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Operational Planning for Emerging Distribution Systems: A Unique Perspective on Grid Expansion

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Full text available at: http://dx.doi.org/10.1561/3100000033

Foundations and Trends® in Electric Energy Systems

Published, sold and distributed by:
now Publishers Inc.
PO Box 1024
Hanover, MA 02339
United States
Tel. +1-781-985-4510
www.nowpublishers.com
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Outside North America:
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The Netherlands
Tel. +31-6-51115274

The preferred citation for this publication is

A. Stuhlmacher *et al.*. *Operational Planning for Emerging Distribution Systems: A Unique Perspective on Grid Expansion*. Foundations and Trends® in Electric Energy Systems, vol. 7, no. 2, pp. 63–164, 2023.

ISBN: 978-1-63828-301-0
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Volume 7, Issue 2, 2023

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Foundations and Trends® in Electric Energy Systems, 2023, Volume 7, 4 issues. ISSN paper version 2332-6557. ISSN online version 2332-6565. Also available as a combined paper and online subscription.

Contents

Operational Planning for Emerging Distribution Systems: A Unique Perspective on Grid Expansion

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ABSTRACT

The electrical grid has undergone significant transformations, which have had a profound impact on its distribution system development and expansion. These changes have been primarily driven by changing load profiles, distributed generation sources, and increasingly extreme weather events. Advancements in sensor and communication technologies have played a pivotal role in addressing and adapting to these changes. These changes have also led to an increased focus on reliability and resilience in planning, with priority placed on ensuring robust grid connectivity and flexibility.

Three decades ago, power distribution systems were primarily radial with unidirectional power flow. Today's electrical distribution systems have distributed energy resources, leading to bidirectional power flow. The utility's geographic information system network, advanced metering infrastructure, and other technologies are leveraged to allow feeders

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Anna Stuhlmacher, Chee-Wooi Ten, Lawrence Dilworth and Yachen Tang (2023), "Operational Planning for Emerging Distribution Systems: A Unique Perspective on Grid Expansion", Foundations and Trends® in Electric Energy Systems: Vol. 7, No. 2, pp 63–164. DOI: 10.1561/3100000033.

and distributed energy resources to be interconnected. This has facilitated the integration of the electric grid with networked microgrids, which has improved the overall resilience and efficiency of the distribution system.

While there have been notable improvements in grid planning, the power grid remains vulnerable to high-impact, low-frequency events caused by climate change, such as hurricanes and tornadoes. This monograph outlines potential solutions for addressing future electric grid issues, including transformer overloading due to electric vehicles, optimization challenges, advanced feeder reconfiguration, and contingency planning for extreme events. The proposed approaches focus on the implementation and operation of new technologies, such as renewable energy sources, batteries, flexible loads, and advanced sensors, that have the potential to transform distribution network planning and operation. From traditional methods to innovative networked microgrids within existing infrastructure and non-wire alternative strategies, this monograph provides a comprehensive overview of state-of-the-art strategies for future problems.

Full text available at: http://dx.doi.org/10.1561/3100000033

1

Introduction

The electrical distribution grid has a long history dating back to the late 19th century, consisting of overhead lines, transformers, and other equipment that deliver electricity to individual consumers. Over time, the grid has undergone significant changes driven by technological advancements, evolving energy demands, and environmental considerations. The original distribution system operated in a unidirectional and radial fashion, where distribution lines linked distribution substations to individual customers. This is illustrated as a one-line diagram in Figure 1.1, where the arrows indicate the direction of power flow and the red squares denote metered points. This system was connected to a simple network of high-voltage transmission lines carrying electricity over long distances. Today's energy system is more decentralized, featuring numerous smaller, distributed energy resources generating power closer to the point of consumption. Regulatory changes helped facilitate this transition, with market competition gradually introduced since the 1970s. While this has led to more complex distribution systems capable of accommodating a wider range of energy sources and dynamic loads, there are new challenges associated with these planning and operational changes.

