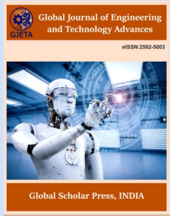
Global Journal of Engineering and Technology Advances

eISSN: 2582-5003

Cross Ref DOI: 10.30574/gjeta

Journal homepage: https://gjeta.com/



(Research Article)

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Power flow and power system stability: Evolution of analysis methods

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Global Journal of Engineering and Technology Advances, 2024, 21(01), 038–049

Publication history: Received on 11 August 2024; revised on 22 September 2024; accepted on 25 September 2024

Article DOI: https://doi.org/10.30574/gjeta.2024.21.1.0173

Abstract

This document explores in depth the calculation of power flow in electrical networks, which is crucial for determining the voltages, currents and active and reactive powers in order to maintain the stability and efficiency of the network. It examines the evolution of calculation techniques, from the early manual methods to algorithms similar to Gauss-Seidel and Newton-Raphson, discussing their advantages and limitations. It highlights the challenges related to convergence and accuracy in large networks, as well as the importance of more modern methods such as machine learning techniques. The paper also addresses contemporary approaches based on numerical optimization and machine learning, which offer flexible and efficient solutions for managing increasingly complex electrical grids, particularly in the context of the integration of renewable energies and smart grids. These advances allow for improved accuracy of model and optimal management of electrical networks to meet the growing needs for precision and integration of renewable energies.

Keywords: Stability; Electrical power flow; Optimization algorithms; Machine learning

1. Introduction

The power flow calculation is a steady-state study of the electrical network, which consists in determining, firstly, the amplitude and phase of the voltage at each busbar, as well as the active and reactive power injected. Knowing the voltages (amplitude and phase) at the busbars and the injected powers (active and reactive), we can then calculate the currents and powers in the lines and those supplied by the sources. It thus enables us to determine the voltages, currents and powers in an electrical network, thus ensuring system stability and efficiency [1],[2],[3].

The most important objectives of power flow studies are [4],[5],[6]:

- Determination of reactive and active powers in the transmission line based on certain a priori considerations associated with the receiver or generator.
- Calculation of potential differences at each node or busbar.
- Check that no lines are overloaded. Overloading may mean that the line is close to thermal stability.
- Monitor the line for reclosing. Determination of the specific power flow leading to optimum dispatching by calculating the state of the network (P, Q, V, δ...) under given production and consumption assumptions.
- With the growing integration of renewable energies and smart grids, the accuracy and robustness of power flow models are becoming increasingly critical. This article provides an overview of the various modeling methods in use.

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2. Electrical power flow

Power flow analysis is used to determine the characteristic values of an electrical network in normal, balanced, steady-state operation [7]. These values include voltages at nodes, power injected at nodes, and power flowing through lines. Losses and currents can be deduced from this information. Power flow analysis is essential for planning the construction and extension of power networks, as well as for their management and monitoring [8]. Many mathematicians, computer scientists and engineers have devoted years of research to developing computational methods for power flow. The sheer volume of publications in this field testifies to the scale of their efforts, including [9], [10], [11], [12], [13], [14], [15], [16].

Prior to 1929, load flow (also known as power flow) calculations were carried out manually. In 1929, Westinghouse network calculators and General Electric network analyzers were used for power flow calculations. It wasn't until 1956 that Ward and Hale developed the first suitable method.

Early methods were based on the iterative Gauss-Seidel algorithm applied to the Y admittance matrix. This method required little memory and was relatively simple to program. However, while small networks required few iterations to converge, large networks required a high number of iterations, and sometimes didn't converge at all. This limitation prompted researchers to explore methods based on the Z impedance matrix. Although the latter showed better convergence properties, they had the disadvantage of requiring a large memory capacity, as the Z matrix, unlike its Y reciprocal, was not directly calculated.

Faced with these challenges, the researchers turned to another iterative method, the Newton-Raphson method. Although this method requires more time per iteration than the Gauss-Seidel method, it offers the advantage of converging in a reduced number of iterations, even for large networks. However, it requires large storage capacities and substantial computing resources.

