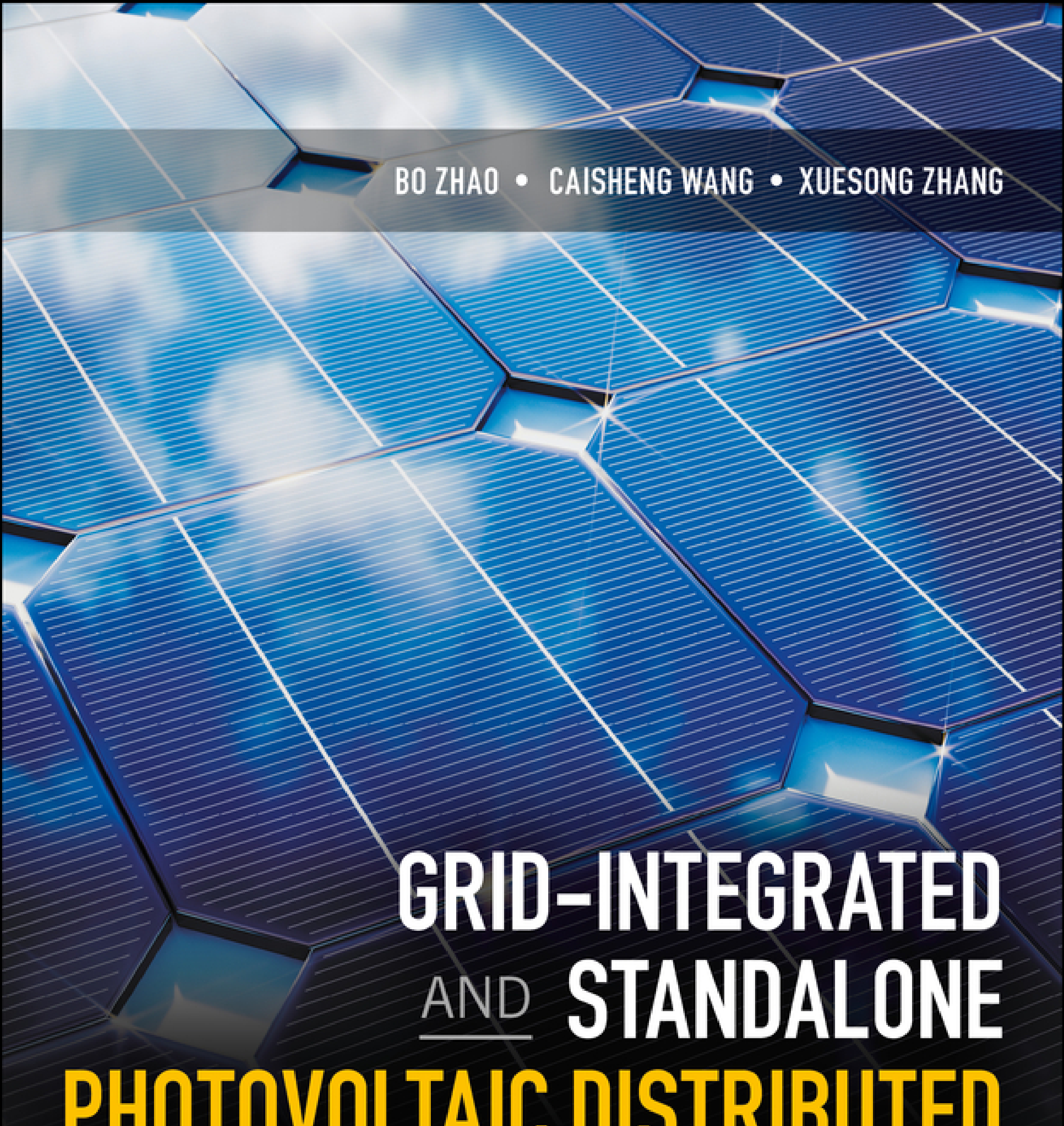

BO ZHAO • CAISHENG WANG • XUESONG ZHANG

# GRID-INTEGRATED AND STANDALONE PHOTOVOLTAIC DISTRIBUTED GENERATION SYSTEMS

## ANALYSIS, DESIGN, AND CONTROL

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**Grid-Integrated and Standalone Photovoltaic Distributed Generation Systems**

# Grid-Integrated and Standalone Photovoltaic Distributed Generation Systems

Analysis, Design, and Control

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# Contents

# Preface

With the progress of technology, human beings have undergone the transition from industrial civilization to ecological civilization, from extensive and inefficient expending to economical and efficient consumption, and from high carbon production to low carbon production. The present fossil-energy-dominated world energy paradigm is gradually changing into a multiple energy structure and will eventually be dominated by nonfossil energy. Against this background, the development of distributed photovoltaic (PV) generation systems, characterized by adaptation to local conditions, clean and efficient, decentralized layout, and local consumption, have experienced phenomenal growth in the past two decades. The world total solar power capacity had reached over 227 GW by 2015 and over 50 GW of the solar capacity were added in that year. Over 28 GW of solar power had been installed in the USA by the end of 2016. The PV capacity in Germany is currently over 40 GW. China is expected to deploy 70 GW PVs by 2017. The International Energy Agency estimates that solar power will become one of the mainstream energy sources by 2050 and contribute about 11% of world electricity generation. The majority of these PV systems have been and will be installed in distribution networks. As a result, the PV penetration level will become unprecedentedly high (e.g., well over 50%) and continue to grow in many distribution networks around the world. The high penetration of PV systems has led to great technical challenges, including voltage problems, harmonics, grid protection, and so on, in the operation and development of modern distribution networks.

