Smart Grid Management, Control, and Operation

Subjects: Energy & Fuels | Computer Science, Interdisciplinary Applications | Engineering, Electrical & Electronic

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Smart grid management, control and operation (SGMCO) are key tasks for maintaining their proper functioning as well as for their extension and expansion. The current challenges of power generation, distribution, transmission, and consumption, as well as growing energy demand, facilitate the integration of a large number of smart grids with renewable energy generators and physical information systems, while smart grids are moving toward distribution and decentralization in response to the evolving application of the Internet of Energy (IoE). SGMCO handles not only traditional management, control, and operations, but also the future challenges for smart grids: Collaboration between stakeholders, control of network imbalances (e.g. frequency and voltage regulation), data analysis and management, decentralized network management and operation, and security and privacy.

smart grid blockchain smart grid management smart grid control smart grid operation

1. Introduction

1.1. Smart Grid Architecture

With more and more applications and technological advances, IoT and other power-operated devices are on the rise. To meet the energy demand, numerous small- and large-scale power generation and distribution solutions have been tested worldwide. In addition, the demand for sustainable and renewable energy in all sectors of society is forcing power generation to be versatile. The requirements for a future energy system are also driven by three key principles—Decarbonization, Decentralization, and Digitalization [1]—that ultimately provide the framework for the European Commission's Energy Union Package [2]. The emergence of low-voltage power generation and distribution systems leads to the concept of Internet of Energy (IoE) [3]. The development of IoE has several advantages. It promotes energy generation, distribution, and consumption while meeting the energy demand via smart and automated tools that ensure secure data exchange among stakeholders [4]. The IoE is designed as an open network, which means that all energy sources are equally important [5].

According to the system model proposed by the National Institute of Standards and Technology (NIST) [6], a smart grid domain is a higher-level grouping of organizations, buildings, people, systems, devices, or other actors that share similar goals to exchange, store, process, and handle information needed in the smart grid. The domains of the smart grid include generation, transmission, distribution, consumption, operation, service provider, and market. An overview of the interaction between the different smart grid domains that is extracted from [6] is shown in **Figure 1**. The generation domain is responsible for energy production using various resources. The service providers control the energy flow and are responsible for energy distribution, operation, and trading. Customers refer to the various Advanced Metering Infrastructures (AMI), automation stations, demand response, smart appliances, sensors, smart objects, supervisory control and data acquisition (SCADA), electric vehicles, and home energy management [7].

