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A Review: Traditional and AI-Based Load Flow Solution Algorithms

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ABSTRACT

A diagnostic report or assessment must be carried out to discover the real status of the power system under inquiry before designing, expanding, and analyzing it. This diagnostic report is called power or load flow analysis, and it is the bedrock for all power system analysis. In this research, an extensive and elaborate review is being conducted on various traditional and modern load flow solution algorithms with the aim of evaluating their strengths and weaknesses for an informed research gap consideration. This study considered recent (last five years) research conducted using traditional load flow solution algorithms like Newton Raphson (NR), Gauss Siedel (GS), and fast decoupled (FD) with modern artificial intelligence based LF algorithms to discover recent trends for knowledge advancement and power system stability and reliability. According to the research, NR is the most effective of the numerous conventionally employed LF solution algorithms because it converges more quickly than GS and FD do in the face of network complexity. Also, the bulk of modern AI-based LF solution algorithms such as genetic algorithm (GA), particle swarm optimization (PSO), and differential evolution (DE) tend to be computationally quick with lower accuracy. To strike a balance between speed and accuracy, future research should focus on comparative reviews of various AI algorithms for the best LF solution.

KEYWORDS: Power, Diagnostic, Artificial Intelligence, Swarm, Newton-Raphson, Differential Evolution, Particle Swarm Intelligence.

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1 INTRODUCTION

Power flow analysis is an essential study that should be conducted when considering the development or expansion of a new or existing power system under steady-state conditions to ascertain the level of active and derive network parameters such as voltage, current, and real and reactive power (Ahiakwo *et al.*, 2018). The power flow equation is non-linear and requires a non-linear solution. The power system is primarily divided into generation, transmission, and distribution, and under complicated network conditions, standard techniques of solution find it challenging to converge, particularly in the distribution domain where significant values of X/R are recorded.

The aim of this research is to review traditional and modern AI load flow solution techniques evolved and implemented in recent times (within the last five years) for algorithm performance evaluation and identification of unexplored areas (research gaps) within the subject.

The objectives of this research are itemized in order of prosecution below.

i. Review of current literature on power flow analysis
ii. Identification of some widely used traditional and AI-based power flow solution algorithms.

iii. Identification of strengths and weaknesses of the selected traditional and AI-based load flow algorithms
iv. Identification of research areas or gaps

1.1 Review of Current Literature on Power Flow Studies

Araujo *et a*l. (2018) conducted a comparative study between Newton-Raphson-based methods and backward-forward sweep methods for load flow studies. Both methods were compared in terms of variation of the X/R ratio, load's increase up to the convergence limit, load model impact, and voltage regulators modeling impacts. Both methods were tested on the 34-bus and 134-bus systems, and results showed that the Newton-Raphson-based model converged strongly with a minimal increase in the number of iterations, while the backward-forward sweep (BFS) gave a considerable increase in the number of iterations and computational time. The NR-based methods showed better computational qualities in handling voltage regulators with lesser computational time, but the BFS performed better than the NR-based models when it comes to heavy loads. Considering network complexity and size, the NR offered a better solution than the BFS for solving extremely meshed networks.
Gurski et al. (2019), in a bid to ascertain daily power flow results in a photovoltaic distributed generation-enabled grid, developed an algorithm enabling the use of Gauss Siedel (GS), Newton Raphson (NR), and backwards-forward sweep (BFS) for power flow studies. According to the findings, radial and linked systems should employ NR for the transmission zone while GS and BFS should be used for the dispersed zone.
Ghaisi (2018) conducted comparative load flow studies on the Tehran Metro Line 2 Newton Raphson, fast decoupled (FD), and accelerated Gauss Siedel (AGS) in ETAP 12 with the aim. assessing the strength of the proposed methods. The results obtained placed NR ahead in terms of computation speed, while AGS was ranked highest in terms of precision with an accelerated factor of 1.45. In their research, a more sophisticated load flow algorithm was recommended for future researchers.