In recent years, the authors and their teams have undertaken a series of PV-related projects, such as the implementation of PV systems for Jiaxing PV Science Park, Jianshan New Industrial Zone in Haining, and Hangzhou Bay New Zone PV Science Park. The main characteristic of these projects was to analyze the impact of integration of distributed PVs into the distribution networks at high penetration and develop measures to better accommodate those sources.

This book is the result of over 10 years of research on distributed PVs and integration of PVs in distribution networks and microgrids. It combines the theory, modeling, analysis and control, and the actual implementation of distributed PVs in one place. The book is focused on the operation and control of distribution networks and microgrids with high penetration of distributed PVs, covering the topics of PV hosting capacity analysis, power flow of distribution networks, reactive voltage regulation, short-circuit current calculation, power quality evaluation, methods of integrating distributed PVs into distribution networks at high penetration levels, and actual system implementation experiences. The book is intended to be a resource for all engineers, and for all those interested in designing policies for facilitating renewable energy development. An overview of the chapters covered in the book is now presented.

Chapter 1 introduces the current status and future development trends of PVs around the world. The PV industry development history of different countries, including the USA, Japan, Germany, and China, and the relevant policies, laws, and demonstration projects in these countries are also briefly introduced. Chapter 2 gives a brief coverage of the basic techniques of distributed grid-connected PV systems, with focus on their configurations, components and maximum power point tracking techniques. Chapter 3 presents the load characteristics of a distribution network with and without distributed PVs and provides theoretical foundations for further analysis on PV penetration and power flow in distribution networks.

Chapter 4 covers the concepts of PV power penetration, capacity penetration and energy penetration, analyzes the key challenges in different development stages of distributed grid-connected PV, studies the impact of grid-connected PVs on distribution networks, explores the maximum allowable capacity of grid-connected PVs under the requirement of safe and stable operation of the distribution networks, and presents the methods to increase PV penetration in distribution networks.

Chapter 5 introduces various power flow calculation methods for distribution networks. It then shows the impact of PVs on the power flow in distributed networks, including voltage variation and distribution loss caused by the PVs added. Models of voltage and distribution loss considering PVs are established, which are then used to analyze the impact of different PV capacities and locations.

Chapter 6 addresses one of the important issues caused by high PV penetration: the voltage control of distribution networks with distributed PVs. In this chapter, the impacts on voltage due to distributed PVs are analyzed first and three control strategies (the constant power factor control strategy, variable power factor control strategy, and the reactive voltage control strategy) and relevant modeling methods are then introduced.

Chapter 7 analyzes the short-circuit characteristics of distributed PVs under symmetrical and asymmetrical grid voltage sags, discusses different low voltage ride-through (LVRT) standards for PVs and the LVRT control strategies, and characterizes the fault currents of PVs. An iterative algorithm is given in the chapter for the calculation of fault currents for distribution networks with distributed PVs.

Chapter 8 discusses the impact of grid-connected PVs on power quality. Chinese and international standards on PV integration harmonic requirements are compared and discussed. The differences in power quality terms and the methods for analyzing the impacts due to distributed PVs on distribution network power quality are given.

Chapter 9 discusses various technologies, including energy storage, demand response, and a network partition-based zonal control technology to better accommodate PVs for distribution networks.

Chapter 10 is a good addition to the other chapters in the book by addressing microgrids with PVs. The chapter reviews the configurations of AC, DC, and AC/DC hybrid microgrids, system unit sizing of microgrid components, and the control framework and the implementation of microgrids. The optimal design, planning, and control of microgrids are given in the chapter through a discussion of the implementation examples of two real standalone microgrids. The implementation and operation experiences and lessons learned from the two microgrids are also summarized in the chapter.

The authors are honored to have the privilege to work with their collaborators for this book, which is a result of an exemplar group effort. Mr. Yibin Feng and Dr. Junhui Zhao are the main authors of Chapter 1. Dr. Xuesong Zhang and Dr. Junhui Zhao are the leading authors of Chapter 2, along with Dr. Jinhui Zhou for Chapter 3, Miss Chen Xu and Dr. Jian Chen for Chapter 5, Prof. Li Guo for Chapter 7, Mr. Peng Li and Prof. Zaijun Wu for Chapter 8. Professor Ming Ding and Professor Hongbin Wu of Hefei University of Technology offered a great deal of help to the authors. Professor Saleh A. Al-Jufout from Tafila Technical University kindly helped proofread Chapter 5. The authors also would like to thank team members and students for their help and contributions to this book, including Da Lin, Ke Xu, Xiaohui Ge, Ziling Wang, Ke Wang, Meidong Xue, Xiangjin Wang, Chuanliang Xiao, Zhichen Xu, Haifeng Qiu, Tingli Hu, Chang Fu, Zhongyang Zhao, Michael Fornoff, and Nicholas Lin.

An important feature of this book is that there are case studies accompanied with simulation studies for many chapters. We hope this book and the examples given in the book will be useful to industry professionals, educators, students, and researchers worldwide in developing distributed PVs at high penetration level.

