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Introduction

1.1 The Concept and Worldwide Development of Smart Grid

1.1.1 Concept of Smart Grid

The Smart grid, driven by many factors including better environmental quality, more powerful capabilities to resist natural disasters and external disturbances, energy independence and high efficiency, is committed to creating smarter, cleaner electricity systems around the world. In a smart grid, modern monitoring, analysis, control and communication capabilities are incorporated into the electric grid, in order to improve reliability, optimize asset utilization, improve cyber security, increase energy efficiency and allow diverse generation and storage options. Therefore, the smart grid is regarded as one of the most promising solutions for sustainable development [1–3].

The traditional electric power grid was designed to operate as a vertical structure consisting of generation, transmission, and distribution and supported with controls and devices to maintain reliability, stability, and efficiency. However, system operators are now facing new challenges including the penetration of distributed energy resource (DER) in the legacy system, rapid technological change, and different types of market players and end users. The smart grid will be equipped with communication support schemes and real-time measurement techniques to enhance resiliency and forecasting as well as to protect against internal and external threats [4]. The design framework of the smart grid is based upon unbundling and restructuring the power sector and optimizing its assets [5]. The smart grid will be capable of:

- handling uncertainties in schedules and power transfers across regions;
- accommodating renewables or any other DER;
- optimizing the transfer capability of the transmission and distribution networks and meeting the demand for increased quality and reliable supply;
- managing and resolving unpredictable events and uncertainties in operations and planning more aggressively.

The smart grid represents the full suite of current and proposed responses to the challenges of electrical energy systems [6, 7]. Because of the diverse range of factors there are numerous competing taxonomies and no agreement on a universal definition. However, the basic concept of smart grid is to add monitoring, analysis, control, and communication capabilities to the national electrical delivery system to maximize the throughput of the system while reducing the energy consumption. Figure 1.1 depicts the fundamental objectives and technical implementation of smart grid [8]. The fundamental objectives of smart grid include reliability, sustainable development, efficiency, security and energy independence. And the basic

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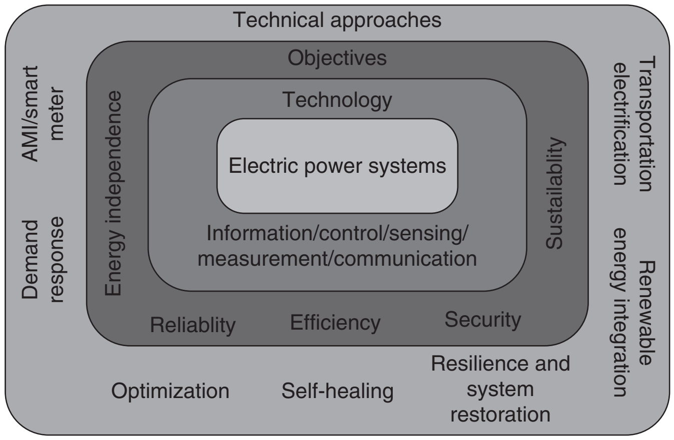

Figure 1.1 Layered smart grid architecture.

technologies are information and communication technology (ICT), and control [9]. Advanced sensing and measurement technologies will acquire and transform data into information and enhance the multiple aspects of power system management [10], and hence is one of the key enablers of smart grid.

At the application level, there might be various solutions to improve or facilitate the 5 fundamental objectives mentioned above. For instance,

- Re-investment of infrastructure of power system may help improve the reliability, revolutionize electrical systems with digital technologies, and increase the efficiency of energy production, management, distribution and consumption.
- Advanced Metering Infrastructure (AMI) together with smart meter can help improving customer understanding of their electricity usage, reducing operations and maintenance costs, and improving awareness of and response to distribution system outages.
- Demand response, in which electric usage by end-use customers is dynamically changed from their normal consumption patterns in response to changes in the electric power system, is changing the over-100-year-long traditional practice in which power system operator only controls generation to match the load variation, hence increasing the flexibility of the electrical energy system.
- Taking advantage of the unique digital platform for fast and reliable sensing, measurement, communication, computation, control, protection, visualization, and maintenance of the entire transmission and distribution set of systems, some fast fault isolation or system restoration strategies can be implemented. The grid is expected to not only alert us about the potential adverse effects of disruptive events, but also to maintain a high functionality level following disruptions. Therefore, the grid isolates problems immediately as they occur, before they cascade into major blackouts, and reorganizes the grid and reroutes energy transmissions, so that services may continue for all customers, enhancing the security of the electric power system.
- For sustainable development, one direction is renewable energy integration, which advances system design, planning, and operation of the electric grid to incorporate renewable energy, distributed generation, energy storage, thermally activated technologies, and demand response into the electric distribution and transmission system. Another direction is the electrification of transportation, which is regarded as one of the main sources of carbon dioxide emission. This massive deployment of batteries in electric vehicles may provide a potential solution for distributed energy storage.