The performance of the traditional load flow methods of NR and GS was evaluated in Mohsin (2022), and NR performed better, especially with increasing buses and network complexity, against the GS solution method.
Chowdhury *et al.* (2021), in the redesign of a 2500 kVA, 11/0.4 kV substation, used the adaptive NR in ETAP software for power flow analysis with the aim of improving the voltage profile and power flow in the network.
Sharma *et al.* (2018) conducted load flow analysis in a static radial distribution network using graphical theory. The results obtained after testing two different static radial distribution networks revealed faster computation with minimum complexities.
Ignatius *et al.* (2017) studied the load flow assessment of the Nigerian 330 kV power system and used NR as an optimization tool for power flow problems due to its quadratic convergence features and ability to analyze large power networks. The NR method of solution was able to efficiently analyze the system in light loading conditions with quick convergence, though it will diverge for heavily loaded systems. Yasar *et al.* (2017), in their research, used a novel data inputting method for Newton Raphson for AC power flow analysis in a 118 bus, 54 generator system. The algorithm was implemented and tested in a MATLAB environment, and the results obtained were adjudged good. Onah *et al.* (2021), in a bid to evaluate technical loss in the Nigerian 330 kV grid, engaged the GS solution model for power flow analysis with and without integration of STATCOM devices.

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The loss index evaluation report from the GS implementation on the Nigerian grid stressed the need for the introduction of appropriate STATCOM devices.

Tostado-Veliz *et al.* (2021) proposed and implemented a novel Runge-Kutta-inspired method for power flow studies. The proposed methods of explicit Heun and embedded Heun Euler, which were allegedly practicalized and resulted from analyzed simulations, offered robustness and efficient convergence. In their submission, they advised future research to be channeled towards validation of their claims by comparing the efficacy of the proposed methods with other optimal power flow algorithms.
Egoigwe *et al*. (2020), in their research on the improvement of power flow control using phase shift transformers, engaged NR for power flow studies in a MATLAB environment to ascertain the state of the IEEE 5-bus network before and after improvement. Djalal *et al.* (2021), in the presence of renewable power plants in the Sulselrabar system, deployed NR in the ETAP premise for power flow studies and power system analysis with the aim of solving the lingering power issues in the region.
Zdiri *et al.* (2023) conducted research to propose solutions to the bottlenecks surrounding the traditional methods of NR and GS as influenced by the wide range of resistance and reactance ratios, especially in radial distribution networks. In this research, the authors used an iterative AI-based method for power flow analysis and evaluation of the impact of photovoltaic systems in a radial distribution network.

Ruliyanta *et al.* (2021) considered capacitor placement as a tool for voltage profile control and power loss reduction in their research. One of the traditional methods of load flow solvers was used in ETAP to determine the existing and improved states of the distribution networks.

Abirami and Ravi (2021) engaged Newton Raphson for power flow analysis in a 10-bus loop distribution network in the presence and absence of power system stabilizers (PSS) and automatic voltage regulators (AVR) for voltage stability evaluation. To correct the deficiencies of traditional methods, especially NR, researchers have explored various AI solutions, and some of these solutions are being considered with a key focus on research conducted in the last five years.
Fikri *et al.* (2018) compared deterministic methods and artificial intelligence-based neural network results for power flow calculations. Results obtained after simulation revealed better accuracy for NR against GS and ANN. The ANN was better in terms of computational speed compared to GS and NR. Ahiakwo *et al.* (2018) used the artificial bee colony swarm intelligence technique developed by Karaboga (2005) to propose an optimized load flow solution in the Port Harcourt Electricity Distribution Company (PHEDC) zone 4 distribution networks. A similar approach was adopted by Jagun et al. (2021) for power flow studies in the Port Harcourt section of the Nigerian 132 kV network. Huynh *et al.* (2018) proposed and implemented a probabilistic solution approach for power flow studies in the IEEE 118-bus network. The hybrid solution employed in this research combined principal component analysis and differential evolution (DE), and the results were compared with Monte Carlo simulation.

Remha *et al.* (2018) utilized the bat algorithm based on the weight sum method (WSM) as a tool for solving multi-objective optimization problems. Test results on the standard IEEE 12-bus, 33-bus, 69-bus, and 85-bus feeders proved that the proposed algorithm could maximize the voltage stability index and minimize total active power losses.

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Comparative results from other solution algorithms validated the proposed algorithm.

