**UNIVERSITI PUTRA MALAYSIA**

# *HYBRID FIREFLY AND PARTICLE SWARM OPTIMIZATION ALGORITHM FOR MULTI-OBJECTIVE OPTIMAL POWER FLOW WITH DISTRIBUTED GENERATION*

**ABDULLAH KHAN**

**FK 2022 95**

# HYBRID FIREFLY AND PARTICLE SWARM OPTIMIZATION ALGORITHM FOR MULTI-OBJECTIVE OPTIMAL POWER FLOW WITH DISTRIBUTED GENERATION

**By**

**ABDULLAH KHAN**

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

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Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of
the requirement for the degree of Doctor of Philosophy

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**ABDULLAH KHAN**

**January 2022**

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An optimal power flow (OPF) solution is an essential approach in electric power system operation. Electric service providers are continually working on power generation planning to improve different factors: electricity demands, deregulation of the markets, increasing utilization of distributed generation (DG), and the increasing role of decision-makers. These factors affect the operation plans, have raised the OPF problems' complexities, and require an unfailing optimization algorithm to solve economic and security concerns in different interconnected power systems.

This thesis proposes and simulates the three novel optimization algorithms to handle DG allocation, different single-objective, and multi-objective OPF problems. A new formulation for the multi-objective optimal power flow (MOOPF) problem and DG unit allocation in the power system is also presented. The suggested approaches have been scrutinized and confirmed based on the IEEE 30-bus and 57-bus test systems.

The requirement of the DG installation in the distributed system is to fulfill the power network operation necessities, generally to improve the total loss rises in the system. The DG units have to be allocated with optimal sizes in the network to reach maximum efficacy.

A new meta-heuristic optimization technique called the Slime Mould Algorithm (SMA) approach has a high convergence rate or a few iterations and superior optimization indices analyzed against other algorithms. It can guarantee to enhance the efficiency of exploitation and exploration, based on a sustained balance between exploitation and exploration, to achieve promising statistical results. Therefore, the SMA method is redesigned for optimal location and sizing based on the total active power loss of the systems. And optimal results for single, two, and three DG allocation cases are obtained.

The simulated results from the proposed DG-based SMA approach are also matched with the calculated solutions of the biogeography-based optimization (BBO) approach. The comparison and graphical analysis showed that the total active power loss, required iterations, percentage of the total loss minimization, and DG installed capacities are relatively improved using the suggested SMA algorithm based on the optimal DG unit sizing and location problem in the power systems.

Secondly, a novel and competent meta-heuristic, population-based Hybrid Firefly Particle Swarm Optimization (HFPSO) algorithm is designed to handle various convex and non-linear, single-objective OPF problems. The HFPSO technique hybridizes the Firefly Optimization (FFO) algorithm and the Particle Swarm Optimization (PSO) method to improve the exploitation and exploration strategies and enhance the convergence rate. Moreover, the achieved results revealed the efficacy of the suggested HFPSO algorithm considering the acceptable convergence rate. The statistical examination demonstrated that the proposed method is a reliable and robust optimization approach to deal with OPF problems. Thus, evaluating the applicability and performance of the HFPSO algorithm, it is evident that the proposed method provides a better tool to solve OPF problems of electric power networks.

Finally, a crowding distance and non-dominated-sorting-based multi-objective hybrid firefly & particle swarm optimization (MOHFPSO) algorithm is designed for MOOPF problems. The proposed algorithm is simulated for simultaneous OPF-based conflicting objectives, respectively. Besides, the approach's acquired optimized results are also compared against the simulated original OPF-based MOPSO method and the optimal values of the present literature work to authenticate its effectiveness. Comparing and analyzing the resultant optimal values indicated the proposed MOHFPSO method's dominance in the optimal solution. Consequently, the proposed algorithm with a non-dominated sorting approach can be efficiently applied for small and large power networks.

