

BRIDGING TWO WORLDS: A MODERN LOOK AT LOAD FLOW IN HYBRID AC/DC GRIDS

An Overview of the Structures, Methods, Challenges, and Applications for Analyzing AC/DC Distribution Networks

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MODERN ELECTRICAL DISTRIBUTION SYSTEMS are undergoing a fundamental transformation. A flood of clean energy from local sources—like rooftop solar panels and community wind turbines—is changing the paradigm. At the same time, our world is increasingly powered by direct current (DC), from batteries in electric vehicles (EVs) to the massive data centers that run our digital lives. This

evolution is not just a technical curiosity; it is a critical response to global imperatives for decarbonization, enhanced grid resilience, and the accommodation of a new energy consumer who both produces and consumes power.

This new landscape exposes the inefficiencies of purely alternating current (AC) architecture. In response, the hybrid AC/DC distribution network has emerged as a promising solution, integrating dedicated DC subgrids within the traditional AC

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framework. By establishing these DC pathways, such networks boost efficiency by minimizing lossy conversion stages. Furthermore, they enhance system reliability and significantly increase the grid's capacity to host renewable energy sources without disrupting existing AC systems.

However, this integration introduces significant operational complexities. The behavior of a hybrid network is governed not only by conventional AC physics but also by the sophisticated control of the power electronic converters that form the active interface between the AC and DC domains. Consequently, a robust understanding of the network's steady-state operating point is paramount for effective system planning and operation, establishing load flow analysis as the central computational challenge. This challenge is magnified in distribution networks, where distinct characteristics hinder traditional analysis methods. Unlike highly meshed transmission systems, they typically have a radial structure, an extremely large number of branches, and *high resistance-to-reactance (R/X)* ratios. Furthermore, they are defined by multiphase and unbalanced operation, features that violate the simplifying assumptions underpinning classical power flow algorithms, rendering them inaccurate or prone to diverge.

This article discusses the primary methods for load flow analysis in hybrid AC/DC distribution systems, beginning with a review of the overall structure of these networks and followed by an examination of the challenges and possible applications of load flow solutions. A clear understanding of these computational methods is essential as they form the foundation for the planning, operation, and optimization of future distribution grids.

Hybrid AC/DC Distribution Systems: A Component-Level View

A hybrid AC/DC distribution network is characterized by the

coexistence and coordinated operation of both AC and DC subgrids, interconnected through one or more power electronic converters. Figure 1 represents the conceptual general structure of this type of network. This architecture is designed to leverage the strengths of both systems: the mature infrastructure and conventional compatibility of AC and the high efficiency and controllability of DC for integrating modern distributed energy resources (DERs). The fundamental components and their relevance to load flow studies are detailed next.

Foundational Grid Components

A distribution system is composed of various components that provide power from the utility to customers. Understanding the systems begins with their foundational components, each with a distinct role and characteristics relevant to load flow analysis.

- ✓ *AC and DC subgrids:* The AC subgrid is the conventional portion of the network, serving as the backbone of the electrical grid; it is often multiphase and operates under unbalanced conditions. It accommodates the vast infrastructure of existing AC loads, ranging from commercial heating, ventilation, and air-conditioning systems to residential appliances. The DC subgrid, in contrast, is the modern core designed to efficiently manage