1.1.2 Worldwide Development of Smart Grid

The smart grid is generally envisioned as the platform for implementation of strategic development of power grids and optimized allocations of energy and resources [11]. It is not only a revolution of electric power industry but also the catalyst to create or breed new industries, and helps foster economic growth by helping meet the electricity requirements of industry.The smart grid is also an industry in itself which presents governments with an opportunity to invest and support initiatives that foster (a) innovation (both technological and intellectual) and (b) economic development through skills development and jobs growth, while addressing its energy security needs [12]. Not surprisingly, some governments like those of the USA, South Korea and Japan – are approaching the smart grid as the next big opportunity for their economies to become global leaders in an industry – in this case, the new energy technology sector. Also, smart grids can empower individuals to participate and even profit from the power system in a manner that was not possible before. For these reasons, particularly in times of global austerity where governments may seek to sustain economic growth levels through fiscal measures, the smart grid appears to be a particularly sound investment choice.

The development of a smart grid has become the major focus of power grid construction in worldwide. Through the application of modern metrology, communications, information, and control technologies, the country's power grid is undergoing a fundamental upgrade. Most of the countries in the world made strategic plan for development of smart grid. Smart grid projects are growing at a rapid pace around the world. According to the latest report by GTM Research, Global Smart Grid Technologies and Growth Markets 2013–2020, the global smart grid market is expected to cumulatively surpass $400 billion worldwide by 2020, with an average compound annual growth rate of over 8% [13].

From a technological view, the most important 3 characteristics of the smart grid are: (a) active distribution power network with integration of distributed generation, (b) interaction among users and power grid, and (c) bi-directional power flow and information flow. However, when implementing the smart grid, a different vision and operation model are used. Among those practices, the USA, Europe and China are most representative.

The United States of America is the pioneer in smart grid initiative. One of the fundamental perception about the traditional power system was that although the current electricity system is 99.97 percent reliable in US, yet it still allows for power outages and interruptions that cost Americans at least $150 billion each year – about $500 for every man, woman and child [14]. Support for the smart grid in the United States became federal policy with passage of the Energy Independence and Security Act of 2007. The law set out $100 million in funding per fiscal year from 2008 to 2012, established a matching program to states, utilities and consumers to build smart grid capabilities, and created a Grid Modernization Commission to assess the benefits of demand response and to recommend needed protocol standards. The law also directed the National Institute of Standards and Technology to develop smart grid standards, which the Federal Energy Regulatory Commission (FERC) would then promulgate through official rulemakings [15]. In the USA, the infrastructure for the power market is well developed. The smart grid in USA is designed to encourage energy saving through the interaction between power grid and end users. It is estimated that just by installing a smart meter, an end user can save up to 20% in energy bill by adjusting the energy use. Therefore, in USA, the development of smart grid focuses on the deployment of smart meters and construction of AMI (advanced metering infrastructure) [16].

EU (European Union) paid a lot of the attention to the utilization of renewable energy in past practice [17]. The penetration of renewable energy in the power system in most of EU members reached more than 20%. The Kyoto Protocol came into force in February 2005 and legally binds signatories to their stated decarbonization targets. In 2007, the European Union obligated its membership to meet climate and energy targets by 2020: a 20% reduction in greenhouse gas emissions (GHG), a 20% increase in energy efficiency, and 20% of EUs energy consumption from renewable energy [18]. Through additional directives, the EU has imposed additional obligations regarding renewable energy, smart meters and smart grids on its membership. The smart grid furthers these goals by integrating renewable energy sources and electro-mobility into the existing power system and introducing new efficiencies through grid modernization.