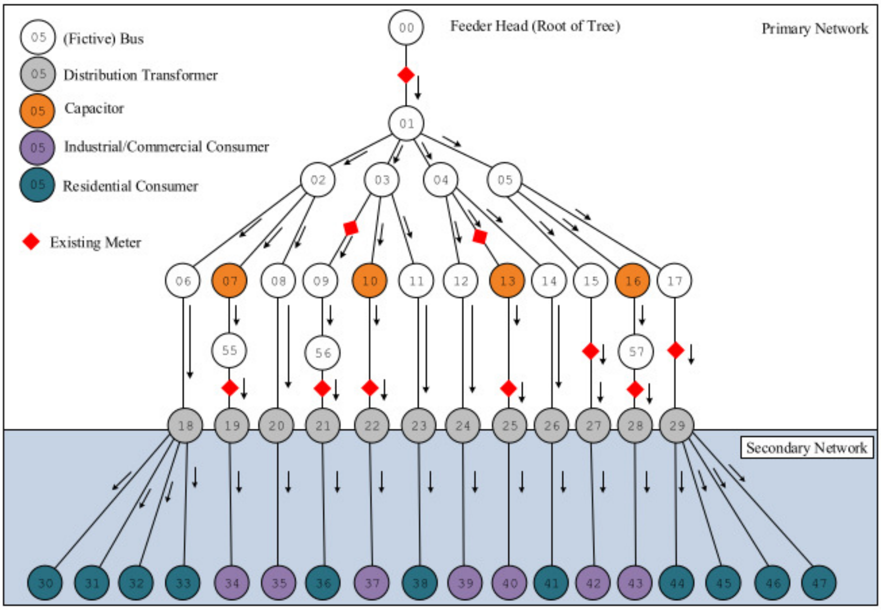

Figure 1.1: One-line diagram of a conventional feeder configuration from a past era.

Advances in technology have played a crucial role in the evolution of the distribution grid, enabling utilities to better monitor and control the flow of electricity. The rise of digital technologies such as smart meters and advanced sensors have enabled greater efficiency, reliability, and flexibility as well as improved customer service. Energy storage has also emerged as a major trend in recent years, with advances in battery technology making it possible to store large amounts of energy at increasingly lower costs, making energy storage an increasingly viable solution for grid operators. However, the integration of new technologies and energy sources into existing grid infrastructure has posed a challenge, requiring significant investments in grid modernization and the development of new standards and regulations to ensure the safety and reliability of the grid. Climate change has also presented challenges, with extreme weather events causing widespread power outages and damage to the grid.

Several key trends are expected to shape the future of the distribution grid, including the growth of distributed energy resources, the importance of data and analytics in grid management, and the development of energy storage technology. Utilities have been investing in smart grid technologies—such as advanced metering infrastructure, distributed control systems, and grid infrastructure upgrades to support bi-directional power flow—to keep up with these trends. Additionally, the development and improvement of protective relaying systems are becoming increasingly important to ensure grid stability and reliability. Investing in advanced protective relaying systems and incorporating them into operational planning is crucial to minimize downtime and equipment damage as well as enhance customer satisfaction.

1.1 Evolution of Distribution System Planning

Over the years, there have been changes in distribution utility planning. Initially, the focus was on meeting growing demand by building more transmission lines and expanding the service area. The distribution system was generally over-designed and largely ignored. Traditional planning methods, such as load forecasting, analyzed data collected from the grid, but their effectiveness was constrained by the limited availability of real-time data. However, with the increase in complexity of the grid and the evolution of customer needs, the planning process became more sophisticated.

In the 1980s and 1990s, the focus shifted to improving the efficiency and reliability of the grid. Distribution utilities invested in new technologies such as computerized monitoring systems and advanced metering infrastructure, which made it possible to collect and analyze data from the grid in real time. Feeder remote terminal units (FRTUs) were employed to automate the distribution system's computerized management system, depicted in Figure 1.2 as solid red squares. FRTUs are often pole-mounted boxes with sophisticated logic devices and small battery packs that constantly send measurements to distribution dispatching center. This centralized framework allows operators in the control room to perform informed decision making based on conclusions from the computer applications. Demand-side management became a