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

# ALGORITMA PENGOPTIMUMAN HIBRID KELIP-KELIP DAN PARTIKEL SWARM UNTUK ALIRAN KUASA OPTIMAL PELBAGAI OBJEKTIF DENGAN GENERASI TERAGIH

Oleh

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**Januari 2022**

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Penyelesaian aliran daya optimum (OPF) adalah pendekatan penting dalam operasi sistem kuasa elektrik. Penyedia perkhidmatan elektrik terus berusaha untuk merancang penjanaan tenaga untuk menambahbaik pelbagai faktor: permintaan elektrik, deregulasi pasaran, peningkatan pemanfaatan penjanaan agihan (DG), dan peningkatan peranan pembuat keputusan. Faktor-faktor ini mempengaruhi rancangan operasi, telah meningkatkan kerumitan masalah OPF, dan memerlukan algoritma pengoptimuman yang berterusan untuk menyelesaikan masalah ekonomi dan keselamatan dalam sistem kuasa yang saling berkaitan.

Tesis ini mencadangkan dan mensimulasikan tiga algoritma pengoptimuman baharu untuk menangani peruntukan DG, masalah OPF objektif tunggal dan pelbagai objektif yang berbeza. Rumusan baru untuk masalah aliran daya optimum pelbagai objektif (MOOPF) dan peruntukan unit DG dalam sistem kuasa juga ditunjukkan. Pendekatan yang dicadangkan telah diteliti dan disahkan berdasarkan sistem ujian IEEE 30-bus dan IEEE 57-bus.

Keperluan pemasangan DG dalam sistem yang diedarkan adalah untuk memenuhi keperluan operasi jaringan kuasa, secara umum untuk memperbaiki jumlah kerugian yang meningkat dalam sistem. Unit DG harus ditempatkan secara ukuran optimum dalam rangkaian untuk mencapai keberkesanan maksimum.

Teknik pengoptimuman meta-heuristik baru iaitu *Slime Mold Algorithm* (SMA) mempunyai kadar penumpuan tinggi atau beberapa lelaran dan indeks pengoptimuman unggul yang dianalisis terhadap algoritma lain. Ini dapat menjamin untuk meningkatkan kecekapan eksploitasi dan eksplorasi, berdasarkan keseimbangan antara eksploitasi dan eksplorasi, untuk mencapai hasil statistik yang menjanjikan. Oleh itu kaedah SMA direka bentuk semula untuk lokasi dan ukuran yang optimum berdasarkan kehilangan kuasa aktif keseluruhan sistem. Dan hasil yang optimum untuk kes peruntukan tunggal, dua, dan tiga DG diperoleh. Hasil simulasi dari pendekatan SMA berdasarkan DG yang diusulkan juga dipadankan dengan penyelesaian yang dihitung dari pendekatan pengoptimuman berdasarkan biogeografi (BBO). Perbandingan dan analisis grafik menunjukkan bahawa jumlah kehilangan daya aktif, iterasi yang diperlukan, peratusan pengurangan kerugian total, dan kapasiti pemasangan DG relatif lebih baik menggunakan algoritma SMA yang dicadangkan berdasarkan ukuran unit DG dan masalah lokasi dalam sistem kuasa.

Kedua, algoritma novel dan meta-heuristik, berdasarkan populasi *Hybrid Firefly Particle Swarm Optimization* (HFPSO) berasaskan populasi dirancang untuk menangani pelbagai masalah OPF cembung dan tidak linear. Teknik HFPSO menghidupkan algoritma *Firefly Optimization* (FFO) dan kaedah *Particle Swarm Optimization* (PSO) untuk meningkatkan strategi eksploitasi dan penerokaan dan meningkatkan kadar penumpuan. Lebih-lebih lagi, hasil yang dicapai menunjukkan keberkesanan algoritma HFPSO yang dicadangkan dengan mempertimbangkan kadar penumpuan yang boleh diterima. Pemeriksaan statistik menunjukkan bahawa kaedah yang dicadangkan adalah pendekatan pengoptimuman yang boleh dipercayai dan mantap untuk menangani masalah OPF. Oleh itu, dengan menilai kebolehlaksanaan dan prestasi algoritma HFPSO, terbukti bahawa kaedah yang dicadangkan menyediakan alat yang lebih baik untuk menyelesaikan masalah rangkaian kuasa elektrik OPF.