China is the world's largest consumer of electricity, and Chinese electricity demand rapidly increased during the first decade of the 21st century. It is expected to double over the next decade and triple by 2035 [2]. In China, the situation is that most of the energy production bases are located in the west, while the load centers are located in the developed east area. In order to balance the energy, China has to deliver the electricity thousands of miles from west to east [19]. This is highly dependent on ultra high voltage (UHV) power transmission technology. Due to the fact that China does not have a mature power market, renewable energy is generally not used in a distributed manner. Contrary to the practice of using renewable energy by distributed generation, China builds many large-scale renewable energy bases such as solar generation bases or wind farms [20]. Therefore, the vast majority of smart grid investment in China centers around transmission, distribution automation and automatic metering reading (AMR) to support a developing grid and robust renewable energy build-out. The development may include six key areas: power generation, transmission, transformation, distribution, consumption, and dispatching. The smart grid covers all voltage levels to achieve optimum power flow, information flow, and business flow, along with a high degree of integration. The electric power system is operated mainly by two large power companies, State Grid Corporation of China (SGCC) and China Southern Power Grid Company (CSG). SGCC covers most of the power supply area. In 2009, SGCC proposed the Strong & Smart Grid plan. In this plan, ultra high voltage and transmission level strengthening are the two most important concerns [21]. By 2015, UHV and other intra-regional transmission capacity will be 240 GW, and by 2020, UHV and other intra-regional transmission capacity will reach 400 GW. The plan is split into Three Phases 5-year Plan for implementation: Phase 1 – Planning and Pilot Projects Phase (2009–2010); Phase 2 – Comprehensive Construction Phase (2011–2015); and Phase 3 – Leading and Promotion Phase (2016–2020). The total investment from SGCC reaches 5000 billion RMB. China has a unique structural context that could enable it to leap ahead in the development of the smart grid, government ownership of the T&D sector, the market's ability to drive down equipment costs, and the central role that government can play in the economy make this possible. The market for smart grids in China is anticipated to grow at a significant rate of nearly 20% to 2020, becoming the largest smart grid market in the world, accounting for over 24% of the global market [13]. In research & development area, China outlined its focuses on the following four aspects: smart power transmission technology, smart dispatch and control technology, smart power distribution technology, and large-scale intermittent power source inter-connection and energy storage technology.

1.2 Importance and Necessity of Measurement and Test in Smart Grid

The term "smart grid" defines a self-healing network equipped with dynamic optimization techniques that use real-time measurements to minimize network losses, maintain voltage levels, increase reliability, and improve asset management [22]. Smart grid is regarded as an ideal advanced management of energy production, delivery, distribution and utilization. The smart grid environment requires the upgrade of tools for sensing, metering, and measurements at all levels of the grid [23]. To some degree, the kernel of smart grid is to combine advanced sensing and measurement technology, information communication technology, analysis and decision-making technology, automatic control technology and electrical energy technology, to realize the objectives of building a highly reliable, secure, economic, efficient and environment-friendly power network, as shown in Figure 1.2 [24]. The electric power system (EPS) is a geographically dispersed system. The operator controls the EPS through planning, operation or control (changing the inputs). These inputs are changed corresponding to a decision-making system, which makes optimized decision based on measured responses. For complex control systems, it is necessary

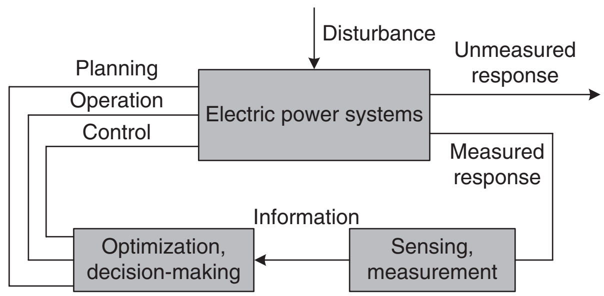

Figure 1.2 Operation and control of smart grid.

to extract useful informations from measured responses. The EPS is also subject to many types of disturbances, and some of the responses are not measurable or not obtained by sensor systems.

At present, the most obstructive barrier to the smart grid is that there are not enough sensors to provide an information interface for the implementation of a smart grid. In order to route the power in more optimal ways to respond to a very wide range of conditions in a smart manner, it is necessary to deploy more sensors in the power system to obtain more information. With the objective in mind of being smart, it is necessary to add more new types of sensors to the existing infrastructure of power system, not only the traditional sensors (such as current and voltage transformer). The added sensors in a smart grid would preferably possess the following characteristics [25]:

- Electrical or non-electrical sensing (e.g., mechanical, chemical, or video or image).
- Contact or noncontact sensing.
- Compatible, integrated.
- Low power consumption.
- Communication capability.

The new types of sensors that would be beneficial to the construction of smart grid would include:

- Electrical: voltage, current, electric field and magnetic field.
- Enviomental: temperature, climate.
- Mechanical: pressure, tension, displacement.
- Other enviomental sensors, such as chemical sensors.

Sensing and measurement technology plays a fundamental role in monitoring, analysis and control. The development of smart grid provides an arena for a lot of novel emerging sensing and measurement technologies, which will boost the development of this industry in return [26].

Another area is the development of test technology for smart grid. It is always important to prove that the individual items of equipment, which are interconnected to form systems, circuits and substations, are suitable for their intended purpose and acceptable for services. This is generally achieved by testing.