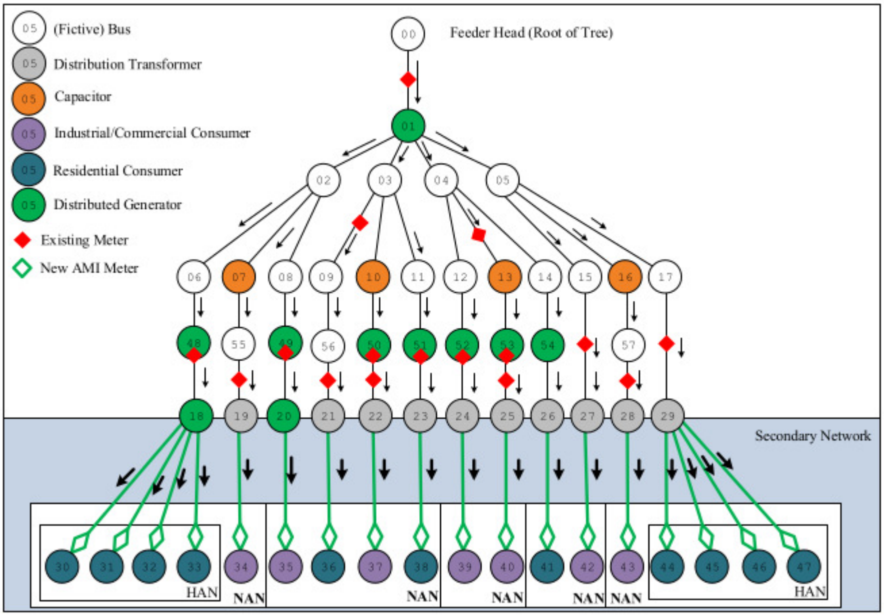

Figure 1.2: One-line diagram showcasing AMI placement and unidirectional flow of power from the feeder head to all connected customers.

focus, and customers were encouraged to reduce energy consumption during periods of high demand. This helped to reduce the need for new infrastructure investments and improve the overall efficiency of the grid.

The 2000s marked a critical era for the utility industry, characterized by a wave of new challenges driven by the increasing prevalence of renewable energy sources (RESs), notably solar photovoltaic panels and wind turbines. This shift in the energy landscape compelled utilities to adopt innovative tools and techniques for modeling and analyzing the profound impact of RESs on the grid. The key transformation lay in the need to effectively manage the two-way flow of power, which departed from the traditional one-way energy distribution model. To address this, utilities invested significantly in emerging technologies, with distribution automation standing out as a prime example. This technology enabled remote monitoring and control of power flow on the grid, ushering in a new level of grid management efficiency.

Consequently, the planning process underwent a remarkable evolution, characterized by a transition to a more data-driven and complex approach. Utilities found themselves adapting to changing customer needs and the rapid pace of technological advances. They had to integrate the fluctuating and often unpredictable energy generation from RESs into their grid infrastructure while ensuring grid stability and reliability. This required a holistic reevaluation of grid design, operational procedures, and investment strategies, ultimately reshaping the utility landscape into one that embraced sustainability, advanced technology, and a greater degree of adaptability in the face of ongoing energy transformations.

Another trend in distribution system planning is the increasing use of underground cables in various parts of the world, especially in densely populated areas and locations with challenging terrain or extreme weather conditions. While generally more expensive due to the installation process involving digging trenches, laying cables, and backfilling them, underground cables may be more cost-effective in certain situations, such as in densely populated areas where they reduce the risk of outages and have lower maintenance costs and a longer lifespan than overhead lines. Undergrounding cables is also a strategy of utilities to reduce the risk of wildfire ignition by power lines in high wildfire risk areas. In general, the use of underground cables can impact the planning of the grid by requiring additional considerations around cost, infrastructure, and overall grid capacity and flexibility.

In conclusion, the planning process for distribution utilities has recently undergone a significant evolution. The focus has shifted from meeting growing demand to improving the efficiency and reliability of the grid, and then to adapting to the challenges posed by distributed energy resources. Today, utilities are using a wide range of tools and techniques to optimize grid performance, reduce costs, and improve the customer experience. The planning process has become much more complex and data driven, reflecting the changing needs of customers and the pace of technological change.