In a bid to solve the limitations of the backward-forward sweep and branch impedance matrix (BIM) methods of load flow solution, Sur *et al.* (2022) deployed a modified set theory-centered approach for unbalanced load flow analysis. The proposed method was tested using the standard 10 bus, IEEE 13 and 123 three-phase unbalanced radial networks, and the IEEE 28 bus balanced radial system. The performance of the deployed algorithm proved better computational speed and convergence over the traditional BFS and BIS. Artale *et al.* (2020) proposed a virtual tool for load flow studies in microgrid systems. The virtual algorithm was centered on the backward-forward sweep load flow solution technique and validated with results derived from measurements of voltage and current acquired at the beginning of the medium voltage (MV) feeder. A dynamic radial basis function artificial neural network was suggested by Baghaee et al. (2018). The suggested technique is suitable for radial and ill-conditioned networks with larger R/X ratio values, according to the results. Additionally, the method's validity was checked by applying it to various power and distribution test systems and comparing the findings to those of other load flow methods. Dong *et al.* (2018) proposed an upgraded continuous power flow (CPF) model coupled with an evolutionary mechanism-based particle swarm optimization (PSO) technique via coordinate transformation to predict the load margin for voltage stability. Parallel processing was also utilized in programming for high performance. Tests on the IEEE 14-bus test system demonstrated that the suggested technique is efficient and capable of delivering high accuracy and reliability numbers for load margin concerns. Sa'ed *et al.* (2019) proposed and deployed an analytical tool for optimal distribution generation (DG) sizing, allocation, and penetration using the IEEE 12, 33, and 69 buses as a test case. The results obtained were adjudged satisfactory in the validation report with improved analytical (IA) and PSO methods.

Avelar *et al.* (2018) used open-source distribution system simulation (Open DSS) and an AI technique called artificial neural network for power flow analysis and self-recovery in a distribution network using the IEEE 123 node as a test system. Riaz *et al.* (2021) employed a hybrid particle swarm gray wolf optimizer (HPS-GWO) algorithm for optimal power flow with the integration of renewable energy sources. The algorithm was tested on the modified IEEE 30-bus system with the aim of optimizing power flow through improvement of convergence rate and minimization of generation cost and emission. Results from simulation highlight the success of HPS-GWO in all three objectives compared to the individual performance of the PSO and GWO algorithms.

Nusair and Alhmoud (2020) developed and deployed an equilibrium optimizer (EO) algorithm for power flow optimization with the integration of renewable energy sources. Test results from the simulation report show the superiority of the proposed EO when compared to other standalone solutions.

Calasan *et al.* (2019), in their research, arrived at an optimized power flow solution through the application of the CONOPT solver in the generalized algebraic modeling systems (GAMS) software.

1.2 Identification of some widely used Power Flow Algorithms

According to the literature, a lot of effort has been put into developing both conventional and AI-based LF optimizers, but no comprehensive answer has been found. So far, three algorithms have been identified in the traditional and Artificial intelligence domains.

Gauss Siedel (GS), fast decoupled (FD), and Newton Raphson (NR) have been identified as good load flow solvers. In the artificial intelligence domain, particle swarm optimization (PSO), genetic algorithms (GA), and differential evolution (DE) have also been identified. Out of the three AI-based methods, GA and DE are evolutionary algorithms, while PSO is a swarm intelligent algorithm.

2. MATERIALS AND METHODS

Research outputs published in top-tier power systems journals within the last five years were considered for a comprehensive review. For thorough and adequate research output, various power system networks, both imaginary and real-time, were used as test cases. Amongst these imaginary networks are IEEE 6, 13, 14, 33, and 118 buses for balanced and unbalanced scenarios. The load flow problem is a non-linear equation that requires a non-linear solution, whether traditional or AI-based. The essence of the explored methods is to find an optimal solution for the fundamental load flow equation as contained in equations 2.1 and 2.2 under certain equality and inequality constraints (Ahiakwo *et al.,* 2018).

The fundamental power flow equations remain unchanged but require newer solutions.

$$P_i = \sum_{i,k=1}^{n} Y_{ik} V_i V_k \cos(\theta_{ki} + \delta_{ik}) \quad (1)$$

$$Q_i = \sum_{i,k=1}^{n} Y_{ik} V_i V_k \sin(\theta_{ki} + \delta_{ik}) \quad (2)$$

Equations (1) and (2) are used to obtain calculated values of real and reactive power, while the modular difference between the specified and the calculated values is expressed using Equations (3) and (4).

$$\Delta P_i = \left| P_i^d - P_i^{cal} \right| \quad (3)$$

where,

P_i^d= declared real power at bus i

P_i^{cal}= calculated real power at bus I using Equation (1).