The smart grid empowers active management, oversight and participation by both producers and consumers of electrical energy. Achieving this empowerment requires overlaying communications infrastructures and related products on the power grid connecting all of the pieces in a power grid to the Internet so communication can take place in real time. Facing the development trend in which IP (Internet Protocol) technology is used for real-time control and exchange of information and data, testing is of paramount importance to ensure the reliability, security and successful deployment of the smart grid. For the smart grid to work correctly, all of its components must interoperate in order to achieve the goals that the smart grid system is expected to produce [27].

The testing of smart grid may include:

- System testing: interoperability testing, conformance testing and operations testing.
- AC and DC capacity testing.
- Commissioning, start-up and field trials.
- System acceptance validation.
- Functional testing.
- EMI/EMC and device regulatory testing.
- Environmental testing.
- Reliability/availability analysis.

1.3 State of Art in Measurement and Test of Smart Grid

Building the smart grid is a huge and expensive endeavor. The power grid is considered one of the most complex machines ever built, and converting it to a smart grid will not be easy. It entails overlaying the current infrastructure with hundreds of millions of smart meters numbering, adding a new communication infrastructure, as well as making an untold number of equipment upgrades throughout the electric transmission and distribution system. As we transition to the smart grid, how can we be sure it will all work correctly, how can we quantify the benefits it will deliver, and how can we guarantee we obtain enough information to make the optimal decision? The answer, or at least part of the answer, lies in the innovative measurement and testing solution.

1.3.1 Sensor and Measurement

As stated above, implementation of the smart grid is mostly dependent on the powerful communication network. The telecommunication infrastructure network, with its sophisticated architecture and technological maturity, is the basis for the smart grid [28]. Yet the telecommunication infrastructure network is completely different from the smart grid, although telecom and the smart grid share the same core, high speed, and interoperable communication layers. Traditional telecom endpoints result in a human-to-machine interaction, with telephones, computers, and nowaday smartphones. The smart grid is truly a machine-to-machine network. The endpoints of a machine-to-machine network consist of sensors, functional machines, or both. These machines are often not under immediate human control and, therefore, cannot necessarily express or report the status or the health of the network. Therefore, sensor and measurement play a fundamental role in smart grid, not only for operational parameter, but also for status of the devices.

Advanced sensing and measurement in smart grid may extend to the whole electricity production and consumption chain, including power generation, transmission, distribution and end usage. The fundamental functionalities of an advanced sensing and measurement system in a smart grid can be categorized into the following four applications: 1) Enhance power system measurements and enable the transformation of data into information; 2) Evaluate the health of equipment, the integrity of the grid, and support advanced protective relaying; 3) Enable consumer choice and demand response, and help relieve congestion; and 4) Advanced Metering Infrastructure (AMI), which provides the interface between the utility and its customers for bi-direction control, real-time electricity pricing, accurate load characterization and outage detection / restoration.

The current measurement technology in smart grid can be categorized into four types, as shown in Table 1.1, according to the intention and objective of measurement.

1. The energy measurement technology, including smart meter and other metering systems, may facilitate the interaction between user and utility, provide metering for utility and provide essential support

Table 1.1 Measurement for smart grid

Type of measurements	Applications
Energy measurement	Energy balance; metering (smart meter, AMI); renewable integration; user participation; measurement for power market
Power quality measurement	AC harmonics and other waveform distortions; DC bias
Monitoring	State measurements; stability monitoring; power device status monitoring; secondary devices (such as control, metering, protection, etc.) monitoring; efficiency monitoring; fault location; environmental monitoring
Measurement for control and optimization	SCADA; WAMS; Measurement for protection

to ensure security of electricity supply and grid stability, grid quality, and fair trade between commercial parties employing the grid. Other applications, such as renewable energy integration, staggering power consumption, are energy balance (load balance) highly dependent on energy measurement technology. For instance energy users can implement energy savings with pricing signal with energy measurement from smart meter and utility can prevent electricity theft with traceable on-site energy measurement.

2. The power quality measurement will be essential to anticipate, detect, and respond to system and power quality problems, and service disruptions and the key to a continuous improvement of power supply and its use, by knowledge of the relevant local system circumstances in detail, using the information of all available sources connected to the system. In a modern power system, utility companies and end users are not only concerned with the steady power quality issues such as voltage fluctuation, flicker, frequency fluctuation, and harmonics, but also with transient power quality issues such as voltage swell, voltage sag and voltage interruption. As most power electronics devices are working at 20 kHz and above, current measurement capable of fast response and broadband is required [29]. For instance current sensors are required to capture the fast varying (ms or s) transient waveform, which is not achievable for traditional CTs (Current Transformers).