Akhir sekali, algoritma jarak jauh dan algoritma *multi-objective hybrid firefly dan particle swarm optimization* (MOHFPSO) berasaskan jarak yang tidak didominasi dan disusun dirancang untuk masalah MOOPF. Algoritma yang dicadangkan disimulasikan untuk objektif bertentangan berasaskan OPF serentak. Selain itu, hasil pendekatan yang dioptimumkan juga dibandingkan dengan kaedah MOPSO berasaskan OPF asli yang disimulasikan dan nilai optimum ini berfungsi untuk mengesahkan keberkesanannya. Membandingkan dan menganalisis nilai optimum yang dihasilkan menunjukkan keberkesanan kaedah MOHFPSO yang dicadangkan dalam penyelesaian optimum. Hasllnya, algoritma yang dicadangkan dengan pendekatan penyisihan yang tidak didominasi dapat diterapkan secara efisien untuk rangkaian kuasa kecil dan besar.

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| | |
|---|---|
| ABC | artificial bee colony algorithm |
| $\mathrm{a_i}, \mathrm{b_i}, \mathrm{c_i}$ | fuel cost coefficients of the *i-th* generator |
| AFPA | adaptive flower pollination algorithm |
| BHBO | black-hole-based optimization |
| DSM | different search method |
| FFO | fruit fly optimization |
| FC | total fuel cost as an objective function |
| $F_{ij}$ | component of complex a matrix |
| GSA | gravitational search algorithm |
| $G_{ij}, B_{ij}$ | conductance and susceptance amid the node *i* and *j* |
| HFPSO | hybrid firefly & particle swarm optimization |
| ICB | improved colliding bodies |
| IEEE | Institute of Electrical and Electronics Engineers |
| KHA | krill herd algorithm |
| $L_a$ | voltage stability enhancement as an objective function |
| MOHFPSO | multi-objective hybrid firefly and particle swarm optimization |
| MOPSO | multi-objective particle swarm optimization |
| MODE | decomposition-based modern meta-heuristic algorithms |
| MOTLBO | multi-objective teaching learning based optimization |
| MOMICA | multi-objective modified imperialist competitive algorithm |
| MOHSA | multi-objective harmony search algorithm |
| MOALO | multi-objective ant lion optimizer |
| MJAYA | modified jaya algorithm |
| MODE | multi-objective differential evolution |

| | |
|---|---|
| N | No of lines |
| NSGA | non-dominated sorting genetic algorithm |
| OPF | optimal power flow |
| $P_{gi}, P_{di}$ | active power of a generator and load of the *i-th* power line |
| $P_{gi}$ | real power of the *i-th* generator |
| $P_{gi}^{mn},\ P_{gi}^{mx}$ | limits of real power based on the *i-th* generator |
| PL | active power loss as an objective function |
| $Q_{gi},\ \ Q_{di}$ | reactive power of a generator and load of the *i-th* power line |
| $Q_{gi}$ | reactive power of the *i-th* generator |
| $Q_{gi}^{mn},\ \ Q_{gi}^{mx}$ | limits of reactive power based on the *i-th* generator |
| $Q_{Ci}$ | VAR injection of the *i-th* shunt capacitor |
| $Q_{Ci}^{mn}, Q_{Ci}^{mx}$ | limits of VAR injection based on the *i-th* shunt capacitor |
| SSO-PSO | salp swarm optimization with particle swarm optimization algorithm |
| $S_{linei}, S_{linei}^{mx}$ | apparent and maximum apparent power of the *i-th* power line |
| TLBO | teaching learning based optimization |
| $T_i$ | turn-ratio of the *i-th* transformer |
| $T_i^{mn},\ \ T_i^{mx}$ | limits of turn-ratio based on the *i-th* transformer |
| UPM | Universiti Putra Malaysia |
| VD | minimization of  bus voltage deviation as an objective function |
| $V_{gi}^{mx}, V_{gi}^{mn}$ | limits of voltage based on the *i-th* generator |
| $V_{gi}$ | voltage of the *i-th* generator |
| $V_{l_i}$ | voltage magnitude of the *i-th* load bus |
| $V_{l_i}^{mn}, V_{l_i}^{mx}$ | limits of voltage based on the *i-th* load bus |

# CHAPTER 1

# INTRODUCTION

## 1.1 Background of the study

The electrical power sector has evolved in the previous three decades, demanding the requirement to change the power network operation schemes to handle security and economic interests. The current variations consist of continuous growth of the electrical power loads, increasing involvement of decision-makers in the system operation field, relaxation of the power market, and expanding incoming distributed generation (DG) units. These substantial variations can be handled with a capable approach named optimal power flow (OPF) solution in the power operation field.