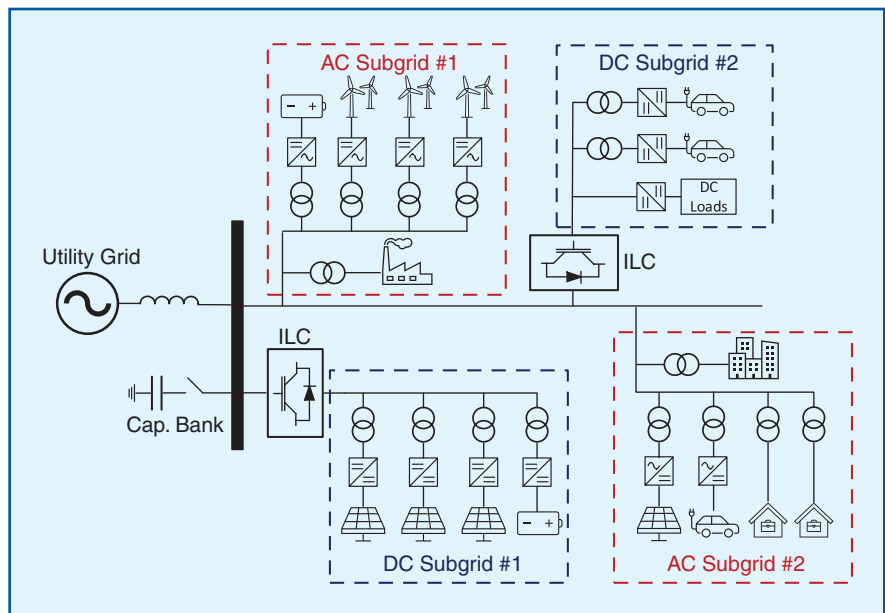


Figure 1. The conceptual hybrid AC/DC distribution network. Cap.: capacitor.

The primary function of transformers is to modify voltage potentials, enabling the interconnection of network sections operating at various voltage levels.

native DC power flows. In this context, “native DC” refers to technologies—such as solar panels, batteries, and electronics—that naturally generate or consume DC. Connecting these devices directly to a DC subgrid eliminates the energy losses that would otherwise occur during conversion to AC. The DC subgrid has the advantage of having no reactive power circulation or frequency synchronization requirements.

- ✓ *Lines and cables:* These are the physical components responsible for transporting energy throughout the network. This category includes both overhead lines and underground cables, which, for load flow studies, are represented by detailed mathematical models, such as multiphase pi representations.
- ✓ *Transformers:* The primary function of transformers is to modify voltage potentials, enabling the interconnection of network sections operating at various voltage levels. In addition to this primary function, transformers with tap-changing mechanisms, also known as voltage regulators, provide a crucial voltage regulation function to maintain stable voltage along a feeder. For analysis, specialized multiphase models are required to account for the various phase winding connections found in these unbalanced systems.
- ✓ *Capacitors:* Capacitor banks are installed in distribution systems to perform two primary functions; they help control voltage along the feeder and provide reactive power for power factor correction, which in turn helps reduce overall system losses. In load flow equa-

tions, they can be represented as a constant impedance or as a power-voltage (PV) node. Within the power flow equations, a PV node is defined as a bus where active power and voltage magnitude are specified as known variables, while reactive power and the voltage phase angle are calculated as unknowns.

- ✓ *Loads:* This category includes both AC loads and DC loads. For analysis, AC loads like household appliances and industrial motors are represented as a PQ node; however, for realistic studies, this is often a time-varying daily load profile based on measurements or stochastic models. A growing category of DC loads, including data centers and EV fast-charging stations, is also modeled as PQ loads. The aggregate load from multiple EVs is highly stochastic and time variant, depending on factors like driver charging habits, and requires probabilistic methods for accurate planning studies.

Power Electronic Converters: The AC/DC interface

The connection between the AC and DC portions of the hybrid network is managed by power electronic converters, which act as intelligent gateways for electrical energy. Unlike passive components like lines or transformers, the operation of a converter is not fixed; it is actively governed by advanced control strategies. For load flow studies, this means that a converter’s model is defined by its control targets, such as the amount of power to transfer or a voltage level to maintain.

The interlinking converter (ILC) is the bidirectional device that forms the main bridge between the AC and DC subgrids. The ILC’s versatility is central to the hybrid grid’s operation. It manages the exchange of both active and reactive power, provides voltage support to the AC side, and can even take over the role of stabilizing the DC bus voltage. [Figure 2](#) represents the ILC and its simplified control logic between AC and DC subgrids. Crucially, its control system allows it to adapt to different grid conditions, switching between a grid-connected

mode and an islanded mode to ensure reliability during a utility outage.

In addition to the main ILC, other component-level converters perform specialized roles. DC/DC converters are used to match the different voltage levels of DC components, such as connecting a solar array to the main DC bus, while AC/DC converters allow DC-based resources to supply power to the AC side. These converters often incorporate additional control functions, such as maximum power point tracking to optimize generation from renewable sources and harmonic suppression to maintain power quality.

Load Flow Characteristics of DERs

Unlike conventional power plants, the output of DERs is often variable, and their behavior is governed by sophisticated power electronics. Capturing these unique operational characteristics is essential for an accurate load flow analysis as the models must account for a wide range of operating conditions.

