	distributed generation
DM	decision maker
DOPF	decoupled optimal power flow
ED	economic dispatch
EED	environmental/economic dispatch
EP	elitist population
FLP	fuzzy linear programming
MFLP	multi-objective fuzzy linear programming
MJaya	modified Jaya
MOOPF	multi-objective optimal power flow
OBL	opposition-based learning
OPF	optimal power flow
ORPD	optimal reactive power dispatch
QOBL	quasi-oppositional based learning
QOJaya	quasi-oppositional Jaya
QOMJaya	quasi-oppositional modified Jaya
QOP	quasi-oppositional population
SCED	security constrained economic dispatch
SCOPF	security constrained optimal power flow
VSEI	voltage stability enhancement index

CHAPTER 1

INTRODUCTION

1.1 Background of the Study

During the last two decades, electric power industry has been subjected to substantial developments that raise the necessity to modify power system operation strategies to deal with both economic and security concerns. The recent changes comprise the rapid growth of electricity demand, growing role of decision makers in power systems operations, rising penetration levels of distributed generation (DG), and liberalization of energy markets. Optimal power flow (OPF) solution is a promising tool in power grids operation that can be developed to optimally deal with these significant changes.

The sustained growth in electricity consumption is one of the insistent challenges facing the modern electric power systems around the world. In several countries, energy demand has exceeded the planned infrastructure expansion (Frank *et al*., 2012a). Over the last decade, frequent blackouts have been recorded worldwide (Yamashita *et al*., 2008). In many cases, these circumstances have been attributed to overloaded transmission lines (Yamashita *et al*., 2008).

Another rising challenge to operation strategies of modern power systems is the growing role of decision makers. Recently, power systems decision makers have to make important decisions concerning unfamiliar sets of conflicting and disproportionately objectives as many real-world power systems operation strategies engage the simultaneous optimization of such objectives.

Actually, fuzzy set optimization models offer appropriate tools that can be employed to deal with this type of problems. Using this tools, we can get realistic models that cope with given fuzzy objectives formulated based on the subjective goals and past knowledge of power system planners (Taghavi *et al.*, 2012).

At the same time, a widespread increase in the penetration of DG technologies has taken place in large interconnected power systems (Ghosh *et al.*, 2010). This trend appends further intricacy to the optimal power dispatch problems. At present, DG technologies offer economical and technical benefits such as transmission cost minimization, congestion mitigation, and loss reduction (Ghosh *et al.*, 2010; Sheng *et al.*, 2014). These advantages can perfectly be attained by carrying out a careful examination into the optimal placement and sizing of DG units. Thus, proposing modified formulations of the OPF problem that can be utilized to optimize all operational variables as well as penetration level of DG is a necessity.

Lastly, liberalization of energy markets is another important issue to discuss. Recently, many countries around the world have imposed significant reforms on their electric power sectors to terminate the monopoly (Singh and Chauhan, 2011). Legislators have passed laws allowing energy supplier to offer consumers the opportunity to select their electrical provider. In this competitive environment, generation cost minimization is a top precedence. In fact, the deregulated electricity markets require powerful and intelligent optimization methods for OPF solution that can tackle with the diversity of market participants and requirements of real-time processing.

Over the last three decades, OPF solution has become the leading tool in electric power networks operation and planning. Numerous OPF formulations have been proposed to optimize different objectives through optimum settings of the network control variables at the same time as enforcing operational constraints within their specified limits. The OPF problem is a highly non-linear and non-convex multimodal optimization problem, i.e. there are more than one local optima and one unique global optima (Abou El Ela *et al.*, 2010). It is worth mentioning that the complexity of dealing with the OPF problem extensively raises with increasing system size (Frank *et al.*, 2012a). Furthermore, as earlier stated, the current substantial developments have significantly enlarged the intricacy of power systems operation.

Recently, the multi-objective optimal power flow (MOOPF) solution has gained considerable interest in power utilities because many real-world power system operation issues involve the simultaneous optimization of multiple, competing, and incommensurable objectives (Hazra and Sinha, 2011; Chen *et al.*, 2014). This solution is widely considered as an essential tool for system operators to maintain an economical, secure, and reliable operation of modern power systems (Khorsandi *et al.*, 2013). However, the complexity of solving the OPF problem has conspicuously been increased.

To sum up, proposing competent optimization techniques that can effectively solve new models of the single and multi-objective OPF problems with considering the recent substantial developments in power systems sector is a necessity.