The continuous advancement in power demand is a constant challenge in the present power system. Load demand has surpassed the installed structure growth in many countries (Frank *et al*., 2012b). The continuous shutdown has been noted worldwide over the previous decade (Yamashita *et al*., 2008). These situations are burdened on power lines in various circumstances (Yamashita e*t al*., 2008).

Increasing demands of decision-makers are an additional growing burden to operation schemes of the present power network. The energy decision-maker makes essential estimations regarding conflicting objectives as various practical system operation schemes involve concurrent optimization of these goals.

Allocation of DG equipment in interconnected energy systems has simultaneously increased (Ghosh, Ghoshal, & Ghosh, 2010). The installation of DG technologies has further increased the complexities of dispatching optimal power problems. The system's present DG allocation deals with technical and economic issues and offers benefits, such as loss reduction, congestion mitigation, and transmission cost reduction (Ghosh *et al.*, 2010; Sheng *et al.*, 2014). These problems can be solved by the optimal location and capacity of DG units. Therefore, a formulation that can optimize all dependent variables and allocate penetrated DG units is required for the OPF problems.

Finally, the relaxation of power business is a significant issue to address. Various countries have introduced essential improvements in their energy markets to stop the monopoly in the last few years (Archana Singh, 2011). Legislation has been passed to allow the power providers to facilitate the users to choose their energy suppliers. Generation cost optimization in this private-enterprise situation is the main priority. The liberalized energy enterprises need intelligent and influential optimization approaches for OPF solutions to handle the different competitors with real-time simulation necessities.

The OPF solution is becoming a basic method over the past thirty years to deal with planning and operation in the electricity market. Various OPF mathematical equations are suggested to improve numerous goals over optimal adjustment of the power systems control variables, simultaneously applying constraints for operational purposes within stated limits. These optimization problems are highly non-convex multi-modal, and non-linear, with many local optima and specific global optima (Abou El Ela *et al.*, 2010). It is essential to state that the intricacy to deal with the OPF raises as the system size increases (Frank *et al.*, 2012b) because of the present growth.

Various energy systems operation problems consist of more than one different competitive goal to optimize at the same time; therefore, the multi-objective optimal power flow (MOOPF) approach has acquired attention in power services (Hazra, J., Sinah, 2011; H. Chen, *et al.*, 2014) . This method is broadly used as a fundamental approach in network operation to enhance the modern energy sector's reliability, security, and economy (Khorsandi *et al.*, 2013). There are many growing issues and complexities to deal with the OPF issues.

To summarize, proposing proficient optimization methods to solve the single-objective and multi-objective OPF issues based on penetration of DG units considering the present substantial growth in the power field is a requirement.

## 1.2 Problem Statement

Different optimization algorithms based on OPF problems and DG units allocation are designed and applied for the electrical power system. A genetic algorithm (GA) has been proposed for the unity power factor network to obtain optimal sizing and location of DG unite, based on losses reduction and power enhancement. The main drawback of the approach is its slow convergence because of unbalanced exploration and exploitation. Another proposed approach, called Ant Colony optimization, is used to locate the site of the DG unit with the network reliability improvement as an objective function. The method cannot find the size of the DG unit simultaneously. Many authors have modeled various methods to find the capacity and location of DG units, one of these approaches is the particle swarm optimization (PSO) algorithm. The met heuristic methods are based on a randomly generated population with two stages to update the particle position and calculate its velocity. The PSO needs less memory and simulation time. However, one of its drawbacks is partial optimization.