Solar Photovoltaics: The defining characteristic of a photovoltaic system is its intermittent and variable nature. Its active power output is not constant; it is directly dependent on environmental factors like solar irradiance and temperature, which change throughout the day and with weather conditions. Because of this uncertainty, a single deterministic load flow is often insufficient for planning. Instead, studies frequently use probabilistic or scenario-based approaches to understand the system's behavior across a range of possible solar outputs. For a specific snapshot in time, a photovoltaic system is typically modeled as a source injecting a determined amount of active power.

Wind Turbines: As with solar photovoltaic, the primary char-

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acteristic of a wind turbine is that its active power injection is a function of a variable resource—in this case, wind speed. A key feature of modern variable-speed wind turbines, however, is their power electronic interface. Like the advanced inverters found in modern solar and battery systems, this interface gives them the advanced capability to provide reactive power support to the grid, independent of their active power production. This characteristic allows them to actively participate in voltage support, a crucial function that must be accurately represented in their load flow model.

Battery Energy Storage Systems (BESSs): The key characteristic of a BESS is its versatility and bidirectional capability. It can function as either a load (charging) or a source (discharging), making its load flow model highly state dependent. The

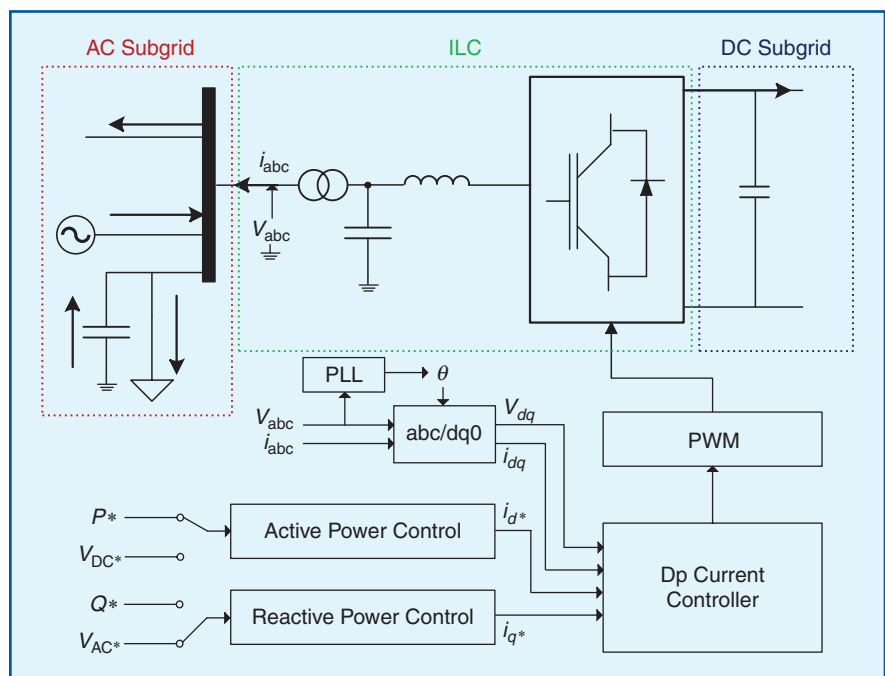


Figure 2. A representation of the interlinking converter (ILC) and its control block diagrams. PLL: phase-locked loop; PWM: pulse-width modulation.

The BFM is a formulation naturally suited to the radial structure of distribution networks that retain branch currents and power flows as explicit variables.

model used depends on the battery's assigned task. In power dispatch mode, a BESS is modeled as a standard load or generator scheduled to absorb or inject a specific amount of power. In grid support mode, particularly in an islanded DC subgrid, its role changes completely. It may be tasked with regulating the bus voltage, in which case it assumes the role of the slack bus, providing whatever power is needed in real time to balance the network.

EVs: While an individual EV charger can be modeled as a simple constant power load, the defining characteristic of EV loads is the unpredictability of their aggregate demand. The collective load from a public charging plaza is highly stochastic and time variant, depending on driver behavior and charging habits. This uncertainty requires the use of load profiles or probabilistic methods in planning studies. Furthermore, the emerging characteristics of vehicle-to-grid technology transform the EV from a simple load into a distributed BESS, capable of both consuming and injecting power.

The combination of these components creates a highly integrated and controllable network. The specific topology can vary, with common configurations being AC-coupled, DC-coupled, or fully integrated AC-DC-coupled systems, with the latter presenting the most complex and interesting case for load flow analysis.