1.2 Energy Consumption of Customers and Billing Workflow

During the 1970s, Automatic Meter Reading (AMR) technology relied on electromechanical meters. Electromechanical meters were incapable of real-time monitoring and detailed consumption data, resulting in unreliable and insufficient data for effective demand forecasting or load management purposes. It was not until the 1980s and subsequent years that AMR witnessed improved reliability and wider adoption, thanks to the emergence of more advanced technologies like solid-state meters and advanced communication protocols. Although AMR technology has been available since the 1970s, its widespread popularity did not occur until the 1990s. Advanced Metering Infrastructure (AMI) is a more recent, sophisticated innovation that commenced its initial deployments in the early 2000s. However, it was not until the mid-to-late 2000s that AMI started to gain significant acceptance within the utility sector, and it continues to undergo ongoing development and expansion even now.

While both AMI and AMR involve the collection of data from utility meters, they possess distinct capabilities. AMR is a technology that facilitates remote data collection from utility meters using wireless or power line carrier communication. AMR systems primarily gather fundamental information, such as the total energy consumption of a customer within a billing period. In contrast, AMI systems facilitate bi-directional communication between the utility and the meter. This enhanced system enables real-time monitoring and remote control of the meter. AMI systems gather data more frequently, usually every 15 minutes, offering utilities detailed insights into customer usage patterns. This data enables estimation of electricity consumption, assessment of the overall distribution system's health, and facilitates load management optimization, fault detection, and energy efficiency enhancements through data analytics.

Figure 1.2 depicts the placement of AMIs in the distribution feeder with hollow green diamonds which are replacing AMRs. Household consumption is sent via IP-based infrastructure, where homes can be grouped into home area networks (HANs) and neighborhood area networks (NANs). The metering data is generally transmitted to the utility's consumer billing center via wifi, wireless communication (e.g., LTE or

5G), or power line carriers. These metering systems incorporate advanced analytics tools to assist utilities in comprehending the enormous volumes of data collected. This data can be utilized for purposes such as demand response, outage management, and load forecasting. However, as demonstrated in [30], there is a potential risk of malware affecting distribution grid operations, which can make meter data unavailable or inaccurate. The study in [31] aims to utilize metered datasets from primary and secondary distribution networks to correlate metering inconsistencies, potentially identifying any foul play. Additionally, the granular details of metering profiles from existing meters implemented in [54] could significantly aid in grid expansion planning.

Figure 1.3 displays a large customer load profile observed over a year, with the data obtained from a meter every 10 minutes. The deployment of new smart meters can have several implications on utility planning. Here are a few ways in which smart meters can impact the planning process:

1. **Demand forecasting:** Utilities have access to more granular data on energy consumption, which can be used to better forecast demand. This information can help utilities make more informed decisions about how to allocate resources, such as building new power plants or investing in energy storage systems. The provided load profile underscores the significance of demand forecasting within emerging distribution systems, especially with the adoption of AMI. Demand forecasting involves predicting future electricity consumption patterns, crucial for ensuring a reliable power supply and efficient resource allocation. AMI systems offer utilities access to highly detailed energy consumption data, collected at short intervals, which greatly enhances the precision of forecasting. Through the understanding of usage patterns, load profiling, and predictions of future demand, utilities can make more informed decisions on infrastructure planning, the deployment of energy storage solutions, and overall resource management. This data-driven approach minimizes waste and optimizes electricity generation and distribution to meet actual demand effectively.