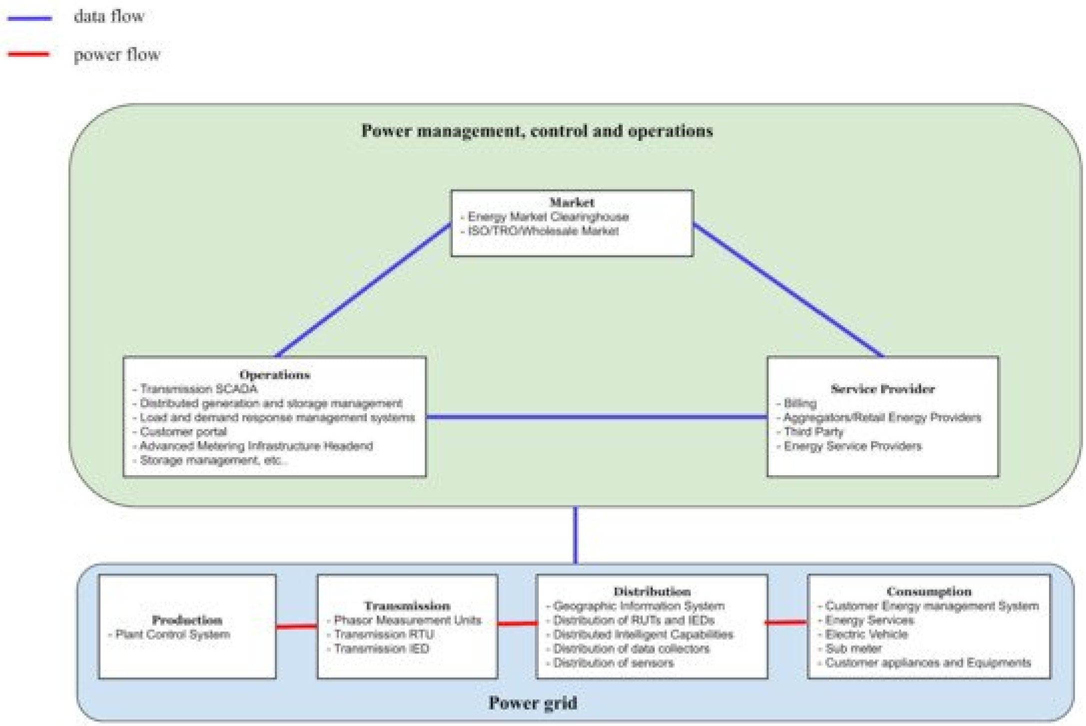

Figure 1. An overview of stakeholders in the different smart grid domains.

The AMI collects, measures, and analyzes energy consumption by enabling bidirectional communication between the utility and the consumer. It consists of three main components: smart meters, the AMI center, and the communication network. Smart meters are devices that record and monitor electricity consumption and transmit real-time data to the AMI center. The AMI center is a server responsible for data management systems. Various communication protocols are used between the household appliances, smart meters, and the AMI center [8].

The SCADA system operates energy systems by measuring, controlling, and monitoring the power grid. The main features of the smart power grid are real-time control, operational efficiency, increased grid stability, and seamless integration with new distributed database technologies as well as renewable energy systems. Smart grids can also be divided into locally managed microgrid infrastructures that deliver emission-free energy and are less dependent on centralized energy sources and high-voltage governmental or corporate-based power units.

Six main requirements have been identified for the smart grid to become intelligent [9]: (1) control of consumer information that enables consumers to have reliable and frequent information about their electricity consumption, (2) accommodation and production technologies that enable a balance between supply and demand, (3) an economic exchange market that enables local market prices and promotes local microgrid production, (4) the prospect of quality energy by diagnosing voltage fluctuations, (5) technical and operational specifications that ensure operational optimization, and (6) security against vulnerabilities that ensure resistance to various types of attackers. The development and implementation of the smart grid have immensely improved the efficiency of management, control, and operation of the power grid and facilitated the integration of renewable energy sources, electric vehicles, bidirectional communication, automated and self-maintaining systems that involve consumers [10].

The current trend toward the development and expansion of microgrids makes centrally controlled intelligent grid management, control, and operation obsolete and difficult to implement. Fossil-free energy generation and distribution vary depending on weather, energy sources, geographic locations, existing infrastructure, and energy demand, among other factors. These variations and the decentralization of the energy system require modern and flexible management and operation systems as well as innovative energy storage systems [11]. It is also important to understand how to balance power generation and distribution in line with demand across seasons. The length of power lines accounts for a large portion of energy losses. Microgrid and renewable infrastructure generation and distribution can drastically minimize this energy loss while protecting the environment [12]. The introduction of the electricity market can be a motivating factor for the expansion of microgrid production, as it could increase the revenue of the generator while minimizing its consumption costs [13]. The challenge is to establish coordinated and systematically automated production and distribution controls of these microgrids as the number of prosumers increases. The available technologies and achievements of the energy sector are not suitable for microgrids, and therefore, many actors in the energy industry propose blockchain [14] to manage power transactions in microgrids with the aim of promoting local consumption of distributed generation, decentralizing grid management, and P2P power trading [13].

1.2. Potential Extension of Smart Grid

Distributed renewable energy sources are in high demand to address the challenges of climate change while efficiently balancing the production, distribution, transmission, and consumption of energy. With a variety of alternative energy sources, most fuel-based devices can be electrified, minimizing long-distance transmission losses, carbon emissions, and pollution [4][15]. Today, small generators and energy storage systems are increasingly connected to the traditional electric grid. The most common energy sources have been fossil fuels and hydro-power, requiring large investment at the state or corporate level. Technological advances in recent decades are opening windows of opportunities for low-voltage renewable electricity generation by private and small businesses. For example, in Sweden, there are a total of 65,819 solar panels and 4333 wind turbines installed in the year 2020, representing an increase in annual renewable energy generation by approximately 40% from 2016 [16]. These numbers are expected to grow rapidly in the coming years as the Swedish government plans to use 100% renewable energy by 2040. The generation and distribution of decentralized emission-free low-voltage energy is highly recommended and can complement the traditional power sources. The 2030 renewable energy targets that have already been incorporated into official policy by 87 governments around the world aim at building an estimated 721 gigawatts of new capacity in wind, solar, and other non-hydro renewable energy technologies over the next decade [17].