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# 1

# Overview

## 1.1 Current Status and Future Development Trends of Photovoltaic Generation around the World

With the growing challenges in global resource depletion, global warming, and ecological deterioration, increasing attention has been given to renewable energy generation, especially to photovoltaic (PV) generation. The global market of PVs has experienced a rapid increase since 1998, with a yearly increase of 35% of the installed capacity. The total PV installed capacity was 1200 MW in 2000, and PV installations rose rapidly up to 188 GW in 2014 and is projected to be 490 GW by 2020 [1]. With the rapid development of the PV industry, the market competition is getting increasingly fierce. The investment in the PV market is being boosted in some countries and regions, like the USA, China, Japan, and Europe. By the end of 2014, the global production of PV modules was around 50 GW, in which China increased 27.2% from the previous year to 35 GW, contributing 70% of the global production [2]. The global production of PV modules is expected to reach 85 GW and maintain the momentum of rapid growth [3].

Recently, a number of countries announced their policies and plans to further promote the development of PVs [4, 5]. The US Environmental Protection Agency (EPA) published its Clean Power Plan on June 2, 2014, promising that the usage of renewable energy (including solar energy) will be doubled within 10 years. The US Department of Energy (DOE) will spend $15 million to help families, enterprises and communities develop the solar energy program [6]. The Japanese Government enacted laws, like the *Renewable Energy Special Measure Law* and the *Renewable Portfolio Standard Law*, to identify the development objectives of new energy in Japan and the responsibilities of the participating parties [7]. China has highlighted a few key and crucial demonstration projects of the PV technologies in the *Outline of the National Program for Long- and Medium-Term Scientific and Technological Development (2006–2020)*, the *National 11th Five-Year Scientific and Technological Development Plan* and the *Renewable Energy 12th Five-Year Plan* [4–8].

It is noteworthy that the USA and Japan have both worked through the PVs "Industry Roadmap Through 2030 And Beyond." Japan expects that the future research and development pattern of PVs could be changed from *creating an initial PV market based on the government's guide* to *creating a mature PV market based on cooperation and work sharing among academia, industry, and government*, and targets to have a total PV installation capacity of 100 GW in 2030. The USA anticipates that the development

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pattern of the PV industry could be changed from export led to national investment oriented, promoting the industry's significant growth by devoting on the advancement of technologies and market and expansion of the domestic demand. It is projected to install 19 GW of PVs yearly in the USA, with the expectation of a total installed capacity of 200 GW by 2030. By then the cost of the PVs will decline to $0.06/kW, and PVs will make up an important part of the electricity market and become one of the main sources of electricity.

As to the development of the PV industry in China, from the viewpoint of the current status and future trend, the estimated installed capacity was for 300 MW, 1.8 GW, 10 GW, and 100 GW in 2010, 2020, 2030, and 2050 respectively in the *Medium and Long Term Development Plan of Renewable Energies (2007)*, which is apparently lower than actual development and lags behind the trend of the PV industry. Meanwhile, China has not proposed clear goals of the method, direction, and path for developing the critical technologies and devices that has already limited the advancement of the PV industry. In terms of the grid-connected PVs, there is a lack of complete and systematic regulations and policies for operation and management, electricity price, and system maintenance. Therefore, actively promoting the research and practical applications in the Chinese PV industry to follow the main stream of the global PV industry development will be of profound significance in the future.

At present, some developed countries (such as the USA, Germany, Australia, Japan, etc.) are leading the research and development of PV technologies. For example, Australia, represented by Professor Martin A. Green from the University of New South Wales, has made a great contribution to the development of PV cells by leading the research of single crystalline silicon solar cells in the world and proposing the concept of the third-generation PV cells [9]. The USA, the UK, Germany, Spain, Japan, and so on initiated the PV industry and applications early and have experienced rapid development. Although China's PV industry started late, it has experienced exponential growth. Especially after 2004, stimulated by the large demand from the European market, China's PV industry has boomed and saw over 100% yearly growth for five years in a row. In 2007, China became the largest producer of PV cells. China's PV production exceeded 50% of global production in 2010. China has gradually formed an orbicular chain in the PV industry, from silicon material, PV cells, to PV systems and applications [10, 11]. As shown in Table 1.1, China's PV manufacturers now take a dominant role in the world's PV production. Of the world's top 10 PV manufacturers, six are from China and all the top five are from China. Among them, the number one manufacturer Trina Solar produced 3.66 GW in 2014, closely followed by Yingli Green Energy, which yielded 3.36 GW [2].

In 2014, global PV installations increased by 17%, while the total installed capacity reached 47 GW. Figure 1.1 shows the market share of the world's top 10 PV countries in 2014. The top 10 countries were China, Japan, the USA, the UK, Germany, France, South Africa, Australia, India, and Canada with a total installed capacity of 38.3 GW, which accounted for 81.5% of the global increase [12]. As an emerging market, Asia has become the preeminent PV market in the world and took 59% of the global installation in 2014. Although China will maintain its position as the largest PVs market in the world, its development has apparently slowed down recently. Japan has continued its strong

**Table 1.1** World's top 10 PV manufacturers in 2014.

| Manufacturer | Country | Rank | Production | |
|---|---|---|---|---|
| | | | (GW) | (%) |
| Trina Solar | China | 1 | 3.66 | 14.6 |
| Yingli Green Energy | China | 2 | 3.36 | 13.4 |
| Canadian Solar | China | 3 | 3.11 | 12.4 |
| Jinko Solar | China | 4 | 2.94 | 11.7 |
| JA Solar | China | 5 | 2 | 8.0 |
| Sharp | Japan | 5 | 2 | 8.0 |
| Renesolar | China | 7 | 1.97 | 7.8 |
| First Solar | USA | 8 | 1.85 | 7.4 |
| Hanwha SolarOne | South Korea | 9 | 1.45 | 5.8 |
| Sunpower | USA | 10 | 1.4 | 5.6 |