Similarly, the reactive power changes may be expressed as:

$$\Delta Q_i = \left| Q_i^d - Q_i^{cal} \right| \quad (4)$$

where,

Q_i^d= the declared reactive power at bus i, and

Q_i^{cal}= the calculated reactive power at bus i, using Equation (2) (Ojuka & Wokoma, 2019).

3. STRENGTHS AND WEAKNESS OF POWER FLOW SOLUTION ALGORITHMS

3.1 Traditional Power Flow Solutions

3.1.1 Gauss-Siedel

Gauss-Siedel (GS) is a widely used non-linear load flow solution technique due to its simplicity, low implementation cost, low computational time per iteration, and low computer memory demand. On the contrary, the GS method is encumbered by a clumsy rate of convergence due to the large number of iterations. Also, one of the drawbacks of the GS method is its sensitivity to the selection of a slack bus, as the rate or speed of convergence is dependent on it.

3.1.2 Newton Raphson (NR)

Apparently, NR is the most used traditional power flow solution technique, and it is based on Taylor series and partial derivatives.
Holistically, the NR method is cost-effective, computationally fast, and more accurate, and the number of iterations is less dependent on the system or network size.
The disadvantages of the NR method are difficult and complex solution techniques, resulting in a larger computational time per iteration.

3.1.3 Fast Decoupled

The fast decoupled (FD) solution method is a modified version of the NR formulated in polar coordinates.

According to implementation reports derived from the literature, the FD approach is quick and easy to use, with accuracy that is only marginally inferior to the NR.
Despite its computational speed, the precision of the FD solution lags that of the NR solution, which forms part of its weakness.

3.2 AI-Based Power Flow Solutions

In a bid to improve the drawbacks of traditional methods, especially NR, various AI-based algorithms have been developed and deployed for power flow analysis. Among these AI-based methods are artificial neural networks (ANN), swarm intelligence (SI), and evolutionary algorithms. According to the review, swarm intelligence and evolutionary algorithms with natural inspiration have been rapidly developed and applied in recent years.
Though the performance of ANN is better in computation time, it is limited by low precision, leaving the defect of NR half-solved. Due to the shortcomings of the ANN, researchers have moved attention towards evolutionary and swarm intelligent algorithms to cushion the precision deficiency of the ANN as a stand-alone.

3.2.1 Evolutionary and Swarm Intelligent Algorithms

This research narrows its focus to evolutionary and swarm intelligence-based algorithms.
Three evolutionary algorithms, particle swarm optimization (PSO), genetic algorithm (GA), and differential evolution (DE), are compared for the purpose of obtaining the best winner algorithm considering speed and accuracy. A detailed requirement-based computational report from the implementation of all three evolutionary algorithms is contained in Table 1. Also, the implementation procedures for the three algorithms are shown in Figure 1.

Table 1: Requirement-based Comparative Report for Three Evolutionary Algorithms

Requirement	GA	PSO	DE
Solution ranking	Yes	No	No
Population size and time relationship	Exponential	Linear	Linear
Dependence of best solution on population	Medium	Most	Less
Convergence speed	Medium	High	Low
Density of search space	Less	More	More
Ability to find viable solutions devoid of local search	Less	More	More

According to the tabulated data, PSO provides a more dependable and accurate outcome than the other two evolutionary algorithms without sacrificing speed, convergence, or accuracy. Though in small networks, it is difficult to differentiate between the efficacies of PSO and GA, for medium and large networks, GA produces a near-accurate solution that is inferior compared to the results of PSO (Wihartiko *et al.,* 2018). Differential evolution (DE) offers the least solution in the ranking order of all three algorithms.

3.3 Summary of both Traditional and AI-based Methods

Results from the application of the traditional methods of Newton Raphson (NR), Gauss Siedel (GS), and fast decoupled (FD) on various power system test bus networks revealed both the merits and demerits of the various traditional methods.

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A holistic review evaluated the performance of all three methods and ranked NR best due to its robustness, accuracy, and better convergence ability in large networks compared to GS and FD. Unarguably, Newton Raphson stands tall above FD and GS when it comes to accuracy and reliability, as it can derive convergence under slightly complex network arrangements.