The shuffled frog leaping population-based method is used for optimum sizing and location of DG units. The approach is applied for handling various multi-modal, nonlinear, non-differentiable, and complex problems. However, the main limitations of the method are premature and slow convergence because of unbalancing between exploration and exploitation. Genetic algorithm (GA) is an easy technique widely applied for DG optimal integration. The approach can solve the non-continuous, non-differential, and non-dimensional problems. The optimum values can be achieved in real-time but with disadvantages of low convergence speed and random solutions. The bacterial foraging optimization approach (BFOA) has been applied to handle different power system optimization cases due to its capacity in searching for the favorable region of the solution space. However, due to the complexity of the technique, the authors are interested in designing a straightforward approach to improve the convergence rate.

The above algorithms have been employed to effectively solve DG sources' optimum allocation problems. However, each approach has its disadvantages in terms of convergence time, unbalance between exploration/exploitation, simulation time, small-scale network effectiveness, and economic aspects.

Many developers designed and used classical gradient methods to solve the OPF problems, such as the newton method, quadratic programming (QP), linear programming (LP), interior-point methods (IPMs), and decomposition algorithms. These techniques get the optimum global point as a solution in particular cases. However, these approaches have some drawbacks, such as failure to handle the non-differentiable objective functions, confining in local optimal points, and being very sensitive to initial search or exploration points. Therefore suggesting substitute approaches to avert the mentioned weaknesses is essential. Subsequently, to remove the shortcoming of the above classical optimization techniques, different natural-inspired optimization algorithms are proposed and used to tackle the OPF problems, such as particle swarm optimization (PSO) method, genetic algorithm (GA) algorithm, harmony search (HS) method, gravitational search approach (GSA), artificial bee colony (ABC), and differential evolution (DE) technique. These stated techniques effectively obtain optimized values of various non-linear OPF objectives. Unfortunately, apart from their benefits, some of these methods are ineffective for global optimization, such as trapping in local optima because of unbalancing between exploration/exploitation and premature convergence for various OPF problems.

Recently, various hybrid optimization algorithms have been suggested to handle several OPF problems. The basic idea behind offering these hybrid approaches is to take advantage of each method, such as a balance between exploration/exploitation and design a more effective method that can deal with the population and classical-based algorithms weaknesses in the OPF field.

To sum up, proposing efficient optimization methods that can remove the shortcomings of present optimization algorithms and successfully solve various SOOPF/MOOPF problems and DG units allocation is required because of the current essential growth in the energy sector.

## 1.3 Research Aim and Objectives

The primary purpose of this thesis is to design and develop optimization methods to allocate DG units and solve various single and multi-objective OPF problems. The thesis’s main objectives are:

1. To utilize an efficient Slime Mould Algorithm (SMA) based on optimal location and sizing of different numbers of DG units.

2. To apply a population-based Hybrid Firefly Particle Swarm Optimization (HFPSO) algorithm for various single-objective OPF problems.

3. To develop and use a technique based on Hybrid Firefly Particle Swarm Optimization (HFPSO) algorithm to deal with multi-objective OPF problems.

## 1.4 Motivations

Various reasons motivated this research: -

1. The wrong location and size of the DG units cause power loss, reverse power flow, voltage instability, power quality problems, and it could lead to complete system failure in an energy system. Therefore, proposing an approach to deal with DG's optimal size and the suitable location of the system to reach maximum efficiency is required.

2. Optimization approach of the present hybrid population-based optimization techniques designed and applied for solving the OPF problems needs a balance between exploitation and exploration to achieve an optimum solution. Any unbalance results in trapped in the local optima or produces the computational load. So, one of the key motivations for accomplishing this research work is applying a new hybrid meta-heuristic optimization algorithm that balances exploration and exploitation to lessen premature convergence, avoids trapping in local optima, and improves the convergence rate.

3. Designing a practical optimal Pareto front in a single simulation for MOOPF problems is complicated. Unfortunately, various proposed MOOPF based optimization algorithms can't simulate a Pareto optimal set and then global Pareto optimal front in a single execution. The conventional optimization approach converts a MOOPF problem to a single objective optimization problem based on the proper weighting factor approach. But the method mentioned above should be run as many times as the number of Pareto optimal sets to construct a global Pareto optimal front (Sivasubramani & Swarup, 2011). Therefore, a multi-objective hybrid firefly & particle swarm optimization (MOHFPSO) method based on non-dominated sorting and crowding distance is needed to design to deal with the MOOPF problem that can generate a global Pareto optimal set and global Pareto optimal front in a single execution. Euclidean distance approach is essential to select an optimal compromised solution. Also, a balance between exploration and exploitation in the method is necessary. Thus suggestion of a new multi-objective optimization method that can efficiently solve MOOPF problems in a single execution is a requirement.