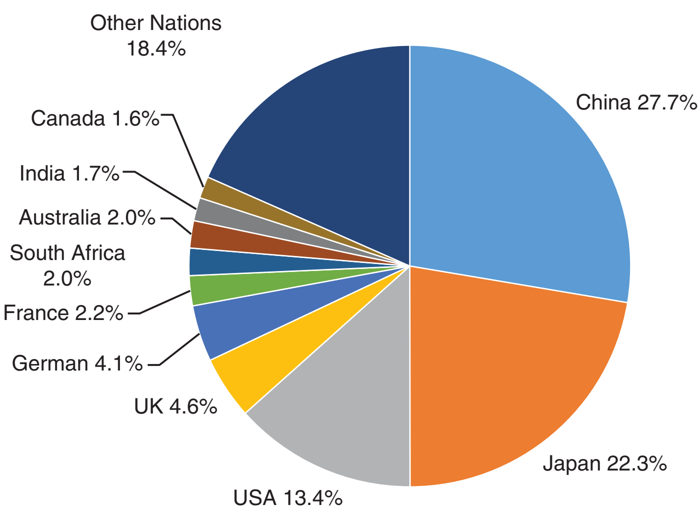


**Figure 1.1** Installation percentage of the world's top 10 PV markets in 2014.

growth. The USA surpassed Europe to be the second largest PVs market and took 19.3% of installations in 2014. The European PVs market kept shrinking in 2014 and took only 16.8% of new installations. Spurred by the renewable energy laws, the UK's PVs market flourished in 2014 and exceeded Germany for the first time to be the country with the most new PVs in Europe [2].

### 1.1.1 USA

Way back to June 26, 1997, President Clinton announced the "Million Solar Roofs Initiative," which planned to install 1 million roof-top solar systems by 2010, including

PV panels and solar thermal collectors. This initiative was driven by the trend of social development and the professionals dedicated to the research and development of PV generation. Two immediate reasons for proposing this initiative were:

- Large greenhouse gas emissions lead to global warming, which requires the reduction of the reliance on conventional energy sources. If the "Million Solar Roofs Initiative" was implemented successfully, the $CO_2$ emissions would be reduced by more than 3 million tons by the end of 2010.
- In the USA, the technologies of PV panels and solar thermal collectors were mature and implemented in mass production.

At present, the "Million Solar Roofs Initiative" has been carried out in some regions, such as the Civano project in Tucson, AZ. Owing to the huge potential of renewable energy resources in Hawaii, solar power has become the mainstream of the local energy supply and an important part of economic development. In 2001, the California State Government proposed the world-famous "California Solar Initiative Program," planning to install 1 million PV systems in 10 years by investing $3.2 billion. In September 2004, the US Department of Energy published "Our Solar Power Future: The US Photovoltaics Industry Roadmap Through 2030 And Beyond," revealing an ambitious development plan for the PV industry. In 2006, the USA passed President Bush's Solar Energy Initiative, which increased research funding to $148 million to strengthen the competiveness of the nation's PV technologies. In April, 2008, the mayor of Philadelphia announced the intention to build the first megawatt-level PV plant in the marine park in Pennsylvania. In May 2008, Duke Energy announced the plan to purchase all of the generation from a 16 MW PV plant in Charlotte, North Carolina. In the middle of June 2008, PEPCO Energy Services signed the contract to build a 2.36 MW PV plant on the roof of the Atlantic City Convention Center in New Jersey. All of the aforementioned projects have been completed.

On March 2015, the US Solar Energy Industries Association (SEIA) released the US Solar Energy Insight Report of 2014 Year in Review. The executive summary of the 2014 report stated that the PV installations in the USA reached 6201 $MW_{dc}$, up 30% over 2013. The cumulative solar PV installed capacity has reached 18.3 $GW_{dc}$, and solar accounted for 32% of new generating capacity in the USA, second only to natural gas. It also investigated all kinds of PVs and concluded that the residential solar has soared over the past 3 years, posting annual growth rates over 50% in 2012, 2013, and 2014. In the report of US Solar Industry Year in Review 2009, which was released in April 2010, by SEIA, Lawrence Berkeley National Laboratory, it was estimated that compliance with existing solar and distributed generation carve-outs would require roughly 9000 MW of solar capacity by 2025 [13, 14].

The National Renewable Energy Laboratory (NREL) of the US Department of Energy began its operation in 1977 as the Solar Energy Research Institute and changed its name to NREL in 1991. Nowadays, there are more and more institutions carrying out research on solar energy in the USA. Various incentives have been issued to encourage the development of renewable generation, like feed-in tariffs, investment subsidies, renewable energy certificates, and so on.

### 1.1.2 Japan

Japan's PV development initially started from a medium- and long-term research and development plan on replacing petroleum by solar-based renewable energy in 1974. The plan, also known as the Sunshine Program, was proposed by the Ministry of Economy, Trade and Industry (METI). After that, the Japanese Government established the New Energy and Industrial Technology Development Organization (NEDO) to take charge of the industrialization of photoelectricity. The industrialization procedure of PV cells was accelerated by large government funds, which dramatically reduced the production cost of PV cells and significantly improved the production technologies. For example, the conversion efficiency of polycrystalline silicon casting substrate increased from 12.7% in 1984 to 15.7% in 1988, while the conversion efficiency of amorphous silicon cells increased from 8.25% in 1985 to 10.1% in 1988.