The coordination and integration of a large number of energy sources could pose a particular challenge to highly regulated, traditional, and centralized energy systems. The transition to a decentralized architecture can modernize the energy management and operation as well as the control and monitoring of the integration and automation process, which are still lacking [18]. Various research has highlighted the challenges in protecting microgrid systems during operation, power balancing, and communication between different distributed generation (DG) units such as wind turbines, coal, photovoltaic systems, biomass, hydro-power, fuel cells, etc. [19]. Therefore, it is desirable to integrate microgrid generation and distribution along with conventional power grids in order to create a common and efficient data exchange mechanism.

1.3. Blockchian-Based Smart Grid

Blockchain technology, with its decentralized and secure platform for information exchange as its main feature, can be an interesting example of unifying information exchange among different actors. The application of blockchain in the energy sector is still in its infancy and has a short history of development [5]. However, there is a growing interest with some research reports, application scenarios, and project initiatives in recent years [1][4][11][12][20][21][22][23][24][25][26][27][28]. Some blockchain-based frameworks have also been proposed with a particular focus on energy trading for microgrids [13] and a distributed energy market for pricing [29]. Ethereum-based energy trading using information transactions between smart meters in households and distribution system operators (DSOs) has also been proposed [23]. In addition, wireless sensor networks (WSNs) and the Internet of Things (IoT) provide alternative solutions to privacy and security problems through efficient data aggregation and the optimization of energy generation and consumption using smart systems that can monitor and interact with each other [20]. A common platform for smart grid management, operation, and control is needed for the highly diversified energy sector. Proper communication between the different DG units that are connected to the main grid and proper connection contributes to better smart grid performance [19][30]. Communication between DG units is essential for monitoring the voltage and frequency of the microgrid.

2. Challenges for Management, Control, and Operations on Smart Grid

The smart grid currently works with a centralized platform or intermediaries to provide services such as billing, monitoring, bidding, and energy transmission. Although these solutions are mature and work properly, some of the challenges that are related to the current smart grid promote the integration of a large number of smart grids with renewable energy generators and Cyber-Physical Systems. The smart grid is also transforming to a decentralized topology with centralized management and interactive network using IoE (Internet of Energy) [3]. In this new IoE concept, each device is assigned certain attributes based on an identifier, geographic marker, address, bid price, and offer price based on its requirements. The introduction of these new technologies along with the diversity and expansion of energy sources, complicates the management, control, and operation of the energy sector. We discuss these challenges in detail based on five categories; see **Figure 2**.