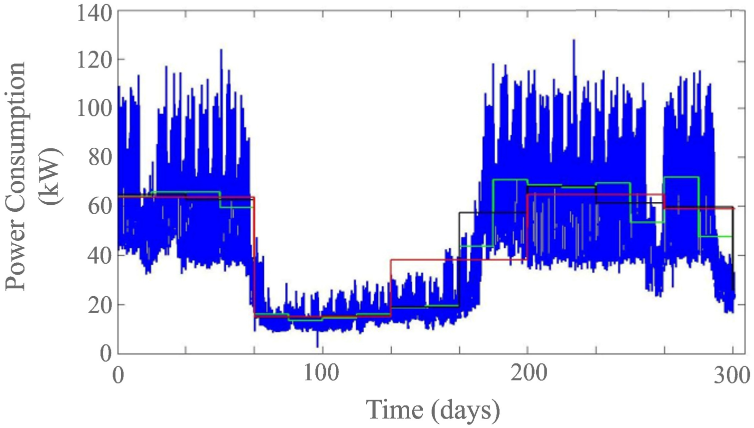

Figure 1.3: An example load profile captured by an AMI meter. The blue line represents the instantaneous power consumption collected every 10 minutes. The solid green, red, and black lines represent different power consumption averages over the time horizon.

2. **Load balancing:** Load balancing is a vital component in efficiently managing an electricity grid and ensuring the consistent delivery of power to consumers. Smart meters, particularly those within AMI systems, play a pivotal role in enhancing load balancing. They achieve this by collecting intricate data on electricity consumption, not only quantifying the energy used but also precisely when it is used. This granular data empowers utilities to gain profound insights into consumer behavior and usage patterns. With this information, utilities can pinpoint peak demand periods, often occurring during specific times of the day, and effectively manage heightened electricity consumption. By monitoring real-time demand and making necessary adjustments, smart meters help prevent grid overloads, which can lead to power outages or blackouts. Furthermore, they facilitate load-shifting strategies, encouraging consumers to use electricity during off-peak hours to optimize resource utilization and reduce the risk of grid overloads during peak periods. Consequently, this approach significantly mitigates blackout risks, ensuring grid stability and the reliable availability of power, even during high-demand periods. The im-

plementation of incentive-based control policies by utilities has effectively mitigated operational risks, ensuring a more efficient load balancing and reducing stress on the transmission system, especially during hot summer periods.

3. **Asset management:** Asset management within utility infrastructure is of paramount importance, and smart meters assume a pivotal role in this domain. By continuously collecting and transmitting real-time data on the performance of critical equipment like transformers and switches, smart meters offer a dynamic perspective that transcends conventional scheduled inspections. Their true value lies in the early detection of potential issues, allowing utilities to proactively address anomalies, irregularities, and signs of wear and tear before they escalate into major problems. This preventive approach not only averts costly equipment failures but also guarantees a more dependable power supply for consumers, resulting in significant cost savings and reduced downtime. By optimizing operational efficiency through data-informed decisions, smart meters contribute to more efficient and reliable power distribution systems.

4. **Customer engagement:** Within today's utility sector, active customer engagement stands as a critical priority, with smart meters assuming a central role in driving this engagement. Smart meters furnish customers with comprehensive, real-time insights into their energy consumption behaviors, transcending the traditional monthly billing approach. This empowerment enables consumers to gain a deeper understanding of their electricity usage, facilitating informed decisions to curtail consumption and opt for rate plans tailored to their habits. The outcomes extend beyond mere cost savings; they encompass heightened customer satisfaction through the bestowal of transparency and personal control over energy consumption. Ultimately, smart meters actively contribute to diminished energy consumption, thus nurturing a more sustainable and eco-friendly energy landscape, while concurrently fortifying the relationship between utility providers and their customers.

The deployment of new smart meters offers utilities a plethora of data that can be utilized to enhance planning and operation. By leveraging this data, utilities can more effectively manage their assets, balance energy supply and demand, and offer improved services to their customers. The implementation of smart meters can significantly influence utility planning as they are electronic devices capable of measuring and recording electricity usage in real time, enabling more precise billing and enhanced visibility into energy consumption patterns.

1.3 New Additions and Challenges Ahead

The modernization of the distribution grid has resulted in substantial changes in the planning, design, and operation of utilities. In the past, grid planning focused on ensuring there was enough power to meet demand and maintaining system reliability and safety. Today, the planning process is much more complex, taking into account several factors, such as changes in energy demand, advancements in technology, integration of renewable energy sources, and the need to lower greenhouse gas emissions.