1.2 Problem Statement

Many classical solution methods have been utilized to deal with the OPF problem like gradient algorithms, Newton method, linear programming (LP), quadratic programming (QP), decomposition algorithms, and interior point methods (IPMs). Although these methods can achieve the globally optimal solution in some cases, they have certain shortcomings, such as trapping in local optima, inability to tackle non-differentiable goal functions, and high sensitivity to initial search points. Thus, proposing alternative methods to address the above-mentioned drawbacks is necessary. Later, to avert the drawbacks of the classical optimization methods, various nature-inspired optimization techniques have been suggested and utilized to deal with OPF problems, like genetic algorithm (GA), particle swarm optimization (PSO), differential evolution (DE), harmony search (HS) algorithm, artificial bee colony (ABC) algorithm, and gravitational search algorithm (GSA). These algorithms are more efficient in discovering global solutions to different nonlinear OPF problems. Unfortunately, regardless of their advantages, each of these population-based optimization algorithms requires appropriately tuned algorithm-specific controlling parameters, because improper tuning of such parameters will raise the computational burden (i.e. affects the convergence property) or leads to a sub-optimal solution. In addition, many of these population-based algorithms produce infeasible solutions for many kinds of OPF problems in terms of violation of operational variables constraints. In fact, the existing heuristic optimization methods lack an effective technique for enforcing constraints. Hence, introducing powerful population-based optimization algorithms that can effectively solve the OPF problem, do not involve controlling parameters to be tuned, and strictly enforce security constraints within their permissible limits is important.

More recently, many of hybrid optimization methods have been proposed to deal with different OPF problems. The main aim of proposing these hybrid methods is to combine the benefits of each approach, leading to more efficient algorithms. To contribute to the field of OPF solution, new powerful hybrid algorithms that can perfectly address the above-mentioned drawbacks of the classical and population-based optimization are required.

Overall, proposing competent optimization techniques that can avert the drawbacks of existing optimization methods and effectively solve different OPF/MOOPF problems considering the recent substantial developments in power systems sector is a necessity.

1.3 Research Aim and Objectives

The aim of this thesis is to develop a set of modified and novel optimization algorithms for solving different single and multi-objective OPF problems. The main objectives of this thesis are:

1. To design an efficacious multi-objective fuzzy linear programming (MFLP) approach for OPF considering DG.

2. To solve different single-objective OPF problems using the basic Jaya algorithm and two novel Jaya-based algorithms namely, quasi-oppositional Jaya (QOJaya) algorithm and FLP-QOJaya algorithm.

3. To develop novel Jaya-based optimization methods namely, modified Jaya (MJaya) algorithm, quasi-oppositional modified Jaya (QOMJaya) algorithm, and MFLP-QOMJaya algorithm for solving different multi-objective OPF problems.

1.4 Motivation

This research was motivated by several reasons:-

1. The optimization process of the existing population-based optimization methods that have been used to solve the OPF problem require proper tuning of different algorithmic parameters. The incorrect tuning of such parameters results in rising the computational burden or produces local optima solution. Thus, one of the main motivations for conducting this work is using a new meta-heuristic optimization method algorithm that does not involve any algorithm-particular parameters to be tuned. This research work has not been yet studied.

2. Producing real and well-distributed optimum Pareto front when solving the MOOPF problem is a very intricate task. Unfortunately, none of the existing population-based optimization algorithms that have proposed to solve the MOOPF problem can guarantee producing a true and well-distributed Pareto optima set that is very close to the global Pareto-front. Furthermore, as mention above, the existing methods require appropriate tuning of different algorithmic parameters. The controlling process of such parameters is not trouble-free. Thus, suggesting new optimization algorithms that can effectively solve the MOOPF problem, is a necessity.

3. Many heuristics algorithms may lead to infeasible solutions for several OPF problems in terms of violation of dependent variables constraints, as reported in (Rezaei Adaryani and Karami, 2013; Christy and Raj, 2014; Radosavljević *et al.*, 2015). Generally, the stochastic-based optimization algorithms lack powerful approaches that strictly enforce the operational constraints. Consequently, modifying an approach that strictly handles all the constraints is important.

4. The increasing role of decision makers in power systems operations has motivated the research efforts in terms of developing efficient optimization algorithms to solve the OPF/MOOPF problems considering DM's experience and preferences.

5. With the increasing penetration levels of DG in electric power systems, updating the current formulations of OPF problems to deal with the DG effect is crucial. Notably, the DG effect has not been incorporated into the existing OPF formulations while considering all other classical control variables. In other words, the previous optimization algorithms have not been examined DG effect when solving the ordinary OPF problem. Thus, proposing a modified formulation of the OPF problem that considers DG effect is significant.

6. Both of the classical and population-based optimization algorithms that were proposed to deal with many OPF problems have certain shortcomings. Thus, one of the key motivations for carrying out this research is the necessity to

develop hybrid algorithms that can combine the benefits and avert the drawbacks of the existing optimization methods.