Other techniques have also emerged, notably those exploiting the sparse structure of the Y matrix and the Jacobian (which represents the variation of power as a function of voltage and phase angle) to optimize storage. In addition, methods that take into account the strong coupling between active power P and phase shift angle Θ, as well as between reactive power Q and voltage V, have been developed to speed up calculation times.

3. Methods for calculating electrical power flow

Optimal power flow calculation methods fall into two categories: conventional or deterministic methods and modern methods.

An efficient and robust solver for distribution systems must be able to handle load flow systems with several thousand nodes and several voltage levels. It must also be able to handle both radial and meshed topologies, taking into account unbalanced loads and distributed energy resources of a random nature that may be connected to them.

This section summarizes the efforts made to solve the problem of load flow in distribution systems, taking into account their specific features and the various challenges associated with their current and future development.

3.1. Traditional methods

Traditional methods, also known as deterministic or conventional optimization methods, have been widely studied and applied in recent research. These methods, based on mathematical programming approaches, are used to solve power flow optimization (PFO) problems at various scales. Depending on the different objective functions, types of applications and nature of constraints, the most commonly used conventional methods can be:

- Newton-Raphson
- Gauss-Seidel
- Fast Decoupled Load Flow
- Linear programming
- Gradient methods
- Quadratic programming
- Non-linear programming
- Interior point

Conventional load flow calculation methods do not always converge when applied to distribution systems. Indeed, these systems, often radial or weakly meshed, present a high R/X ratio, which can lead to conditioning problems for generic power flow algorithms, such as those based on the Newton-Raphson method or Newton-like variants [17],[18]. On the other hand, Gauss-Seidel methods, which use fixed-point iterations, show poor convergence.

In this paper, the conventional Newton-Raphson, Gauss-Seidel and Fast Decoupled Load Flow methods will be presented.

The study [19] presented a linear optimization model based on programming for calculating an optimal power flow. The results show that convergence was achieved in a single iteration for a five-node 220 kV system, with a significant reduction in CPU time.

In study [20], a linear programming model was proposed to minimize power losses and determine them.

Study [21] presented a linear programming-based model for power flow optimization (OPF), aimed at minimizing power losses and optimizing generation reactive margins.

In [22], a quadratic model for OPF was proposed. The construction of this OPF algorithm incorporates feasibility, convergence and optimality conditions. It is also capable of using hierarchical structures to include several objective functions. The algorithm uses the sensitivity of objective functions with optimal constraint adjustments to provide an optimal global solution. Computational memory and execution time requirements have been reduced.

Paper [23] presented a power reactive optimization model based on successive quadratic programming methods.

In the study [24], quadratic programming was used to solve the power flow problem by applying the Lagrange multiplier method and Taylor series expansion. The economic dispatch problem was posed as a quadratic programming problem and solved using Wolfe's algorithm. The method is able to handle both equality and inequality constraints on p, q and v, and can solve the load flow as well as the economic dispatch problem. Convergence was achieved in three iterations for all test systems considered, and the solution time is short enough to allow the method to be used for online dispatching at convenient time intervals.

[25] presented a method called IPM (Interior Point Method) for solving the problem of optimal distribution of reactive power in electrical networks. The method is based on a dual primal logarithmic approach. According to the results presented, this IPM method has been successfully applied to large power systems. Convergence was achieved in just 40 iterations, with a CPU computation time of 398.9 seconds.

[26] presented linear programming and nonlinear programming methods for solving the problem of optimizing reactive power flow (OPF reactive) in a deregulated electricity environment. The objective was to determine the optimal distribution of reactive power among the various generators on the network. The results showed that the linear programming method was able to estimate with reasonable accuracy the overall cost associated with the system's reactive power requirements. However, each generator's individual commitment in terms of reactive power supply could vary significantly from this optimal global solution. Thus, although linear programming offers an interesting approach to optimizing reactive power flow on a system-wide scale, further adjustments seem necessary to better distribute responsibilities fairly among the various generators interconnected on the deregulated power grid.