Load Flow Methodologies for Hybrid AC/DC Networks

The solution of the load flow problem in hybrid AC/DC distribution networks requires a sophisticated approach that accounts for the unique properties and topology of distribution systems while

also managing the complex coupling introduced by power electronic converters. This section reviews the foundational mathematical models, the principal solution algorithms designed for distribution networks, the critical modeling of the AC/DC interface, and the strategies used to solve the hybrid distribution system.

Mathematical Model and Power Flow Algorithms

At its core, the load flow problem consists of a set of nonlinear equations describing the relationship between bus voltages and power injections. For multiphase unbalanced distribution systems, these relationships can be formulated in two primary ways, as illustrated in the diagram in [Figure 3](#).

- ✓ *Bus injection model (BIM):* The BIM is the classical formulation that relates the current injected at each bus to the bus voltages through the *bus admittance matrix* (Y_{bus}). This approach results in a compact set of equations that involves only bus voltages. However, its direct application can face convergence issues in distribution systems.
- ✓ *Branch flow model (BFM):* The BFM is a formulation naturally suited to the radial structure of distribution networks that retain branch currents and power flows as explicit variables. It is built upon fundamental physics for each branch, including Ohm's law and Kirchhoff's current law. While involving more variables, its intuitive structure serves as the basis for highly robust solution methods.

Based on these foundational models, several principal solution algorithms have been developed.

- ✓ *Topology-based methods:* The most prominent algorithm in this class is the backward-forward sweep (BFS). This method directly takes advantage of the tree-like radial topology of most distribution feeders to achieve a robust solution. It works as a two-stage iterative process. The backward sweep starts from the network's extremities and moves toward the substation, calculating the power flow in each branch by summing the loads

of all downstream nodes. The forward sweep then starts at the substation (where voltage is known) and moves outwards, calculating the voltage drop across each branch to update the voltage at every subsequent node. This process is repeated until the voltage solution converges.

✓ *Matrix-based methods:* These methods solve the load flow problem by creating a single large system of equations that is solved simultaneously.

- *Newton-Raphson (NR) method:* The standard NR method uses the Jacobian matrix to linearize power balance equations, allowing for quadratic convergence speeds. However, in distribution systems, the high R/X ratios and radial structure often cause the Jacobian to become ill conditioned, leading to numerical instability or divergence.

- *Current injection method (CIM):* To overcome the limitations of the standard NR method, the CIM formulation was developed. Instead of using power balance equations, the CIM uses current balance equations in rectangular coordinates. This subtle shift is critical; it results in a Jacobian matrix that is typically well conditioned and diagonally dominant, even for networks with high R/X ratios, making it a highly effective and stable alternative for distribution analysis.

- *Modified augmented nodal analysis (MANA):* A more recent and powerful formulation is MANA. Unlike traditional methods that may struggle with the diverse control modes of DERs, MANA explicitly includes auxiliary variables for component states (such as converter control limits) and branch currents di-

rectly in the system matrix. This allows it to model arbitrary topologies and complex active components within a unified framework, offering superior robustness for hybrid AC/DC networks.

✓ *Fixed-point iterative methods:* The Gauss-Seidel method is another classic algorithm that solves the load flow problem iteratively. Conceptually, it sweeps through the system's buses one by one, calculating the voltage for each bus based on the most recently updated voltages of its neighbors. While straightforward, the standard Gauss-Seidel method is known for its poor or slow convergence characteristics, especially in large systems. Adaptations for distribution systems, such as the Gauss implicit Z-matrix method, have been developed to improve performance.

Advanced Modeling of the AC/DC ILC

The ILC is the core component enabling the hybrid network, and its model is the critical link between the AC and DC subgrids. Unlike passive components, the ILC's behavior is dictated by its control strategy, which must be accurately reflected in the load flow equations. Key control modes include the following:

- ✓ *DC voltage control:* The ILC maintains the DC bus voltage at a constant set point, effectively acting as the slack bus for the DC

