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A Review on Load Flow Analysis Modern Techniques

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Abstract **- Recently, many researchers around the globe have been keen on developing new techniques for Load flow analysis, as the traditional techniques, i.e. Gauss-Seidel (GS), and Newton-Raphson (NR), cannot be implemented, due to the high penetration of distributed energy resources (DER). This paper summarizes some of the latest developed techniques on Load flow analysis that can be implemented on a modern power system.**

I. INTRODUCTION

In recent years, a significant penetration of renewable energy sources took place on the existing power systems around the world [1]. As an impact, it became challenging, during planning stage, to perform load flow analysis due to the uncertainties in buses data [2]. In addition, islanded microgrids (MG) do not have a slack bus to begin with, which makes it even more challenging to perform load flow using traditional techniques [3]. However, many researchers recently came up with different techniques to overcome these issues.

Nowadays, MGs play a major role on the overall operation of a modern power system, as they improve its efficiency and reliability. They operate as grid-connected MGs or Islanded Microgrids (IMG) [4]. In both cases, uncertainties on the buses data create obstacles on performing Power Flow (PF) analysis using traditional techniques [1-4]. A keen interest on tackling this issue have been observed in recent literature. For example, a decoupled extended PF Analysis based on NR method was proposed [3]. Another publication [5], proposed introducing nature-inspired algorithms such as Differential Evolution (DE), Flower Pollination Algorithm (FPA), Grasshopper Optimization Algorithm (GOA), and Genetic Algorithm (GA). Furthermore, nature-inspired Hybrid algorithms were proposed by merging the algorithms with (ICA) to form four hybrid algorithms [4]. In addition, a data-driven method based on exact linear regression was proposed [6].

Modifications to the existing load flow analysis techniques, NR, and GS, also took place in recent literature. The author of [7], proposed a high convergence NR based predictor-corrector. In preceding of this work, a hybrid algorithm for PF analysis of VSC-HVDC systems emerged, based on $1+\sqrt{2}$ order NR and simplified Newton method (SN) [8]. In addition, the author of [9], suggested including loads and generation on the bus admittance matrix. Moreover, for integrated energy systems (IES), a published paper proposed a fast-decoupled multi-energy flow technique (FDMF) instead of Newton-Raphson multi-energy flow (NRMF) [10]. For a power system with an arbitrary number of phases, a matrix-based generalization for power mismatch NR load flow was proposed [11].

Recently, Flexible AC Transmission System (FACTS) devices became widely used in a power system, as they improve its overall operation, a published paper [12], proposed modeling C-UPFC in the NR power flow calculations. Another author proposed a non-linear iterative solver (NLIS), which can increase the practicality of traditional GS method [13].

For a large-scale power system, the solution for power flow can be obtained using traditional load flow techniques. However, it takes the CPU a long time to process input data, in [1]. The author addressed that fact and developed a CPU-GPU paralleling algorithm. In addition, to avoid numerical iterations. Another publication proposed a dynamized power flow method based on differential transformation [14].

Regarding distribution systems, it was found that only few methods can deal with both mesh and radial structures [15]. The author proposed a numerical analysis based on successive approximations.

This paper summarizes all the mentioned works and discusses their results. Section II of this paper describes the methodology along with the obtained results of each previous work, section III concludes this paper

I. METHODOLOGY AND RESULTS

Decoupled Extended Power Flow [3]

Due to the absence of the slack bus in MGs, the frequency of the system is no longer maintained constant. Instead, it is considered as a variable along with active and reactive power. In this method, the existing modifications on Newton-Raphson method applied for IMGs are enhanced by a droop control scheme for DGs in a system, this way, controlling injected active and reactive power by these DGs was made possible taking into account their buses voltages along with the system's frequency. As a consequence of introducing this droop control scheme, the scheduled power generations for DGs vary. In order to overcome this issue, additional partial derivatives were added to the Taylor series expansion to minimize the deviations

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in scheduled active and reactive power, and to improve the accuracy of the obtained JM in each Iteration. This method was performed on 6-bus and 38-bus IMGs.