[27] presented a solution to the optimal power flow (OPF) optimization problem in rectangular form, using an interior point method (IPM) for nonlinear programming. The rectangular approach allows voltage and current variables to be represented in Cartesian form (real part and imaginary part) rather than polar form (modulus and angle). The interior point method (IPM) is an efficient numerical optimization technique for solving nonlinear optimization problems, such as the OPF. Using this rectangular formulation combined with IPM, [27] therefore proposed a powerful method for solving the problem of optimizing power flow in electrical networks.

Researchers [28] presented new and improved versions of interior point methods (IPM) applied to the optimal power flow optimization problem (OPF). The search for the optimal solution is based on the combination of two directions of displacement in the solution space: Affine scaling: which dynamically adjusts the algorithm's steps to accelerate convergence; Centralization: which regularly brings the solution back towards the center of the admissible region, thus improving the algorithm's stability and reliability. The authors have shown that the appropriate combination of these two displacement directions can significantly enhance the performance of the IPM algorithm in terms of convergence speed and robustness in solving the complex problem of power flow optimization. This hybrid approach therefore seems promising for efficiently dealing with OPF problems, which are crucial for optimal management of modern power grids.

3.2. Gauss-Seidel method

Early methods were based on the Gauss-Seidel method for the Y admittance matrix. It doesn't require much memory space and is relatively simple to program. For a multivariate system, the Gauss-Seidel method uses the most recently calculated value at each iteration. The Gauss-Seidel method is characterized by poor convergence; it can diverge completely if the initial value is poorly chosen. But small networks require few iterations to converge. Larges networks, on the other hand, require a large number of iterations if they are to converge. This disadvantage prompted researchers to develop the Newton-Raphson method.

An optimal control scheme and a triangular factorization of the admittance matrix were suggested in [29]. A phase-decoupled solution method, also based on the implicit Gauss Zbus approach, was presented in [30]. This decoupling technique can also be applied to asymmetrical line and transformer models to reduce total computation time. A method based on a Gauss-type approach and using a reference loop frame of reference was recently presented [31] for the solution of unbalanced three-phase distribution systems. A Gauss-Seidel method is also used in GridLab-D [32].

In short, the principle of this method is based on the sequential adjustment of power variables until convergence is reached. Advantages include simplicity and ease of implementation. However, this method also has its limitations, notably slow convergence and inefficiency for large systems.

3.2.1. Newton-Raphson method

This method requires more time per iteration than the Gauss-Seidel method, whereas it requires only a few iterations even for large networks. However, it requires significant storage and computing power. Because of the quadratic convergence of the Newton-Raphson method, a high-precision solution can be obtained in just a few iterations. These features are the key to the success of the fast decoupled Newton-Raphson method.

Conventional Newton-Raphson or Newton-type methods may fail to converge when solving the load flow problem for ill-conditioned systems. Several approaches using Newton-type solutions have been developed to solve this problem [33],[34].

One of the first methods was presented in [33] as a subroutine for optimal capacitor sizing. In fact, this method uses an iterative procedure similar to that employed by the forward/backward sweep method. The method also starts with the voltage given at the root node and all loads, but is solved by the iterative solution of two equations corresponding to the real and reactive power at the root node; the Jacobian matrix of the system is obtained by means of the chain rule. Three different algorithms derived from this have been proposed in [35].

Another Newton-type method that attracts some attention is the so-called current injection method, whose formulation is based on nodal current injections written in rectangular coordinates and considering voltage-dependent loads [36]. This method has been modified to cope with unbalanced three-phase distribution systems [34],[36]. For a comparison between the convergence of the current injection method and the forward/backward sweep method, see [37].