After the 1992 World Economic and Environmental Conference, more attention was paid to environmental problems, such as climate change due to human activities. Since 1994, METI has implemented preferential policies to subsidy residential PV systems by up to 50% of the total cost, including the cost of inverters, PV panels, grid connection system, and construction. In addition, contractors can also get the same subsidization. The promotion greatly prompts the growth of residential PV installation. Although Japan was falling into the bursting of the bubble economy at that time, the citizens still actively applied for roof-top PV projects. For instance, the total number of applications was 33 000 (121 MW) between 1994 and 1999, while there were 26 000 applications in 2000 (96 MW), which was nearly the summation of the total installation of the previous 5 years.

In 2000, Japan set out the "PVs Industry Roadmap Through 2030 And Beyond," which aimed to transfer the PV research and development from creating an initial PV market guided by government to creating a mature PV market based on the collaboration among academia, industry, and government, and expected the total installed capacity to be 100 GW in 2030. If it can be realized, PV generation can provide approximately 50% of residential electricity consumption, which is 10% of the total electricity demand in Japan. To accelerate the increase of PV generation, on June 28, 2009, NEDO amended the roadmap and predicted the cost of PV generation could decline to \$0.14/kW in 2020 and to \$0.07/kW in 2030 [15].

As one of the measures taken after the 2011 Fukushima nuclear power plant accident, Japan started to strive to develop PV-based renewable energy generation. On July 1, 2012, the PV Subsidies Act was enacted in Japan. According to this act, Japan's electric companies must purchase the electricity generated by home and industry solar energy, and the feed-in tariff was set as ¥42/kWh (approximately \$0.54/kWh) [16]. Although the feed-in tariffs gradually declined in 2013 and 2014, Japan is still the country that has the highest subsidy on PV systems around the world.

### 1.1.3 Germany

Germany has the largest PV installed capacity in the world so far. Its experience in promoting PV development from the aspects of policymaking, management, and technologies has been the model for several other countries. In 2000, the German Government released the German Renewable Energy Act (EEG-2000) and successfully completed the "100,000 Roofs Programme" in 2003. In 2004, the accumulated PV capacity in Germany surpassed that in Japan and became a leading country in PV generation. The new PV installations in Germany was 1.5 GW in 2008, 3.2 GW in 2009, and peaked at around 7.5 GW between 2010 and 2012. At that time the plan to reach a PVs installed capacity of 10 GW in 2020 had been achieved in advance. However, since 2013, there have been some issues raised related to this renewable energy, such as overload operation and fast growth of electricity price caused by renewable energy subsidies. Therefore, on August 1, 2014, the German Government published the revised German Renewable Energy Sources Act to strictly control the increasing scale of renewable energy generation and reduce funding on newly built projects. Under this new policy, newly installed PVs capacity decreased by 41.3% to around 1.9 GW and kept decreasing for the next 2 years [2]. By the end of 2014, the total German accumulated PV capacity reached 38 GW, and PV generation has turned out to be the largest renewable energy source in Germany: 6.3% of the total energy generated in Germany was from PV generation.

Some effective measures were taken by the German Government to promote PV generation, such as bank loans, feed-in tariffs, and so on. In Germany, if people install PV panels on their own roofs, the generated power can be sold to power grids just like they are running a small power plant, and the country subsidizes up to €0.574/kWh. Currently, the PV industry in Germany has become very active. However, impacted by the widespread European debt crisis and the price decline of PV modules, Germany has begun to repeatedly slash PV subsidies since 2009. The subsidies were cut on July 1 and October 1 of 2010. Compared with 2009, the feed-in tariff of PV installations was decreased by 33–35% in 2011 [17]. According to the latest Renewable Energy Act, the subsidies for renewable energy will be settled through bidding no later than 2017.

While striving to develop its domestic PV industry, Germany also actively expands oversea markets based on its superior technologies. For example, in 2009, Solon SE won the bidding over an 11 MW PV plant project in Spain, which was invested in by Renewable Energies and PVs Spain S.L. (REPS), a majority owned subsidiary of the Norwegian energy company Statkraft AS. In addition, at present, the German company SMA has the largest market share of PV inverters.

### 1.1.4 China

China has excellent natural resources for exploiting solar energy. Two-thirds of China has considerably good solar irradiance. Provinces like Xizang (Tibet), Qinghai, Xinjiang, Gansu, Ningxia, and Inner Mongolia have the richest solar resources in the country. Eastern, southern and northeastern China are in the second class of the solar irradiance, while the areas of Sichuan Basin and Guizhou Province come last in terms of solar resources.

In the late 1980s, through importing equipment, complete production lines, and manufacturing technologies, the production capability of PV cells reached 4.5 MW in China, and the PV industry was preliminarily set up then. In 2008, the annual production capacity of PV cells reached 2 GW, which took more than 30% of the global market. In 2009, the yearly yield was 7.5 GW, which accounted for 44% of the global production. However, prior to 2008, PV installations in China were very limited, and 90% of PVs production was exported overseas. In 2009, the Chinese Government announced its supporting policies and incentives, such as the Golden Sun Demonstration Project and the Rooftop Project, to promote domestic demand and initiate the massive installation of PV panels in China. The localization in both of the upstream and downstream chains of the PV industry was accelerated, and the production line of PV panels and some key equipment for polycrystalline silicon production was supported by domestic research and development [18]. As Table 1.1 clearly shows, China had six PV manufacturers in the world's top 10 in 2014.