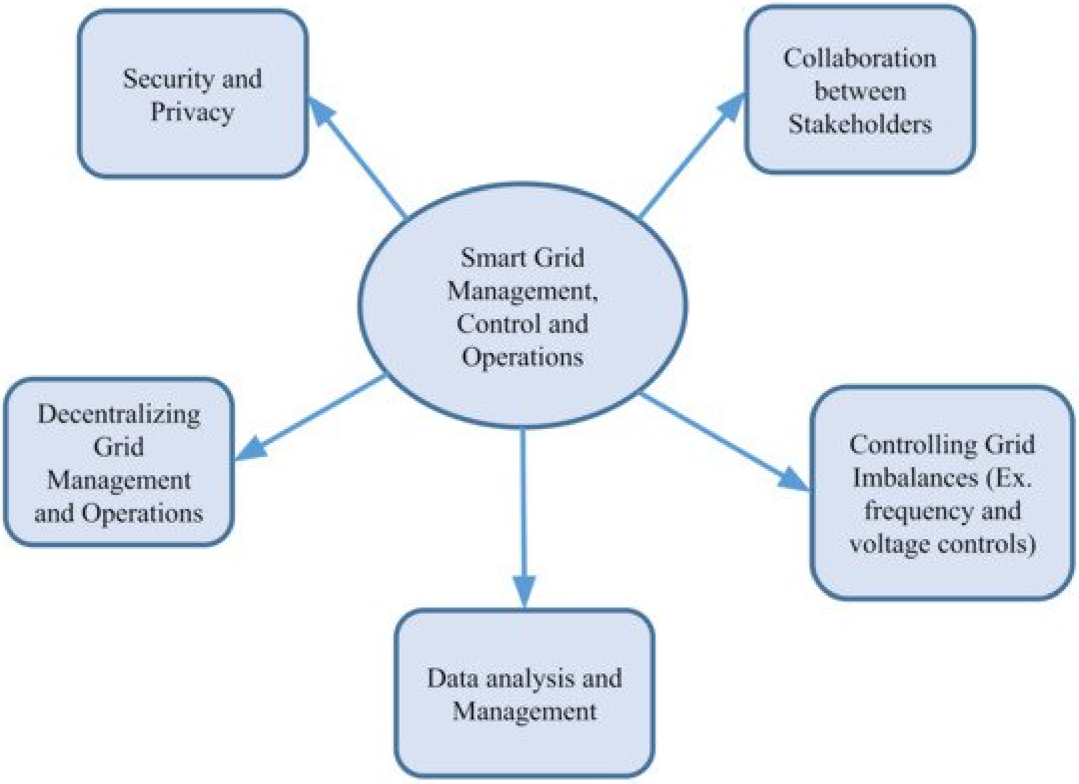

Figure 2. Challenges for management, control, and operation of smart grid.

2.1. Collaboration between Stakeholders

New technologies, high investments, lack of accurate information, etc. complicate the coordination between actors in the energy sector. The current smart grid system faces the problem of energy balancing, especially when different actors are involved in the processes of generation, distribution, trading, and consumption. While much of the literature focuses on the technical aspects of the smart grid challenges, the collaboration between stakeholders is equally important and needs to be properly addressed [25]. Energy suppliers and traders typically request an estimated amount of energy from generators based on their demand analysis. Such an estimate can be inaccurate due to several factors: expansion of the region, population growth, environmental factors, and increase in microgrid generators in the area. This can lead to high distribution losses, unbalanced voltage and frequency loads, and consequent power outages. In addition, some microgrids, such as solar systems, produce more energy during the warm summer months when energy demand is lowest. A modern data exchange system between the stakeholders could pave the way to store the excess produced energy in a local hydrogen gas or battery without affecting the main grid infrastructure. Therefore, it is important to establish close cooperation between relevant players such as generators, distributors, retailers, consumers, and regulators to facilitate grid management.

2.2. Controlling Grid Imbalance

Both physical and technical problems can contribute to imbalances in power generation and consumption. The failure of some network components, such as insulation faults or damaged cables, interference from third parties, vandalism, and natural causes such as wind or storms can contribute to imbalances in power supply. Technical problems such as malicious attacks, frequency deviations, overloads, synchronization losses, and voltage dips can also contribute to power imbalances [9]. Voltage deviations are another potential challenge to grid imbalances. For example, a PV power plant produces more energy during the sunny part of the day when demand is lower. This causes the PV power plant to produce more than the grid load capacity and causes Reverse Power Flow into the transmission grid [31][32][33][34]. Therefore, it is essential to control and monitor the power supply in each period. The article [35] examined the emerging challenges for voltage control in the smart grid. All stakeholders need to adjust their power generation, distribution, and consumption to regulate both active and reactive power [9]. However, this becomes a challenge due to the number and diversity of power generation methods and regulatory requirements.

2.3. Data Analysis and Management

Current smart grid data management faces the problem of data aggregation quality, security, compliance control, common scope, and efficiency of the management mechanism [36]. A large amount of data are generated and transferred between different entities [25]. Accurate and consistent incoming data streams such as weather forecasts and power generation status allow operators to control and monitor the grid system. Such information is very important to avoid sudden and unexpected power supply disruptions. In addition, such big data can also be used for grid operations, alarms, demand forecasts, generation estimates, price adjustments, etc. The data collected tend to be quite large, as multiple smart grid domains are involved in the process. For example, an Advanced Metering Infrastructure that collects data every 10 min instead of every month could increase the data analysis process by more than 4000 times. There is also a regulatory requirement to provide accurate data as frequently as possible, which is challenging. Modern, automated, and secure data processing technology can improve data management, storage, and reporting for the smart grid.