[24] presented a method based on the Newton-Raphson algorithm for solving the problem of optimal distribution of real-time emissions in power grids. Their approach incorporates specific sensitivity factors, allowing the Jacobian matrix and coefficients of the optimization problem to be developed as a function of a generalized generation change distribution factor. This makes it easy to calculate the emissions penalty factor and additional system losses. The authors claim that this method has a lower execution time than conventional models for solving this real-time emission optimization problem. This contribution therefore appears to offer an efficient and fast solution for optimally managing the distribution of emissions in power grids, taking real-time constraints into account.

The authors [38] have proposed two new methods for calculating load flows: the fixed Newton method, and a modification of the right-side vector method. These methods aim to simulate line failures more effectively in contingency analysis. The authors compared these approaches to the full Newton-based AC load flow method, as well as to the fast decoupled load flow, showing better convergence characteristics.

The author [39] presented a unified modeling of the Unified Power Flow Controller (UPFC) in the context of the Power Flow Optimization Problem (OPF), using Newton's method. This UPFC modeling is very flexible, allowing simultaneous control of active power, reactive power and voltage amplitude. The author has modified the networks to include several UPFC devices, reliably solved with this approach.

In summary, this method uses iterations to adjust the power variables until a convergent solution is found. It relie on successive approximation of the nonlinear function using Taylor series [40]. The advantages of this approach include rapid convergence and high accuracy for well-conditioned systems. However, it also has limitations: it may fail or converge slowly under heavy load conditions or in the presence of pronounced nonlinearities.

3.2.2. Fast Decoupled Load Flow method

Variation in active power is less sensitive to variation in voltage V, but is sensitive to variation in phase θ. On the other hand, variation in reactive power is more sensitive to variation in voltage V, and less sensitive to variation in phase θ. The fast decoupled method (FDLF) performs the same runtime as the Newton-Raphson method for very small networks.

However, it becomes faster for larger networks and for the usual tolerances [41].

[42] describes the fast-decoupling method. Its approach is based on the principle of decoupling active (MW) and reactive (MVAR) power flow calculations. This means that interactions between active and reactive power are minimized to simplify calculations. The key steps in the principle are:

- MW-θ / MVAR-V decoupling: The method separates active power and voltage angle (θ) calculations from reactive power and voltage magnitude (V) calculations into two separate sets of equations.
- Approximation of susceptance matrices: Susceptance matrices for active and reactive power flows are simplified, neglecting secondary effects such as shunt reactances and phase transformer angle changes.
- Alternating iterations: The equations are solved iteratively, alternating between updating voltage angles and voltage magnitudes, until a convergent solution is reached.

The fast decoupled load flow method offers several significant advantages. Firstly, it stands out for its speed of convergence, outperforming traditional methods such as Gauss-Seidel or even Newton's method, with solutions generally obtained in just 4 to 7 iterations. The method is also highly efficient in terms of storage, requiring less memory than Newton's method, making it particularly suitable for systems with limited storage capacity. What's more, the algebraic simplicity of the method, achieved through the approximations used, simplifies the matrices to be manipulated, making calculations faster and easier to program. The method also proves highly adaptable, being able to be applied to a wide range of practical problems, including complex networks with varied configurations. In addition, it has proved numerically stable, proving robust even to networks with convergence problems with other methods such as Newton's [42]

However, the method also has certain limitations. For example, although it is fast, it does not achieve the quadratic accuracy of Newton's method, and geometric convergence may require more iterations to obtain a highly accurate solution. Due to the simplifications made, results may be slightly less accurate, particularly in situations where unaccounted-for side effects become significant. The speed of convergence may also vary according to the complexity of the network and the initial conditions, which may require additional iterations to solve certain complex problems. Finally, the method requires several iterations to balance errors between active and reactive power flows, which can sometimes slow down overall convergence.

3.3. Alternating Current (AC) and Direct Current (DC) Methods

[1], explores the differences between alternating current (AC) and direct current (DC) power flow models, and highlights the trade-offs between DC and AC power flow methods. The DC method, despite its reduced accuracy, is fast and straightforward, ideal for initial calculations or market studies requiring rapid estimation. The AC method, on the other hand, offers high accuracy and reliability, indispensable for detailed analyses and critical decisions in the management of complex power networks. For practical applications, the choice between these methods often depends on the specific requirements in terms of accuracy, speed and complexity of the system to be analyzed.