One of the essential changes in grid planning is the move toward a more flexible and decentralized grid architecture. This shift is driven by the growing use of distributed energy resources (DERs), such as rooftop solar panels, energy storage systems, and electric vehicles. The integration of these resources necessitates a more adaptable grid structure that can accommodate two-way power flow and provide real-time energy flow control. To facilitate this shift, utilities invest in advanced technologies like AMI and distribution management systems (DMS) that provide real-time grid condition data. The use of data analytics and modeling tools has also been increasingly incorporated in grid planning to make informed decisions. These tools enable utilities to analyze a massive amount of data from diverse sources to identify patterns and trends that can guide planning and operations. Predictive analytics, for instance, can be used to predict energy demand and optimize resource allocation for cost-effectiveness and efficiency.

Moreover, utilities are concentrating on reducing greenhouse gas emissions and tackling the impacts of climate change by deploying strategies such as adding renewable energy sources, improving energy efficiency, minimizing the carbon intensity of electricity generation, demand response participation, and hardening the grid to natural hazards. To achieve these objectives, utilities are developing long-term plans, taking into account a range of scenarios, and involving stakeholders like customers, regulators, and environmental groups. There is also an increasing focus of considering the power grid's interactions and interdependence with other critical infrastructure systems to improve overall reliability and resiliency.

Overall, the modernization of the distribution grid is steering significant changes in grid planning, design, and operation, aimed at creating a more flexible, resilient, and sustainable grid that can address the evolving needs of customers and society. To achieve this, utilities are investing in new technologies, systems, and strategies while collaborating closely with stakeholders to align their actions with their communities' requirements. This will ensure that the grid can overcome emerging reliability and resilience challenges and prepare future grids.

1.4 Organization of This Monograph

This monograph presents an interconnected discussion of new developments in distribution systems, encompassing networked microgrids, prosumers, net metering, and non-wire alternatives (NWAs). To make the content more accessible to a wider audience, this section offers a high-level overview of the content flow between the sections. A flowchart in Figure 1.4 illustrates the connections between the various sections, articulating the relationship of loads and distributed generation.

The introduction serves as the starting point of the monograph, providing a broad overview of its contents, which are subsequently explored in greater detail in Section 2. Sections 1 and 2 offer essential information that lays the foundation for the subtopics that follow. Section 3 focuses on the management and control of Distributed Energy Resources (DERs). The next three sections examine different types of DERs more specifically: Section 4 covers Renewable Energy Sources (RESs), Section 5 covers Battery Energy Storage Systems (BESSs) and Section 6 covers flexible loads (FLs). Section 7 represents the extension

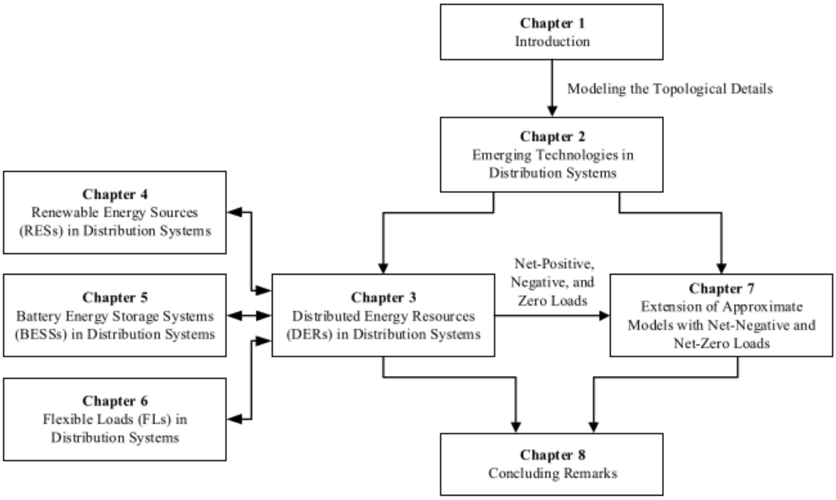

Figure 1.4: Interdependencies between sections and organization of the monograph.

of approximate models with lumped loads along the future feeders, considering the gradual lumping of loads leading to net-negative load effects.

Finally, in Section 8, the paper concludes by summarizing the entirety of the subject matter covered, particularly focusing on the topics of security and the complexity of cyber asset management within an organization.

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