According to the Medium and Long-Term Renewable Energy Development Plan published by the National Development and Reform Commission, the total PV capacity would be 300 MW by the end of 2010, including 150 MW in remote agricultural and pastoral areas, 50 MW on buildings and public facilities, 20 MW large-scale grid-connected PV plants, and 80 MW for the others. The plan also projected to have a total PV capacity of 1.8 GW by the end of 2020, including 300 MW in remote agricultural and pastoral areas, 1 GW on buildings and public facilities, 200 MW large-scale grid-connected PV plants, and 300 MW for the others. This goal was already achieved in 2011, much earlier than the original deadline.

Since several promoting policies and incentives were issued in 2009, like the Solar Rooftop Program, the Golden Sun Demonstration Project, and the Memorandum of Actively Supporting Golden Sun Demonstration Project, new opportunities were opened up for the development of the PV industry [19, 20]. The three programs also showed China's determination on developing the PV industry. In the same year, a number of large-scale PV plants were successively built, such as the Grid-Tied PV Project in Hangzhou Energy and Environment Industrial Park (a total of 20 MW planned and 2 MW completed in the first stage), the 66 MW PV plant in Yulin, Yunan, and China's first 10 MW-scale PV plant in Shizui Mountain. The total PV installed capacity is projected to be 50 GW by the end of 2020, which is equivalent to the capacity of more than 50 large-scale coal-fired power plants.

Figure 1.2 shows Qaidam Basin's million kilowatts solar energy demonstration project, which is the largest grid-connected PV plant in the world. In December 2011, this PV plant's $1.003 \times 10^6$ kW generation was successfully interconnected with the Qinghai power grid. It was the first time for the Qinghai grid being penetrated by a million-kilowatt-level of PV power. This project sets five records worldwide: it was the largest group of PV plants, the most concentrated area of PV installations, the largest short-term PV installation in the same region, the largest grid-connected PVs project, and the first time for grid integration of a million-kilowatt-level PV station.

In October 2012, China's State Grid issued the *Suggestions on Supporting Grid-Tied Distributed PV Generation*, in which 15 commitments were made, such as improving the efficiency of the grid-connection service for the distributed PV plant, fee free for some services, and so on. It required all power utilities to fulfill the commitments and to ensure the grid-connection service being carried out in order and smoothly. By the end of January 2013, the utilities had addressed 850 consulting cases in total on grid connection of distributed PV generation, completed 119 grid-connection systems, and installed 338 000 kW of PV panels.

**Figure 1.2** Qaidam Basin's million kilowatts solar energy demonstration project.

## 1.2 Current Research Status of Grid-Connected Photovoltaic Generation

### 1.2.1 Characteristics of Grid-Connected Photovoltaic Generation

As a distributed generation source, a grid-connected PV system converts the DC output of the PVs to AC power via an inverter; the AC power is then fed into the power grid. Owing to the regional unbalanced, random, and volatile characteristics of the solar resources, the PV generation itself is not dispatchable. Thus, the grid-connection requirements of PV systems vary based on the PV capacity, grid-connection mode, and the target grid. From the perspective of the power grid, on the one hand, as PV generation differs from traditional generation, conventional techniques and calculation methods for grid connection are not suitable for PV systems. On the other hand, at present, the mutual influence between a grid-connected PV system and the grid are still being research, and comprehensive, clear, and operational management standards and technical manuals have not been established yet. It is hard for utilities to do a thorough and credible assessment, covering the aspects of power quality, reliability, stability, security, and standard management. Therefore, connecting PV systems to the power grid can be complex and difficult.

According to the designed capacity, a PV system can be connected to the distribution network at a voltage level of 35 kV, 10(20) kV, or 400 V. The actual operation of a grid-connected PV system has the following characteristics:

1) Currently, a PV grid-connected inverter, normally a voltage source converter (VSC), is primarily controlled by current control to track the voltage of the point of common coupling (PCC) and synchronize with the power grid by controlling the output

current of the VSC. At present, the output PV inverter is pure active power with a unity power factor. However, accompanying the release of relevant standards and regulations, more and more products are equipped with the function of adjusting reactive power output for reactive power support when needed.

2) In order to efficiently explore solar energy, maximum power point tracking (MPPT – see Chapter 2) is normally used for maximizing the output power of the grid-connected PV system.
3) The output of PV generation is heavily dependent on weather. On cloudy days, the PV output can be very volatile.
4) Because of the fast and random fluctuation of the PV output, it is highly possible to have a large peak-to-valley difference of demand from the power grid when the PV penetration level is high. Therefore, it needs the spinning reserve capacity of conventional power units to compensate the power fluctuation, which will increase the overall generation costs.
5) When the output power of a PV inverter is small, the harmonic components become more significant.
6) The correlation between the anti-islanding protection of a grid-connected inverter and the load level is complex. Owing to the low PV/load ratio at present, the protection can identify the islanding by detecting the rapidly declining voltage and frequency when the electric supply from the utility discontinues. However, as the capacity and the number of grid-connected PV generation systems constantly increase, multiple types of inverters with different protection principles will be connected to the power grid and interfere with each other. When the PV generation is close to the load demand level, the anti-islanding detection will take a much longer time or even fails.
7) Overall, the existing PV grid-connection technologies are not grid friendly. With the increase in capacity of grid-connected PV generators the protection technologies of inverters will have a great impact on the safe and stable operation of the power grid and will become a key factor limiting the integration of PV generation. Therefore, it is necessary to study the impact of high-penetration PV generation systems on the power grid.