3.3.1. Power flow methods

DC power flow is an extension of the fast decoupled Newton-Raphson formulation [44]. The DC power flow method considerably simplifies calculations by making several approximations, including [43]:

- Ignore reactive power balance equations.
- Assume that all voltage magnitudes are identically equal to unity.
- Neglecting line losses.
- Do not take transformer reactance dependence into account.

By simplifying the power flow equations in this way, the problem is reduced to a system of linear equations, where the vector of real bus power injections is directly related to the vector of bus voltage angles by a susceptance matrix. This simplification eliminates the need for iterations in the solution process.

The direct current (DC) power flow method offers several notable advantages. First of all, it stands out for its speed of calculation, as it is non-iterative and equations are solved directly. This makes it particularly advantageous for contingency analysis and solving large systems with thousands of buses. The method is also characterized by great simplicity. By considering only real power equations and ignoring the complex details of reactive power, the DC method is less complex to implement and understand, making it useful for rapid studies and initial simulations. In addition, robust load forecasting is another significant advantage. By linearly assigning loads and losses, the method enables a rapid and approximate estimate of energy requirements, which may be sufficient for applications where extremely high accuracy is not critical [43], [9], [45].

However, the DC method also has significant limitations. One of the main limitations is its reduced accuracy. By neglecting line losses and variable reactances, this method can lead to significant errors under certain conditions, particularly when systems are unbalanced or highly non-linear. What's more, the method is unsuitable for detailed analyses. The approximations it uses make it unsuitable for studies requiring fine modeling of reactive power phenomena or specific constraints linked to voltage variations and losses. These limitations mean that, despite its advantages in terms of speed and simplicity, the DC method is not always suitable for analyses requiring high accuracy and complex modeling [43], [9].

3.3.2. AC power flow methods

The AC power flow method is the most accurate for modeling the steady-state behavior of balanced three-phase power systems. It is based on the iterative resolution of a set of non-linear algebraic equations representing the real and reactive power balances at the various nodes of the system [43].

The alternating current (AC) power flow method offers several important advantages, making it a preferred choice for detailed power system analysis. Firstly, it offers high accuracy. By taking into account voltage variations, losses and reactances, this method provides an accurate representation of power flows in the system, which is essential for detailed studies and complex operational decisions. Secondly, the AC method has the ability to handle complex systems. It can handle large systems with varied topologies, including mesh networks or those featuring advanced control devices such as phase-shifting transformers and FACTS (Flexible Alternating Current Transmission System) devices. Compatibility with contingency analyses is another major advantage.

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However, the AC method also has limitations that need to be taken into account. The first limitation is complexity and computation time. Solving AC power flow equations is often complex and requires significant computational resources, especially for large systems or studies requiring numerous contingency simulations. In addition, the method may encounter convergence problems. In addition, the method may encounter convergence problems. These problems are particularly pronounced under stressed load conditions or when there are substantial changes in the system's operating point, which can make it difficult to obtain an accurate solution. These limitations indicate that, although the AC method is highly accurate and capable of handling complex networks, it can be restrictive in terms of resources and time, and may sometimes require adjustments to ensure reliable convergence.

3.4. Modern methods

The modern electrical system is becoming ever larger and more complex. When an accident occurs, engineers have to make a decision in a very short space of time, which presents them with a major challenge. Thanks to the development of computer networks and electrical equipment, the electrical system has now achieved the goal of sharing information resources. The problem of the stability of small signals has attracted a great deal of attention due to their occasional oscillations [46].

Intelligent search methods have become essential techniques for finding optimal global or quasi-global solutions. Also known as non-deterministic or stochastic methods, these techniques offer several major advantages: they are able to handle various qualitative constraints, find several optimal solutions in a single simulation, solve multi-objective optimization problems, and efficiently search for the global optimal solution.