3. The monitoring covers a wide range of applications such as measurement of the state of the system, monitoring of the operation parameters such as stability or efficiency, monitoring of status of the devices including primary HV devices and secondary electronic or communication devices, and other environmental parameters such as temperature, humidity and climate.

4. Measurement for control and optimization includes the measurement for system operation, such as control, protection, regulation, dispatching and planning. In this category, the measurement is generally in the loop of a closed-loop feedback control. The SCADA (supervisory control and data acquisition) and PMU (Phasor Measurement Unit) in WAMS (Wide Area Measurement System) are key elements of the emerging smart grid, handling a wide range of data collection, sharing, and coordinated control actions that make the system more efficient and reliable.

1.3.2 Test

Usually, for a device to be used in a power system, it must undergo the following testing stages: 1) initial stage: laboratory testing (generally test on the modules); 2) medium stage: comprehensive assembling testing (including steady state and dynamic state, etc.); 3) pressure test (including electromagnetic interference, temperature, humidity, and mechanical vibration, etc.); 4) field trial; and 5) final stage: testing for abnormality after commissioning (self-diagnostics and measurement & testing devices).

One of the most important characters of smart grid is the broad use of smart power equipment. This does not mean that the fundamental theory of the power equipment is changed. However, smart power equipment means the visualization of the state and digitization of measurement and control of the HV equipment and its accessaories. This change will bring profound change to the operation of power system. The fundamental change from traditional power grid to smart grid is the digitized information and powerful communication networks, which are a fundamental building block and key enabler of the smart grid that spans transmission and distribution systems and ultimately reaches the home business. Some of the traditional testing solutions, especially those single device oriented but not network oriented, do not work for commissioning, function verification and acceptance check. It is imperative to develop novel testing solutions to verify the advanced functionalities brought by complex application of networked digital information.

The testing in smart grid generally includes all those testing in traditional power systems, but it may have totally different requirements or take different strategies under the smart grid environment. The testing of smart grid can be categorized into the following types, according to the applications:

- Communication and network testing.
- Control system testing.
- Protection system testing.
- Metering system (smart meter & AMI) testing.
- Measurement system testing.
- Software/website testing.

As pointed out above, testing of primary HV power equipment is not discussed here, because it is the secondary equipment system that differentiates smart grid from the traditional electric power system. Actually, secondary equipment has to be tested throughout its lifetime from development and manufacturing through commissioning and regularly while in service. For instance protection systems play a key role for the safe and reliable operation of todays electricity power systems. Properly working protection devices help to maintain the safety of the system and to safeguard assets from damage. In order to ensure reliable operation, protective relays as well as recloser controls must be tested throughout their life-cycle, from their initial development through production and commissioning to periodical maintenance during operation.

In China, new issues arise such as the fast deployment of digital substation or smart substation, as a result of smart grid development. In a digital substation or smart substation, all devices form an organic integrity. Unified configuration for all the network communication and functions of devices are needed, and it is necessary to verify and test the function and performance of the configured devices/systems as a whole. This is so-called integrated testing [30]. Traditional factory testing, mainly performing random inspection, cannot achieve full-system-scale configuration and testing. Different from traditional substation, digital/smart substation needs system modeling, configuration and corresponding verification. Also, in order to ensure the reliable commissioning of the system, the performance testing of network and devices are needed.

1.4 Outline of the Book

The book is divided into two parts. In the first part, the sensor, measurement and data management of smart grid will be presented. This includes the new types of sensors for the smart grid in Chapter 2, which addresses the application of magnetoresistive sensors and fiber optic sensors in the smart grid; synchronized wide area measurement for smart grid in Chapter 3, which presents the state-of-art time synchronization technologies in smart grid and part of advanced applications based on wide area synchronized measurement; and measurement of energy, power quality and efficiency in smart grid in Chapter 4, which discusses the development in smart meter, power quality measurement and measurement for renewable energy integration. Since various measurement will produce plenty of data, Chapter 5 presents the data management in smart grid, in which the data and data processing in smart grid are discussed, and data integration tools such as the sensor network and data cloud are introduced.

In the second part, advanced test technologies for smart grid will be presented. As the development of the smart substation is the protruding reflection of smart grid, the testing in smart substation is discussed, mainly including the test of secondary systems in smart substation (Chapter 6), the testing of auxiliary monitoring system in the smart substation (Chapter 7), and testing on dynamic performance of electronic transformers (Chapter 8).

Chapter 9 summarizes the results and presents future vision in the measurement and testing solutions for the smart grid.

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