2.4. Decentralizing Grid Management and Operation

Decentralizing grid operations allows stakeholders to control and manage their data locally. The control and operation of a smart grid in a decentralized environment is an important research topic. Demand-side control and optimized operation of the grid are a research area [37]. Distributed automation devices are used to decentralize the operation of the grid. These are devices such as phasor management units (PMUs), remote terminal units (RTUs), SCADA, and smart meters that are used to collect and monitor data. In [10], distributed automation approaches for electric power distribution systems, benefits, and challenges were studied. High-resolution sensors with the ability to report real-time conditions and improve the visibility of the distribution system operator beyond substation assets were also considered. In addition, there are challenges associated with the coordinated and cost-effective integration of distributed smart grid systems, generation assets, and demand response facilities. This complicates the management and operation of distributed energy resources. Further work is needed to facilitate coordination between decentralized and centralized stakeholders.

2.5. Security and Privacy

While decentralizing the operation and management of the smart grid has many benefits, it also brings security and privacy challenges. The SCADA module in modern power systems collects data at remote terminals, transmits, and stores it in plain text to the main control center. This centralized data collection and storage is highly vulnerable to cyberattacks. Cybersecurity is one of the biggest and most difficult challenges facing the current smart grid. Over the years, several cyberattacks have taken place on the smart grid [38]. Attackers use the four steps of Exploration, Scanning, Exploitation, and Maintaining Access [39] to control the system. There are several known attacks on smart grids. One of them is the jabbing attack, in which the attacker installs a malicious smart power meter that sends false data, causing desynchronization and power interruption. The puppet attack sends a signal to the node. Then, the attacker controls the node and sends more signals into the network, causing the smart meter network to become unstable. Another example is the stack smashing attack, which compromises the application layer of the network and leads to the disclosure of sensitive data. An experimental attack, on the other hand, makes the smart grid layer vulnerable to DoS attacks [40]. A comprehensive discussion of attack mechanisms, detection, and countermeasures can be found in [7].

Therefore, security is a major challenge in the management, control, and operation of smart grids. Given the alarming increase in IoT devices with limited security capabilities connected to the smart grid system, much needs to be done to protect sensitive personal and corporate data as well as national security [38].

2.6. Summary of the Challenges for the Current Smart Grid Management, Control, and Operation

In summarizing the challenges of smart grid management, control, and operation, several technical and operational changes can be identified. The dynamic generation and distribution of energy by a large number of distributed generators, the digitization of the grid, and advanced metering systems contribute to fault-tolerant transmission and distribution control. Smart grid owners often have dual roles (generator and consumer), and loads become dynamic and more interactive [22]. Centralized and traditional grid management and operation face challenges, and utilities are seeking viable solutions to these problems. Although distributed energy systems offer benefits such as user tracking, cost savings, and optimized resource allocation [5], technological immaturity and incentive mechanisms compromise the core interests of stakeholders. **Table 1** summarizes the challenges for smart grid management, control, and operation.

Table 1. Challenges on the current and future smart grids.

Challenges	Description	Ref.
Collaborations between stakeholders	• Difficulty in allocating resources • Difficulty in establishing reliable data exchange for common goals	[25][30]

Challenges	Description	Ref.
	• Operational challenges due to the dynamics of renewable energy generation • Problems in developing an up-to-date supply and demand program • Limited role or influence of microgrid generators on the management and operation of the smart grid • Problems with real-time performance • High transaction costs • Microgrid generators' voices may be dominated by large energy companies • Difficulty in getting prosumers to participate in decentralized smart grid management • Overcoming regulatory challenges • Transparency • Accountability	
Controlling grid imbalances	• Need to monitor smart grid sensors and AMI to control grid overloads and power outages. • Problem of overloading the grid • Load balancing in the grid • Can create Reverse Power Flow • Control of voltage and frequency • Automatic fault detection and maintenance	[9][31][32][33][34][35]
Data analysis and management	• Analyzing the quality of produced energy	[25][36]

Challenges	Description	Ref.
	• Large-scale and complex data aggregation and deployment • Data management on energy production, distribution, and consumption • Management of data transactions between all prosumers	
Decentralizing gird management and operations	• Development of a decentralized energy management • Automated P2P energy trading • Automated grid monitoring • Increase in the complexity of energy generation and distribution • Flexibility of energy generation and distribution • Difficulty of scalability • Traceable energy management	[10][37][41]
Security and privacy	• Tamper-proof system for protecting customer data recorded and transmitted in the smart grid • Access control • Authentication • Secure data storage • Security and data protection for smart grids • Data protection and compliance • Establishing secure communications	[7][25][38][39]

Challenges	Description	Ref.
	• Protecting the smart grid from cyber attacks • Implementing a decentralized and secure authentication mechanism • Data privacy	

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