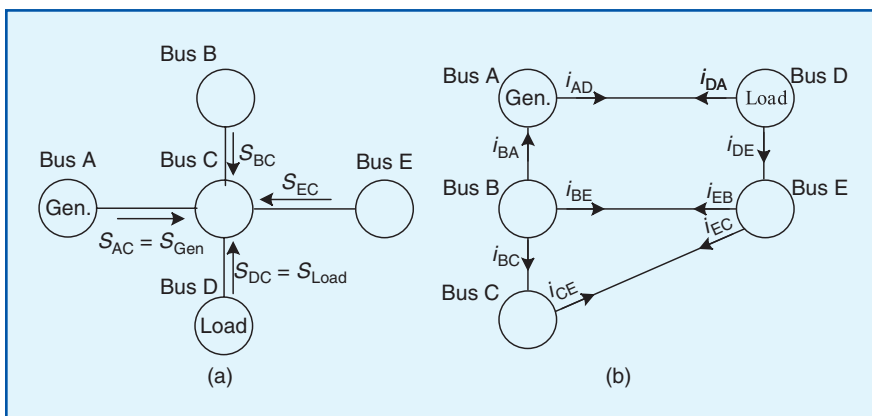


Figure 3. A visual comparison of nodal-based [bus injection model (BIM)] and branch-based [branch flow model (BFM)] formulations for power flow analysis. (a) BIM. Focus: Voltages and power injections (nodal variables). (b) BFM. Focus: Currents and power flows (branch variables). Gen.: generator.

network. Its active power transfer becomes a dependent variable, determined by the power balance on the DC side.

- ✓ *Active power control:* The ILC is dispatched to transfer a specific amount of active power. In this mode, the DC bus voltage becomes a dependent variable.
- ✓ *AC side control (V/Q):* The ILC can be controlled to inject a specific amount of reactive power into the AC grid (Q-control) or regulate the voltage at its point of connection (V-control), providing valuable ancillary services.

The converter model must also include equations for its internal power losses, typically a function of the current magnitude, to ensure that an accurate power balance is maintained between the AC and DC sides.

Frameworks for Hybrid AC/DC Analysis

To solve the more complex problem of a combined AC/DC network, the core algorithms are applied within a higher-level framework.

- ✓ *Sequential framework:* This is an iterative “divide and conquer” approach where the AC and DC subgrids are solved separately (Figure 4). The AC load flow is solved

first; its results at the connection point are used to update the DC model; the DC load flow is then solved, and its results are passed back to the AC model. This process repeats until the solutions for both subgrids converge. While simpler to implement, this framework can struggle with tightly coupled systems where the AC and DC sides strongly influence each other.

- ✓ *Unified framework:* This approach, also called an integrated method, combines all the equations—for the AC network, the DC network, and all the ILCs—into a single large system of nonlinear equations (Figure 4). This system is then solved simultaneously. The unified framework is more complex to formulate but offers superior robustness and faster convergence for highly integrated networks as it inherently captures the tight coupling between the AC and DC domains in one step.
- ✓ *Probabilistic approach:* The methods described previously are typically deterministic, meaning that they solve for a single snapshot in time with fixed inputs. However, the power