It was shown in [3], that even though the time for each iteration is increased, because of introducing the additional partial derivatives, the overall run time for the power flow analysis is significantly decreased due to the accuracy of the proposed DENR method

Differential Evolution Approach [5]

Another way of determining power flow in IMGs is Differential Evolution approach, in which, droop controlled islanded microgrids (DCIMGs) problems are transformed into constrained optimization problems (COP) which are solved by the proposed epsilon based differential evolution with Newton-Gauss-based mutation method in [5]. This method was tested on 6-bus, 33-bus, and 69-bus systems.

The proposed method in [5], was compared with other proposed methods and it has the capability of converging regardless of the system conditioning. In addition, PF results were obtained even for unsolvable test cases.

Nature-Inspired hybrid Algorithms [4]

In this technique, the author of [4], utilized nature-inspired algorithms, such as genetic algorithm (GA), differential evolution (DE), grasshopper optimization algorithm (GOA), and flower pollination algorithm (FPA) by merging them with imperialistic competitive algorithm (ICA), forming four new hybrid algorithms, which are (ICGA), (ICDE), (ICFPA), and (ICGOA). The proposed hybrid algorithms were tested on 6-bus, and modified IEEE 37-bus systems.

The proposed algorithms were compared with each other and it was shown that ICDE was the best amongst the proposed methods in terms of convergence rate and number of iterations.

Data-Driven Power Flow [6]

In this method, the author addressed the uncertainties of power generation in SGs and developed a data-driven PF technique based on exact linear regression which comprises two stages to obtain a solution for PF problems in SGs. The first stage is offline learning stage, and the second stage is Online computing stage. In offline learning stage, Rigid Regression (RR) is used to solve a constructed learning model based on historical data formed as a mapping matrix, while in online learning stage, the historical data with the same current topology are used to obtain the solution without the need for algebraic iterations. This method was tested on multiple IEEE test systems.

The proposed method has no convergence issues, as there are no algebraic iterations. In addition, it was proven that results can be obtained even if the topology of the system changes on a frequent basis.

Newton-Raphson based Predictor Corrector [7]

The standard Newton-Raphson power flow has a convergence rate of 2. The proposed NR-PC method has a higher convergence rate of approximately 2.4 which was verified on multiple systems regardless of their conditioning status. In this method, the author proposed adding two additional steps to the traditional NR method, the first one is Predictor step, in which utilizing the previous iteration solution to fine predictor vector. In the Corrector step, utilizing the previous JM takes place along the predictor vector to reach the solution.

The proposed method was compared with multiple techniques like NR, FD, IM and RK4, and it was shown that it stood the best in terms of computation time as well as number of iterations. In addition, it was capable of reaching a solution even when the test system is ill-conditioned.

Hybrid algorithm for PF analysis of VSC-HVDC [8]

A power system with AC/DC configuration can easily be found anywhere in the world. Consequently, making load flow analysis a challenging task to be performed. This method tackles this issue by taking advantage of $1+\sqrt{2}$ order Newton-Raphson and simplified Newton method. First, $1+\sqrt{2}$ NR method is performed for a preset number of iterations, then SN is performed until the required accuracy is met. This technique was performed on multiple IEEE test systems.

It was verified that this algorithm has the highest efficiency compared to existing algorithms that deals with AC/DC networks, also the solution for load flow can be obtained regardless of the system's working condition.

PF analysis based on bus admittance matrix incorporating loads and generators [9]

Established methods of PF analysis, only transmission lines and generators are included in the bus admittance matrix. In this technique, loads and generators, even the slack bus, are included in the bus admittance matrix. In addition, the generators are considered as current sources instead of voltage sources. The author argued that the conditioning of the bus admittance matrix has the tendency to be improved depending on the size of shunt admittances compared to one and other within the system. The method was verified on multiple test systems along with a real grids networks in Italy.

The proposed method was compared with widely used, open sources software packages, and it was demonstrated that the number of iterations and CPU run time were much better in the proposed method. In addition, as the proposed method improves the conditioning of a given system, it showed that there are no convergence issues regardless of the system's nature.

Fast Decoupled Multi-Energy Flow for IES [10]

In an integrated energy system, power flow cannot be performed using traditional techniques. Instead, Multi-energy flow calculations are performed using the well-known NRMF method in which, the JM is calculated on each iteration. The author of this paper [10] proposed a FDMF for IES by replacing the JM with a constant-diagonal JM throughout the entire analysis. The proposed method was tested on both small and large IES.