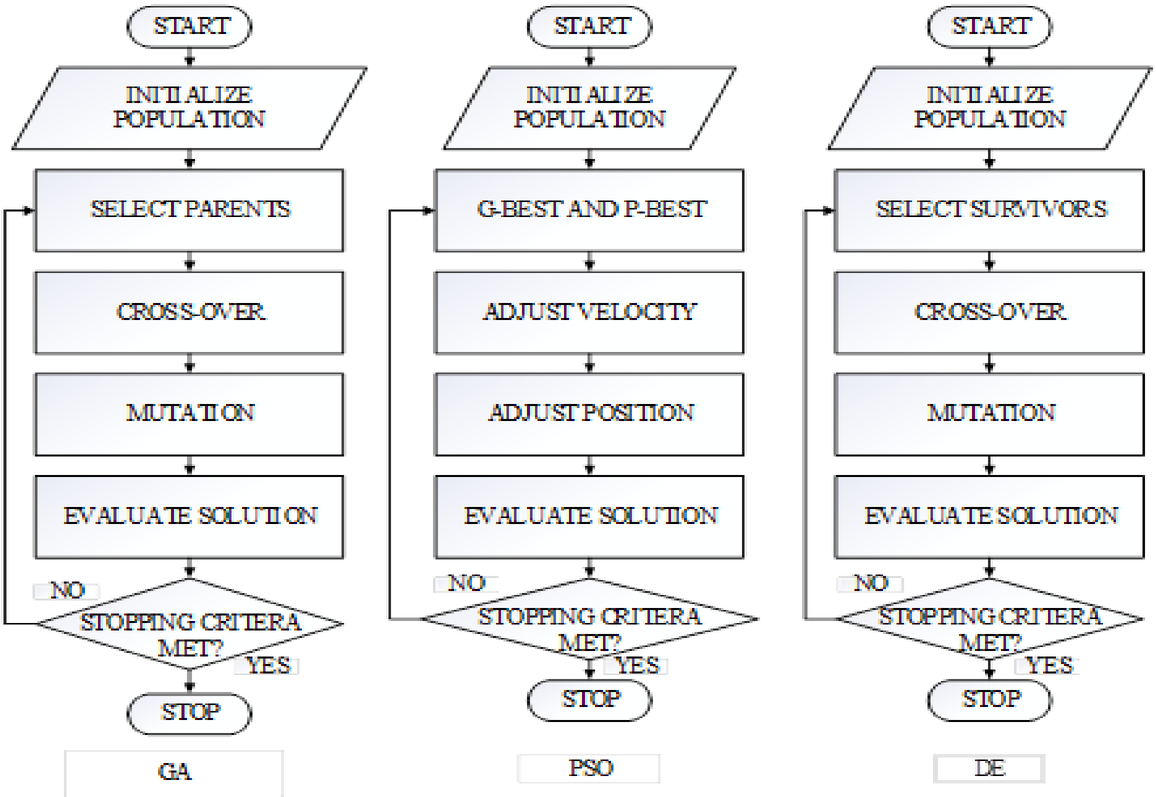

Figure 1: Algorithm Implementation Flowchart

A major drawback of the best traditional method is its failure to converge when required to diagnose complex networks with possibly large mismatch power values. Also, NR is limited to a fewer number of iterations, which implies that if it fails to arrive at a solution after a maximum of 99 iterations, a divergent solution is achieved, defeating the aim of the load flow analysis. Results from individual performances of metaheuristic solutions under evolutionary algorithms like particle swarm algorithm (PSO), genetic algorithm (GA), and differential evolution (DE) posed a better accuracy level compared to the ANN.

3.4 Identification of Research Gap

To identify the algorithm that provides the most accurate or precise LF solution in the manner of NR and PSO, a comparative analysis of at least three swarm intelligence (SI) optimizers through analytical and statistical methods is required. This evaluation report was derived from academic articles published within the last five years.

4 CONCLUSIONS

This research cuts across the use of traditional and AI-based load flow solution methodologies. Also, it captures the essence of load flow analysis and stresses the need to consider computational speed and accuracy when arriving at a better load flow solution.
Finally, the weaknesses and strengths of both traditional and AI-based load flow solution methods were exposed, but with reliance on the strengths of the AI-powered solutions, a comparative review or analysis of key evolutionary AI-based solutions is being recommended to find an optimized LF solution.

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