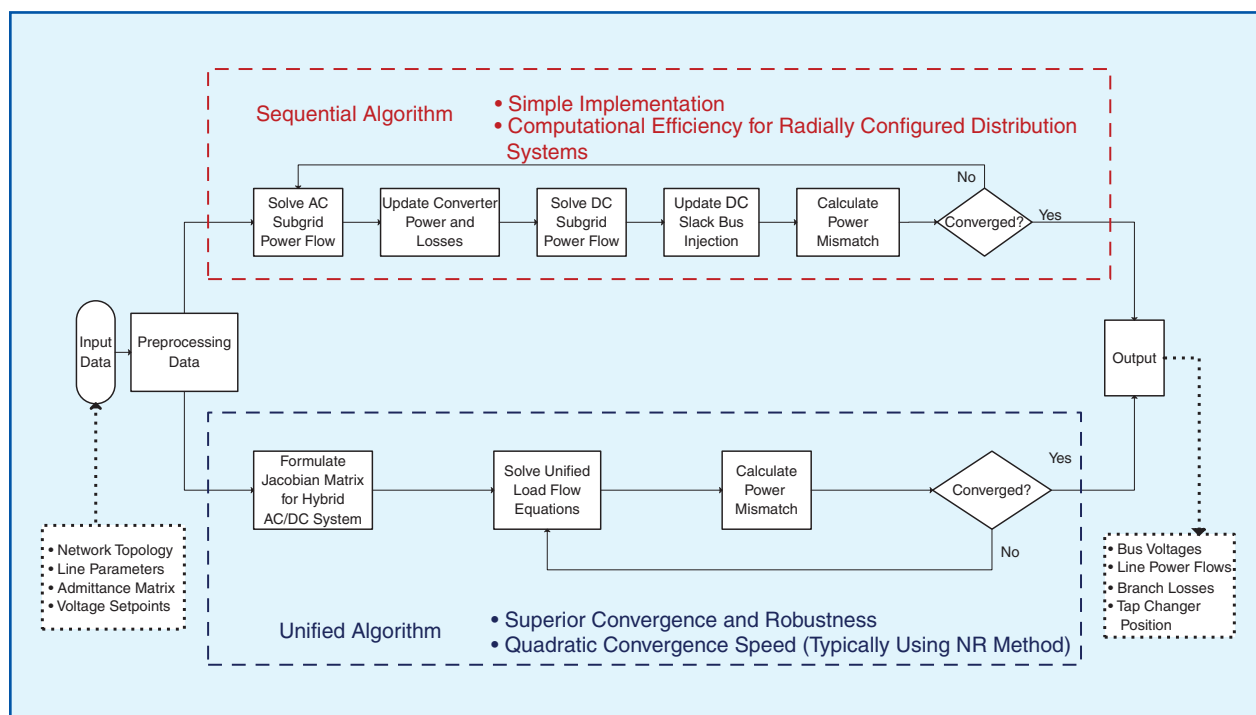


Figure 4. A flowchart comparison of sequential and unified load flow algorithms.

injection from solar and wind, as well as the demand from EV chargers, is stochastic and time varying. A single deterministic solution is often insufficient for planning. This necessitates a shift to probabilistic load flow, which involves running many individual load flow simulations under different scenarios, often using a Monte Carlo approach. Instead of a single answer, the result is a statistical distribution of possible outcomes (e.g., voltage levels), giving planning engineers a much more realistic understanding of the system's potential behavior.

Several advanced methods have been proposed for solving load flow in hybrid AC/DC systems, reflecting ongoing research in this area. The holomorphic embedding load flow method is a noniterative approach that formulates the power flow problem as a series expansion in the complex plane, guaranteeing convergence even under stressed system conditions; it has recently been extended to voltage source converter AC/DC microgrids, demonstrating accurate solutions for coupled networks. Graph-theory-based methods model AC/DC networks as graphs, where buses and converters are nodes and lines are edges, allowing the load flow problem to exploit network topology for computational efficiency; such approaches have been applied successfully to radial hybrid distribution systems. Decoupled hybrid methods leverage the weak coupling between AC and DC subsystems, solving them iteratively or sequentially using sensitivity factors or linear approximations, which reduces computational

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effort and is particularly useful for large-scale hybrid distribution networks.

Comparative Performance of Solution Methods

Selecting a load flow algorithm involves tradeoffs among implementation complexity, speed, and numerical robustness. While topology-based methods often suit simple radial feeders, complex hybrid grids with meshed structures or high R/X ratios require the superior stability of unified matrix approaches. Table 1 synthesizes these characteristics to aid in selecting the appropriate method for specific distribution environments.

Challenges in Load Flow Analysis for Hybrid Networks

While the methodologies described provide a pathway to solving the load flow problem, their application to hybrid AC/DC distribution networks is fraught with challenges. These challenges stem from the inherent characteristics of distribution systems, the active nature of power electronic converters, and the increasing uncertainty introduced by DERs (Figure 5).

Table 1. A comparison of load flow methods for hybrid AC/DC systems.

Method	Formulation	Convergence Speed	Computational Burden	Best Suited for
Sequential (BFS)	Decoupled AC and DC sweeps	Linear (slower)	Low	Radial topologies with weak AC/DC interactions
Unified (NR)	Simultaneous Jacobian solution	Quadratic (fast)	High	Meshed networks; systems with strong coupling
Current injection (CIM)	Current mismatch equations	Linear	Medium	Unbalanced distribution networks require high stability
MANA	Augmented matrix	Quadratic	High	Complex topologies with advanced converter controls; generalized solvers

The model must be able to switch between different sets of equations depending on the active control mode (e.g., DC voltage control versus active power control).

Convergence Robustness

Achieving reliable convergence is the most fundamental challenge. As discussed earlier, the high R/X ratios of distribution lines can cause the Jacobian matrix in traditional NR methods to become ill conditioned, leading to divergence. While methods like the BFS and CIM are designed to be more robust for standard distribution networks, the tight coupling introduced by the ILC in hybrid systems can reintroduce convergence difficulties, especially in the sequential solution framework. If the power exchange between the AC and DC subgrids is large, the iterative passing of boundary conditions between the two decoupled solutions can oscillate and fail to converge to a stable operating point.