### 1.2.2 Impact of High-Penetration Photovoltaic Generations on Distribution Networks

According to the integration methods, grid-connected PV generation can be categorized into centralized and distributed PV systems. A centralized PV plant is usually composed of large-scale PV units and directly feeds the output into a high-voltage grid through inverting. The main problem of centralized PVs is that they need large-scale long-distance transmission to deliver their output power. In addition, since their output is intermittent and random, a large PV plant may bring about severe influences on the frequency and operation of the grid. Distributed PV generation systems are usually connected to low- and mid-voltage distribution networks. A distributed PV generator is close to the load; therefore, it does not require long-distance transmission, and the transmission losses can be significantly reduced. However, the disadvantages of distributed PV generation are low energy density, poor stability, inadequate adjustment, and their output power can be greatly influenced by the surroundings. If distributed PV generation is at a high penetration level, this can induce the following influences [21–23]:

1) ***Bidirectional power flow.*** Different from the one-way power flow in traditional radial distribution networks, distributed PV generation can lead to bidirectional power flow. When the PV output power is higher than the load demand in the distribution network, the extra power is going to be fed back to the transmission grid, which can adversely impact the operation of voltage regulators and the coordination among protection devices.
2) ***Impact on the system voltage.*** The output power of distributed PV generation is heavily influenced by weather and is intermittent. Hence, with high PV penetration, the reverse power flow can increase voltage or even cause overvoltage on some nodes. The rise of voltage is closely related to the position and total PV capacity.
3) ***Impact on the system protection.*** In a distribution network, the short-circuit protection usually takes the approaches of overcurrent protection and fuse protection. As to the distribution network with high PV penetration, the protection may fail to detect the short-circuit faults in the feeder if the PV generation contributes the majority of the short-circuit current. The peak of the short-circuit current is determined by the PV inverter controllers. In addition, when the protection trips to isolate and clear the fault, if the PV generation is still connected to the feeder, an isolated power island powered by the PV generation may be formed, which can lead to the asynchronous reclosing of an automatic reclosing lock and arc restriking at the point of fault.
4) ***Impact on the operation and control of the power grids.*** Because of the uncertainty of PV generation, the accuracy of short-term load forecast is reduced, which makes the planning and operation of traditional generation and the control of exchange power more difficult. Distributed PV generation significantly increases the number of generation in the grid, but these points are dispersed and small, which increases the complexity of the coordination among the power sources and causes the conventional strategies of reactive dispatch and voltage control to be ineffective. In addition, more impacts can also be introduced to peak-shaving, safety reserve, voltage stability, and frequency stability. Therefore, with high PV penetration in the distribution network, the regulation and control of conventional power system is compromised, which brings new challenges for the operation of the power grid.
5) ***Impact on the design, planning and operation of the distribution network.*** With more and more PV generation in the distribution network, the percentage of the power from the central source (i.e., substation) declines, which can result in a significant change in the structure and control patterns of the current grid. The challenges and opportunities due to this call for a fundamental change of the grid in many aspects, such as, but not limited to, design, planning, operation, and control. It is projected that a lot of electricity will be generated in the distribution network; thus, it is markedly important to upgrade and optimize the structure of the distribution network in advance. In addition, when the penetration level of distributed PV generation is high, the customer side can actively participate in energy management and system operation, which will change the traditional operation and sales mode of the distribution network.

### 1.2.3 The Necessary of Research on Distribution Network with High Photovoltaic Penetration

With the improvement of technologies and the decline of cost, there will be more and more distributed PV generation connected to the distribution network, which brings new issues and. Hence, in order to efficient utilization of solar energy, it is necessary to carry out a comprehensive and deep research on grid-connection technologies of distributed PV generation, as discussed in the following points.

1) ***Laboratory development for PV generation–grid interconnection.*** In order to study the impacts of distributed PV generation on the safety and power quality of the distribution network, it is necessary to develop research laboratories to test PV systems and investigate different grid connection scenarios. By analyzing the characteristics of PV generation and developing the models of PV control systems, the present power system simulation platform can be updated to have the capability of including the PV generation in the analysis and calculation. Meanwhile, it is also important to establish a database of typical cases of grid-connected PV generation. Therefore, a well-designed and equipped PVs–grid interconnection laboratory is vital for studying the interactions between distributed PV systems and the distribution network.
2) ***Research on the mechanism of interaction between PV generation and the grid.*** As discussed previously, when the penetration level of PVs is high, it is important to carry out the research on the interaction between PV generation and the grid to discover the mechanisms, which can provide a powerful rationale for updating and improving the technologies for future power systems. Aiming at solving challenges induced by random PV output and power electronic converters, the following mechanisms should be studied by using the simulation platform on the laboratory development for PV grid interconnection. First, the distribution mechanism of power quality distortion. Second, the PVs' response during grid faults and the interaction between the PVs and the grid's control systems. Third, the impacts of PV generation on the voltage, phase, and frequency stability of the grid. The goal of research is to explore the principles of the interaction between the PVs and the grid, develop the relevant theories and methods, and lay out the theoretical framework for the control and stability analysis of the grid with massive PV systems.
3) ***Research on collaborative planning for future distribution systems.*** When PVs penetration is high, the distribution system will transfer from a system with a single purposed energy-distribution function to one with multiple functions of energy collection, energy transmission, and energy distribution. The integration with PVs and the other distributed generation sources can impact the distribution networks from the aspects of economy, voltage, power flow, short-circuit current, reliability, and power quality. Therefore, the following new challenges are emerging in the planning and design of the power grid.
   - Under high PV penetration, load prediction becomes more difficult. The traditional planning of the generation sources is based on the forecasting of the load distribution; the optimal capacity and location of the sources are then chosen for

balancing the demand and supply. When the PVs are connected, the distribution network becomes active, which makes the traditional source planning methods unsuitable.