Modern methods of power flow analysis have been addressed by several researchers, including [47], which tackles the problem of power flow analysis for direct current (DC) networks from a numerical point of view. [46] proposes a new method that can increase the stability of small signals by adjusting the power flow. [48] presents a survey of various optimization methods such as traditional and AI methods used to solve power flow optimization problems. In paper [49], a numerical Gauss-Seidel method was combined with a genetic algorithm approach to provide a purely algorithmic solution, easily implemented in any open source programming software.

The study in [50] presented an algorithm based on the behavior of artificial bees to solve the power flow optimization problem (OPF) in DC networks, taking into account several distributed generators, and mesh grid configurations were presented. In reference [51], the power flow optimization (OPF) problem was tackled using the Newton-Raphson approach and solved with commercial software as the solution technique. The authors of [52] combined the successive approximation power flow method with a metaheuristic approach, the vortex search algorithm, to solve the OPF problem by minimizing comparative errors. Paper [53] presents a convex reformulation of OPF problems in DC networks, using second-order conic programming relaxation. This approach is comparable to the convex approximations based on semidefinite programming reported in references [54], [55] and [56]. These convex methods generate a square increment of the variables to solve the power flow optimization problem (OPF). In [57], a convex quadratic approximation was proposed for OPF analysis, based on Taylor series approximation, as mentioned in [58]. This method provides approximate solutions to the exact nonlinear model by representing the distributed generators as current sources. To reduce the estimation errors associated with this quadratic model, the authors of [59] proposed a sequential quadratic programming model that solves the OPF model iteratively by shifting the linearization point. Importantly, this approach reduces the estimation error to zero by using three different power flow formulations for the OPF problem. Finally, [19] introduced a Hamiltonian formulation to solve the power flow optimization problem (OPF) in DC resistive networks, by modeling constant-power loads as impedances

3.4.1. Numerical solution methods

The main features of a Monte Carlo simulation method are random number generation and random sampling. Basically, probabilistic load flow based on this technique involves solving a deterministic power flow a large number of times with inputs of different combinations, and using the nonlinear form of the load flow equations [60], [45].

The use of exact load flow equations is the reason why results obtained from this approach are usually taken as a reference to results obtained from other probabilistic load flow solutions to check their accuracy. The main drawback of this method is the long computation time it can take due to the large number of load flow solutions that may be required [61].

3.4.2. Optimization algorithms

Optimization algorithms, including linear and nonlinear programming methods, are seeing increasing adoption in power flow analysis. This approach is based on the use of optimization techniques to reduce costs or increase efficiency, while respecting the constraints of the power system [62], [63], [45].

Several authors have presented various optimization algorithms for solving the power flow problem in electrical networks [64], [65], [66], [67], [68]. Among these authors [46] proposed the use of a bee colony optimization (ABC) algorithm to solve optimal power flow (OPF) optimization problems. The authors evaluated the effectiveness of their ABC algorithm through tests on IEEE-14 and IEEE-30 reference power systems. In addition, they compared the performance of their ABC method with other swarm intelligence techniques, namely genetic algorithms (GA) and particle swarm optimization (PSO). Simulation results showed that the proposed ABC algorithm converges slightly faster to the optimal solution, while providing solution quality comparable to other optimization methods. The work of [69] proposed a modified artificial bee colony optimization (MABC) algorithm to solve the optimal power flow (OPF) optimization problem with mixed, discrete and continuous variables. This MABC approach incorporates a fuzzy basis in order to take into account the effects of valve points, which introduce a discrete nature into the classical OPF problem. The MABC algorithm developed by the author is thus able to efficiently handle both continuous variables, such as generator settings, and discrete variables, such as valve point positions, encountered in realistic OPF problems

The work in [70] developed a variant of the artificial bee colony (ABC) optimization algorithm, called "Harvest Season ABC" (HS-ABC). The aim of this new version was to improve the performance of the ABC algorithm, particularly in terms of search mechanism and convergence speed. The authors evaluated the effectiveness of their HS-ABC method on the IEEE-62 reference power system, and compared it to other known ABC variants, such as SFABC, SBABC, MOABC and IABC. Numerical results showed that the proposed HS-ABC method significantly reduced the number of iterations required to converge, compared with other versions of the ABC algorithm.