Modeling Fidelity of Active Components

The accuracy of the load flow solution is entirely dependent on the fidelity of the component models. For hybrid networks, this is particularly challenging for the active components.

- ✓ *ILC*: Accurately representing the ILC's control logic and its associated nonlinear losses is complex. The model must be able to switch between different sets of equations depending on the active control mode (e.g., DC voltage control versus active power control), which adds a layer of logical complexity to the solver.
- ✓ *DERs*: The power output of renewable energy sources like solar and wind is variable and uncertain. Furthermore, the behavior of their inverters, especially advanced “smart inverters” that provide grid support functions like voltage regulation, must be captured by the load flow model. This transforms what was a simple load or generator into a complex controllable element.

Computational Complexity and Scalability

Distribution networks are characterized by an extremely large number of nodes and branches. While algorithms like BFS are effective, their iterative nature can be slow for very large systems. The unified method, which solves a single large matrix equation, is often faster per iteration but faces scalability challenges. The inclusion of multiphase models, the DC network, and the detailed converter equations results in a very large and computationally expensive system of equations to solve. This computational

burden becomes a significant barrier for applications requiring repeated load flow calculations, such as time-series analysis or Monte Carlo simulations.

Handling of Uncertainty and Variability

The transition from deterministic to probabilistic analysis introduces a massive computational bottleneck. Because hybrid AC/DC models are already mathematically complex and computationally expensive to

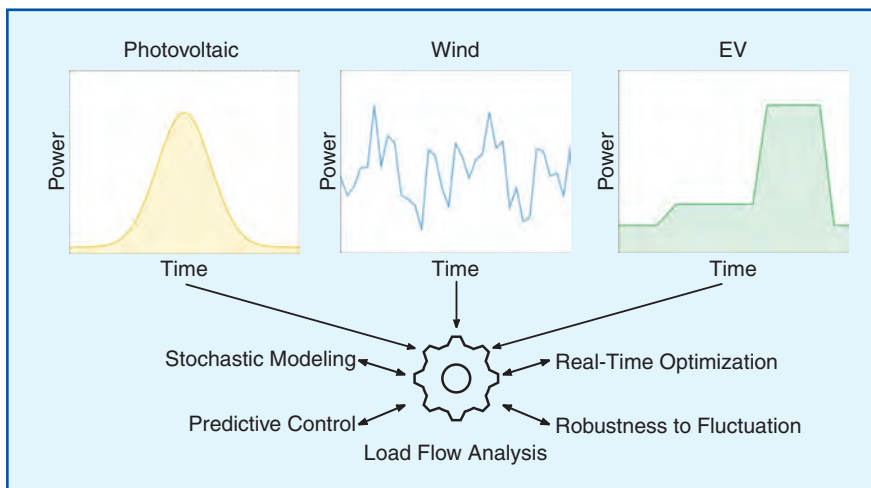


Figure 5. Uncertainty and variability in DERs for hybrid AC/DC load flow.