4. Various heuristic methods may give impractical solutions based on violating the dependent variables constraints for OPF problems (Rezaei *et al.,* 2013; Ananthi *et*

*al.,* 2014; Radosavljević *et al.,* 2015). In general, the optimization techniques based on the stochastic approach can not apply the operational limits. Therefore the method that can deal with all limitations is essential.

## 1.5 Scope and Limitation of the Study

The scope of this research work is bounded to suggest a new efficient single and multi-objective optimization method to deal with AC optimal power flow (ACOPF) problems without and with the allocation of DG units in the power systems. Five single-objective OPF based optimization cases are considered to solve: fuel cost minimization, voltage profile improvement, voltage stability enhancement, active power loss reduction, reactive power losses reduction. Furthermore, various cases of two and three combinations of the goal functions are considered simultaneously for multi-objective OPF optimization.

To authenticate the suggested methods, the scope of the thesis work also includes a complete comparison with OPF based optimization algorithms stated in the present literature. The OPF is a substantial and widely studied problem of power network operational issues such as security-constrained economic dispatch (SCED), economic dispatch (ED), and optimal reactive power dispatch (ORPD) were not included in this research work. Moreover, SMA based optimization algorithm is used to identify the optimal size and location of the DG units in the system. Meanwhile, DG's active power is used as a control variable to find the DG's size. Due to the limitation of this thesis work, only two standard bus test networks, such as IEEE 30-bus and IEEE 57-bus test systems, are used to analyze the effectiveness of the proposed approaches.

## 1.6 Contributions of the Study

In this thesis work, considerable contributions are made to the area of the power system to solve the OPF and MOOPF problems with and without the influence of DG units. In this thesis, the significant educational contributions for the scientific group is detailed as follow:-

1. An efficient SMA-based optimization algorithm is proposed and applied to solve the DG unit's optimum sizing and location in a single run.
An equilibrium is kept between local and global search areas to find optimal value as a main contribution of the algorithm. Moreover, mathematical formulation and set of the associated constraints are implemented considering DG unit characteristics, enhancing the effectiveness of installing DG units in the power distribution system based on total power loss reduction.

2 A population-based hybrid firefly particle swarm optimization (HFPSO) approach is proposed and used for several single-objective OPF issues based on the DG

allocation for the first time in this thesis. Also, this hybrid approach keeps a balance between exploration and exploitation.

3 Another version of the HFPSO method, namely the multi-objective HFPSO approach, is designed, proposed, and applied to deal with multi-objective OPF problems in this thesis work. The proposed algorithm is based non-dominated sorting approach to obtain Pareto optimal front, while the optimal compromised solution is selected by applying the Euclidean distance concept. The proposed algorithm is used to two and three conflicting objectives simultaneously through ten different cases.

## 1.7 Thesis Layout

The rest of the thesis is arranged as follows. Chapter 2 discusses the literature review. Firstly, optimal power flow problems are overviewed. Following the previously proposed heuristic, classical and hybrid optimization algorithms used for various OPF problems are closely reviewed, compared, analyzed, and summarized.

Chapter 3 details the proposed techniques. First, the OPF problem’s mathematical formulations are introduced. Then. Slime Mould Algorithm (SMA) based optimal location and sizing of DG units are designed and illustrated. Next, an effective population-based Hybrid Firefly Particle Swarm Optimization (HFPSO) method for single-objective and multi-objective OPF considering DG unit allocation is introduced and modeled, respectively.

Chapter 4 presents the simulated results, detailed discussions, and analysis of the proposed OPF based optimization approaches with the method stated in the current literature. In this thesis, two standard test systems, such as IEEE 30-bus and IEEE 57-bus test systems, are used to test, validate and demonstrate the efficacy of the suggested methods. Lastly, conclusions considering the proposed algorithm’s implementation illustrated and future research work’s recommendations are detailed in chapter 5, correspondingly.

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