In terms of advantages, these methods offer great flexibility and the ability to integrate complex constraints. However, they can also present limitations in terms of the need for significant computational resources.

3.4.3. Machine learning techniques

Machine learning techniques, notably neural networks and machine learning algorithms, are increasingly being explored in the field of power flow calculation. These approaches aim to model and predict future power system states by learning from large historical data sets [62], [40].

The underlying principle is to train models on these data to capture the complex, non-linear relationships between power system variables, such as demand, generation and transmission constraints.

Several authors have presented various machine learning techniques for solving the power flow problem in power systems. Among these authors [71] presented a new approach to solving the power flow optimization problem (OPF) in power systems. The proposed method uses neural networks to model generator capacity curves. These capacity curves are then integrated as output power constraints in the OPF problem. In addition, the author has also replaced the particle swarm optimization (PSO) algorithm classically used to solve the OPF, with a neural network. This speeds up computation and makes the approach suitable for real-time use. This contribution thus combines deep learning based on neural networks with classical optimization techniques to propose an innovative OPF solution, more efficient and adapted to the operational constraints of modern power grids.

The work of [72] has proposed an approach aimed at speeding up the solution of the power flow optimization problem (OPF) in power grids. Their strategy combines a dedicated artificial neural network (ANN) to perform the power flow calculations, with a genetic algorithm (GA) responsible for performing the optimization itself. Tests have shown that this hybrid method considerably speeds up the process of solving the OPF, compared with using a GA alone. Moreover, the quality of the solutions obtained remains similar.

The work of [73] presented an integrated system called ISCOD (Integrated Security Constrained Optimal Dispatch) designed to solve the power flow optimization problem (OPF) while taking into account the static and dynamic security constraints of the power grid. This ISCOD system is capable of solving the OPF by integrating both static security aspects, linked to the physical limits of equipment, and dynamic security aspects, relating to the stability and transient behavior of the network. This innovative approach ensures that the OPF solutions obtained meet not only conventional technical constraints, but also the safety requirements of the power system, under both static and dynamic operating conditions.

Among their advantages, these techniques offer a remarkable ability to manage complex electrical systems and learn dynamic behaviors that often escape traditional analytical models.

However, they are not without their limitations. They require substantial quantities of high-quality data and significant computing power to train the models. Furthermore, the interpretability of the results can be limited, posing challenges for the detailed understanding of the decisions made by machine learning models in the specific context of electric power flow.

4. Conclusion

This article has provided a comprehensive overview of the issues involved and the main methods for calculating power flow in electrical networks. Power flow analysis is an essential step in the planning, management and monitoring of power systems, enabling voltages, currents and powers in the system to be determined. The key objectives of this analysis are to calculate the reactive and active power in the transmission lines, to determine the potential differences at each node, to check that the lines are not overloaded, and to monitor the network in the event of reclosing, in order to optimize dispatching.

This article traces the historical evolution of power flow calculation methods, from early manual approaches to more sophisticated computational methods such as Gauss-Seidel, Newton-Raphson and fast decoupled methods. These conventional methods have undergone many years of research and improvement to meet the challenges posed by the growing complexity of power grids. With the growing integration of renewable energies and smart grids, the accuracy and robustness of power flow models are becoming increasingly critical. Modern methods, including optimization algorithms and machine learning techniques, offer promising ways of overcoming these challenges by making it possible to model increasingly complex systems. They offer flexibility and the ability to adapt to new constraints, but also require significant computing resources and massive quantities of data. Thus, the future of power flow analysis lies in a judicious combination of these traditional and modern approaches to meet needs.

In short, power flow analysis is an essential tool for ensuring the stability and efficiency of modern power grids. Continued progress in the development of advanced calculation methods will enable us to meet the ever-increasing demands of these complex systems.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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