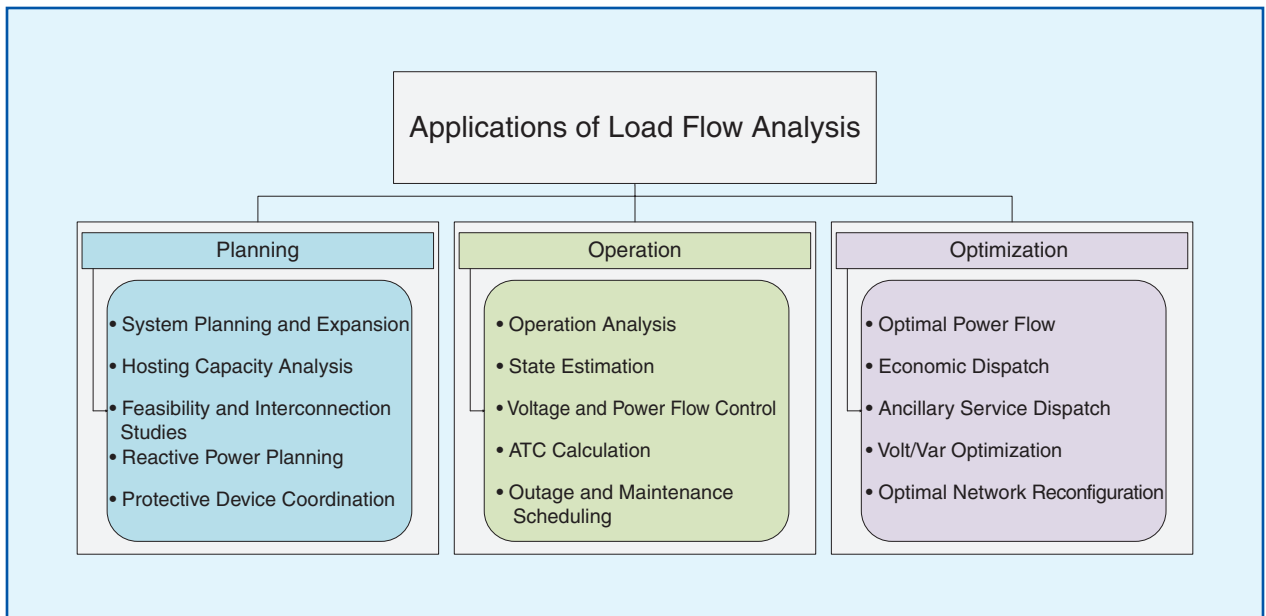


Figure 6. A framework for load flow applications. ATC: available transfer capability.

solve, extending them to probabilistic frameworks—which may require numerous Monte Carlo iterations—can make simulation times prohibitively long. The challenge lies in balancing statistical accuracy with computational speed. This tradeoff drives the urgent need for faster, perhaps linearized, solution algorithms or advanced sampling techniques that can capture the system’s volatility without imposing an excessive computational burden.

Applications of Load Flow Analysis

An accurate and robust load flow solution is not an end in itself but rather a foundational tool that enables a wide range of critical engineering functions for hybrid AC/DC distribution networks. The insights derived from determining the system’s steady-state voltages and flows are essential for both long-term planning and real-time operational decision making. The framework for these applications is illustrated in [Figure 6](#).

System Planning and Expansion

Load flow analysis is indispensable for planning the future development of the distribution grid. Planning engineers run numerous load flow studies to evaluate the impact of various scenarios, such as load growth, the addition of new DC subgrids, or the integration of

large-scale DERs like community solar farms or EV charging plazas. These studies help identify potential issues like voltage violations or thermal overloads of lines and transformers before they occur, ensuring that any necessary system upgrades are performed proactively and cost-effectively.

Hosting Capacity Analysis

A key question for modern utilities is determining the maximum amount of DERs that can be integrated into a specific feeder without causing adverse impacts. This is known as *hosting capacity*. Its calculation relies on performing a large number of load flow simulations under a wide range of generation and load scenarios to identify the point at which operational limits (e.g., voltage limits and thermal limits) are first violated. A fast and reliable load flow algorithm is therefore essential for conducting these computationally intensive studies.

Operational Analysis and State Estimation

In day-to-day operations, load flow is used to understand the current state of the network. While real-time measurements are available, they are often incomplete. State estimation is a process that combines available telemetry data with a network

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model to compute the most likely complete state of the system, with a load flow calculation at its core. An accurate picture of all bus voltages and branch flows allows operators to ensure that the system is operating within safe limits and to anticipate the consequences of potential control actions.

Optimal Power Flow and Economic Dispatch

Optimal power flow (OPF) is an extension of the load flow problem that seeks to find an operating point that is not only feasible but also optimal with respect to some objective, such as minimizing generation cost or network power losses. The load flow equations form the primary constraints of the OPF problem. By leveraging the OPF, system operators can dispatch DERs, schedule battery charging and discharging, and control the power transfer through the ILC in the most economically efficient manner while respecting all physical network constraints.

Concluding Remarks

The transformation to hybrid AC/DC distribution systems represents a critical step toward a more efficient and decarbonized grid, capable of hosting a new generation of renewable resources and DC-native loads. As this article has detailed, the unique characteristics of distribution networks, combined with the sophisticated control of power electronic converters, require load flow calculations to consider a greater range of variables and operational complexities. Developing specialized algorithms, applied within either sequential or unified frameworks, is therefore essential for achieving a robust load flow solution. This foundational analysis underpins a wide range of critical engineering func-

tions, including system planning, operation, and optimization. As the grid's complexity continues to grow, the development of these advanced analytical tools is not merely a technical exercise; it is the essential engineering groundwork for building the intelligent and resilient energy infrastructure of the future.

For Further Reading

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