1.5 Scope and Limitation of the Study

The scope of the research is limited to proposing new effective optimization algorithms to deal with different single and multi-objective AC optimal power flow (ACOPF) problems without and with considering DG effect. Particularly, three single objective optimization cases are chosen for the single OPF solution: generation cost minimization, real power loss reduction, and voltage stability improvement. Meanwhile, different cases of multi-objective OPF using four combinations of the above set of objectives are considered for simultaneous optimization. To validate the proposed algorithms, the scope of this thesis also covers a comprehensive comparison with other approaches presented in the literature. Notably, as the OPF is the most significant and extensively investigated problem among power systems operation problems, other power flow problems like optimal reactive power dispatch (ORPD), economic dispatch (ED), and security constrained economic dispatch (SCED) were not studied in this thesis.

Furthermore, to deal with the proposed formulation of OPF problem that considers DG, the scope of this research includes developing a sensitivity-based methodology to identify the candidate location(s) for DG units placement. Meanwhile, the task of finding the optimal DG size will be performed by the proposed OPF approaches by considering active power generation of DG units as control variable. Owing to the space limitations of the thesis, only two standard power systems namely, the modified IEEE 30-bus and IEEE 118-bus networks are considered for examination the effectiveness of the proposed algorithms. It is worth mentioning that the IEEE 118-bus test system is widely considered as a large-scale power system.

1.6 Contributions of the Study

In this thesis, significant contributions to the field of the solution of OPF and MOOPF problems have been made. The main academic contributions of this thesis to the scientific community and its novelty can be stated as follows:-

1. An efficient multi-objective fuzzy linear programming (MFLP) approach to solve a realistic scheme for the multi-objective OPF problem without and with considering DG is proposed. A considerable contribution has been made in this field in terms of enhancing exploration capability of the proposed MFLP algorithm, modeling new combinations of optimal OPF objectives, combining DG effect, as well fuzzification of the objectives.

2. The application of a new effective meta-heuristic optimization method namely, Jaya algorithm to deal with different single objective OPF problems is proposed and presented for the first time in this thesis. Unlike other population-based optimization methods, no algorithm-particular controlling

parameters are required for this algorithm. Furthermore, a novel quasi-oppositional Jaya (QOJaya) algorithm for solving single objective OPF problems is proposed.

3. A novel modified Jaya (MJaya) algorithm for solving multi-objective OPF problems is proposed. This thesis makes a considerable contribution in terms of upgrading the basic Jaya algorithm to deal with multi-objective optimization problems (in particular, the MOOPF problem).

4. Another novel version of the Jaya algorithm, namely quasi-oppositional modified Jaya (QOMJaya) algorithm is proposed for solving the multi-objective OPF problems. The main contribution is to produce more superior Pareto optimal fronts for the considered MOOPF problems.

5. A novel hybrid optimization algorithm namely, FLP-QOJaya algorithm for single objective OPF problem is proposed.

6. Another novel hybrid optimization algorithm namely, MFLP-QOMJaya algorithm for multi-objective OPF problem is proposed. The main contribution is the algorithm combines the benefits for each of the proposed MFLP and QOMJaya approaches, leading to a more competent algorithm in terms of producing more finer optimal Pareto fronts.

1.7 Thesis Layout

The remainder of this thesis is organized as follows. Chapter 2 is literature review, beginning with an overview of the optimal power flow problem. Then, the classical, heuristic, and hybrid optimization methods that have previously been proposed for solving different OPF problems are critically reviewed, compared, and summarized.

Chapter 3 presents the proposed methodologies, starting with introducing the proposed problem formulation. Then, a sensitivity-based methodology for the optimal Placement of DG is presented. Next, an efficient MFLP Algorithm for the MOOPF Problem considering DG is introduced. This section has been broken down into four subsections: the role of decision makers, fuzzification of objective functions, the proposed optimization model, and the solution procedure. Afterward, the application of the basic Jaya algorithm and the proposed novel QOJaya algorithm to the OPF Problem are demonstrated. Subsequently, the proposed optimization processes of the modified Jaya (MJaya) algorithm and the novel QOMJaya algorithm are introduced with their application to the MOOPF problem. Finally, the chapter ends with the proposed novel hybrid FLP-QOJaya and MFLP-QOMJaya algorithms for OPF and MOOPF problems, respectively.

The simulation results, discussions, and comparisons of the proposed algorithms with approaches reported in the literature are presented and described in Chapter 4. Two standard systems namely, the modified IEEE 30-bus test system and the IEEE

118-bus test system are considered for testing, validation, and demonstration the efficacy of the proposed algorithms. Finally, the conclusions regarding the implementation of the proposed algorithms are drawn and recommendations for future research are given in Chapter 5, respectively.

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