- The topology of a traditional distribution network can be radial or networked, which is selected based on the requirements of power supply reliability. A high PV penetration can introduce a significant amount of stochastic power flow in the distribution network. In order to meet this, there needs to be a study of the maximum random power that can be accommodated in the existing distribution network.
- The output of the PV generation changes with the fluctuation of solar irradiance, which causes uncertainty for reactive power optimization of the grid.

4) ***Study on the control and operation of power systems with high PV penetration.*** On the one hand, when PV penetration is high, stochastic PV generation can lead to uncertain power flows and adversely influence the safe and stable operation of the distribution network. On the other hand, the utilization of PV generation can benefit the distribution network from the aspects of reducing line losses, improving energy structure, increasing energy utilization, and so on. However, how to maximize the benefits by using appropriate economic dispatch is an urgent problem to be solved. Furthermore, extensive research is needed to address the power quality issues, such as the harmonic pollution caused by a large amount of power electronic devices and the grid's three-phase imbalance aggravated by single-phase PVs. Grid disturbances can cause abnormal operations in PV generation, which may in turn intensify the impact of PV generation on the grid. Therefore, research on the operation and control of the power grid with high PV penetration needs to be carried out on the following aspects:
   - optimal energy management of the power grid with high PV penetration;
   - safety operation, economic dispatch, and optimal control of the grid and the PV generation;
   - reactive power dispatch and voltage control strategy;
   - load forecasting;
   - the impact of PV generation on the safe and stable operation of the distribution network;
   - the response of PV generation under grid disturbances.
5) ***Research on coordinated protection of distribution networks with PV generation.*** Protection is a core function to maintain the safe and stable operation of power systems. When PVs is integrated at a high penetration level, the system faults induced electrical characteristics of the distribution network are altered. Therefore, the traditional fault detection and protection methods need to be updated. To solve the theoretical and technological protection problems faced by a grid with high PV penetration it is necessary to carry out following research:
   - To study the characteristics of short-circuit current of grid-connected PV systems and develop simulation models it is required to develop appropriate models of the PVs to accurately characterize external faults.
   - It is necessary to develop principles and methods of protection adjustment for different configurations and types of protection devices.

- To ensure the correct operation of protection devices, the research on coordination mechanisms among protection devices plays an important role.

6) ***Research and development of equipment for the monitoring, protection, and control of power systems.*** After analyzing and studying the impacts of PV generation on the distribution network and the mechanism of interaction, it is necessary to develop devices for monitoring, protection, and control of the power system. The main devices need to be developed are:
   - *Protection devices considering the integration of PV generation.* New protection methods and devices are required to overcome the PV-induced complex changes of electrical quantities after faults.
   - *Islanding detection systems.* For electrical safety and high power quality, there needs to be immediate detection of islanding and taking action on the islanding part and the rest.
   - *Real-time monitoring and control systems.* The integration of PV generation leads to more information that needs to be detected and more tasks to be coordinated.
   - *New electricity measuring devices.* The PVs may change the power flow to bidirectional in the distribution network. Thus, it is necessary to change the one-way electricity measuring and metering to two-way. Meanwhile, as the PV generation cost is currently higher than the cost of traditional generation, it is also important to study how to reflect this difference in the measurement and metering devices.
7) ***Perfecting the technological standards and regulations for integrating PV generation with power grids.*** At present, the development of distributed generation including PVs is still in the initial stage in China and many other regions. Various technologies are under development, and many standards for integrating PV generation with the grid are immature or even missing. To guide and standardize the integration of renewable distributed generation with the grid and ensure that distributed generation systems and their control devices do not interfere with the grid's safe and stable operation, it is important to improve the technological standards and regulations for integrating PV generation with the power grid, including the standards to identify the technical parameters, control functions, disturbance ride-through capability, grid capacity, voltage level of the PCC, and reactive power and power quality requirement of the PV systems, and the standards to regulate the functions of the distribution network for accommodating distributed generation sources.

## 1.3 Summary

The current status and future development trends of PV generation around the world have been presented in this chapter. The PV industry development history of the USA, Japan, Germany, and China and the relevant policies, laws, and demonstration projects of these countries have been also introduced.

According to the integration methods, grid-connected PV systems can be categorized into centralized PV plants and distributed PV generation. There are various impacts of high PV penetration on distribution networks, including power flow direction, system voltage, protection, operation, planning, and so on. Therefore, in order to ensure safe and stable operation of the grid, extensive research needs to be carried out from the aspects of the research laboratory development of PV systems, the interaction mechanism between PV generation and the grid, novel planning methods, operation and control, coordinative protection, technological standards, and regulations of distribution networks with high PV penetration.

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