The proposed technique was compared with both NRMF and Unified steady-state Multi-Energy flow analysis (UMF), and it was shown that the proposed method is almost five times faster than both NRMF and UMF. The only drawback of the proposed method is that it can only handle well-conditioned power systems.

Matrix-based generalization for power-mismatch NRPF with arbitrary number of phases [11]

In this method, a generalized formulation for power flow mismatch based on NR method was proposed for a system with an arbitrary number of phases, the method basically computes power injections along with the JM as submatrices composing the bus admittance matrix of the system. The method was tested on IEEE 4-bus, IEEE 13-bus, and IEEE 123-bus test systems.

It was shown that not only the proposed method provides a compact representation, it also showed a reduction in the computation time of PF problems.

Modelling C-UPFC in load flow analysis [12]

A recent developed flexible AC transmission system (FACTS) device is C-UPFC, which plays a vital role in controlling many parameters in transmission lines, such as voltage magnitude and power flow. This method proposed representing the C-UPFC with injected load as a function of control variables to avoid the modification of the JM. In addition, the maximum limits of the C-UPFC are also considered resulting in the release of specified values that are updated in each iteration. The technique was verified on IEEE 30-bus and IEEE 118-bus test systems.

The simulation results for this proposal showed robustness over conventional approaches that deal with C-UPFC constraints. Also, the computation time is reduced since no \modifications are required to the JM.

Non-Linear Iterative Solver using Graph Computing [13]

For a large-scale power system, Gauss-Seidel method is not as frequently used as NRPF and FDPF to solve power flow problems, due to its low convergence rate and long computation time. the author of this paper [13], proposed a non-linear iterative solver (NLIS) based on Bulk Synchronization parallel computing model (BSP), by restructuring GS using PageRank algorithm on a graph computing platform. The method was performed on IEEE 118-bus test system, 1500 nodes system of one province in China, and MatPower 10790 system.

The proposed method was compared with MatPower, even though the convergence criteria for the proposed method is 0.00025 and for MatPower is only 0.05, it was shown that the proposed method is four times faster.

Fast Parallel NRPF solver for large number of system calculations with CPU and GPU [1]

Many open source tools that deals with PF problems depend entirely on the CPU. In this method, the author proposed paralleling operation of CPU and GPU in order to obtain the results for PF problems, resulting a significant time reduction in the computation process, as it avoids repetitive works on the CPU using batch sparse matrix operation along with batched linear solver based on LU-refactorization. Compared to the open-source tool pandapower, the proposed method was shown to be 100 times faster.

Dynamized PF based on Differential Transformation [14]

As power flow equations are non-linear, the solution is obtained using algebraic iterations. In order to avoid these iterations, the author of this paper [14], argued that power flow equations , which are non-linear in the time domain, can be converted into linear equations in the domain of power series using Differential Transformation (DT). To check the validity of this statement, the author performed this method on multiple test systems along with a 2383-bus system.

The simulation results of the proposed method were compared with the obtained results of CPF solver in MatPower and it was shown that the run time is significantly reduces. In addition, the proposed method is robust and can adapt to non-uniform changes in loads along with generation reactive power limits.

Numerical Analysis based on Successive Approximation for PF Problems in AC Distribution Systems [15]

This technique is basically a modification of the conventional Gauss-Seidel method using successive approximation which does not require derivatives. Instead, requires matrix inversion which is used throughout the remaining iterations. This method can handle both mesh and radial configurations of AC distribution systems. The proposed method was implemented on 10-bus, 33-bus, and 69-bus test systems.

The proposed method was compared with multiple PF techniques such as NR, GS, LM, and BF. It was shown that the execution time for load flow analysis using successive approximation is the least among the tested techniques.

II. CONCLUSION

A keen interest on developing new, accurate, and robust solution techniques to power flow problems can be noticed throughout recent literature. Since conventional approaches such as GS and NR method are obsolete, new techniques that take advantage of modern computer science along with mathematical modifications to the existing methods were proposed. In this paper, it was shown that many researchers came up with different techniques to improve the convergence rate and execution time of load flow problems.

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