Introduction

Md. Rabiul Islam

Abstract Energy and environment are two foremost areas of global crisis. The world's energy demand is growing remarkably which is not only diminishing the reserve of fossil fuels, but also affecting the environment. In 2014, the global primary energy consumption was 12,928.4 million tons of oil equivalent (MTOE) which generates about 10,000 million tons of carbon during the burning of fossil fuels. It is more and more broadly recognized that renewable energy, especially solar energy, can offer effective solutions to these gigantic challenges. Now, renewable energy contributes around 3 % of the world's energy needs. By the end of 2014, a total of 187.24 GW solar photovoltaic (PV) power capacity had been installed in the world. The annual installation of new PV systems rose from 47.60 GW in 2014 to 58.10 GW in 2015, and in 2010, it was only 17.06 GW. Up to 2014, about 1600 installations worldwide were PV power plants larger than 4 MW. Of which 60 plants in Spain and 50 in Germany generating an output of more than 10 MW. A 10 MW solar PV power plant may save about 15,000 tons of CO_2 emissions per annum. In order to push this emerging technology, more research is needed. The book provides a consistent compilation of fundamental theories, a compendium of current research and development activities in the field of solar PV technologies. In this chapter, the development of solar PV technologies is presented in the Preface section. This introductory chapter also presents the objectives and the organization of the whole book.

Keywords Solar photovoltaic power plants · Energy and environment · Power converter topologies · Maximum power point tracking · Grid integration · Stability · Energy storages · Recycling of solar PV modules · Module cost · Land use · Historical development · Recycling of solar cell materials

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1 Preface

The world's energy demand is growing remarkably due to the strong growth of population and economy in the developing countries [1–3]. Figure 1 shows the world population with projections to 2050 [4]. Almost a constant growth rate has been observed during 1950–2015 and predicted same growth rate until 2050. The increasing energy demand is not only diminishing the reserve of fossil fuels, but also affecting the environment. Carbon dioxide (CO_2) gas is generated from burning of fossil fuels, which significantly contributes to the increase of average global temperatures, i.e., global warming. Figure 2 shows the global CO_2 emission form fossil fuel burning and average global temperature [4, 5]. Scientists worldwide are now seeking solutions to these two enormous challenges (energy and environment) from renewable energy sources, which are richly available in almost every country. Many countries have set targets for renewable power generation resulting in much higher average annual growth rates of renewable power generation than those of conventional power generation in recent years [6–8]. Over the decades, a good

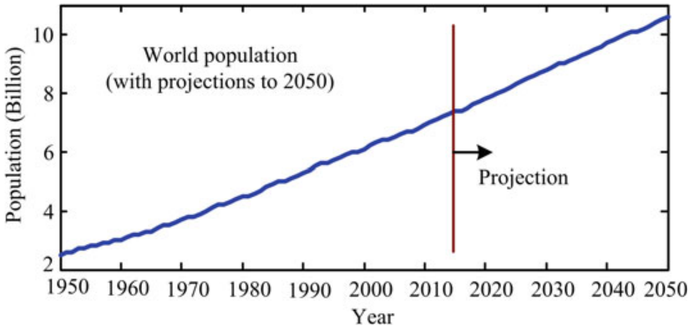

Fig. 1 World population in billion with projections to 2050

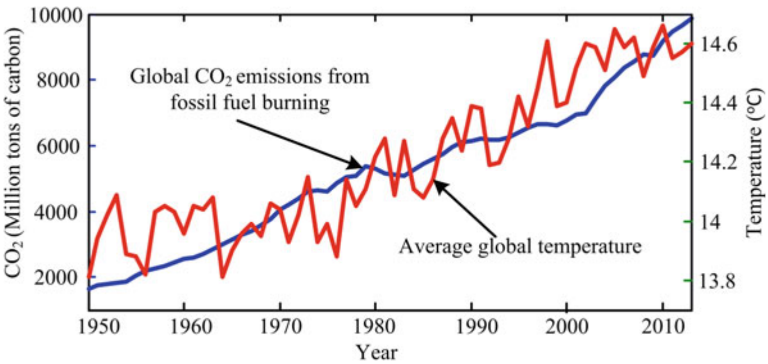

Fig. 2 Global CO_2 emissions from fossil fuel burning and average global temperature

number of countries have implemented specific policies and incentives to support the development of solar PV program, which has led to a rapid increase in the total installed capacity. Solar photovoltaic (PV) represents the highest growth rate due to its abundant source and technological development of PV cells, e.g., fast reduction of PV module cost. Figure 3 shows the world annual growth of energy use by source [4]. The cost of solar PV panels has declined 99 % over the last four decades. Average module cost was USD 74/W in 1972 and reduced to less than USD 0.70/W by 2014. In 2012, Chinese made thin-film (TF) PV modules with an average module cost of USD 0.75/W. It is forecasted that more than 40 % reduction of PV module cost is likely to occur by 2020. In 2012, the cost of small PV systems in Germany was just USD 2200/kW. In 2012, the European PV Industry Association (EPIA) also forecasted that small-scale rooftop PV system and large-scale PV projects cost could decline to between USD 1750–2400/kW and USD 1300–1900/kW, respectively, by 2020 [9]. Due to the fast reduction of module cost as well as the reduction of difference between the cost of renewable power generation and the cost of conventional power generation, the installation of solar PV systems has been gaining interest specially in the energy starved countries in the world. The EPIA projected that PV power may contribute up to 4.9–9.1 and 17–21 % of the global electricity generation by 2030 and 2050, respectively. Currently, there are over 1000 vendors worldwide have been producing PV cells and modules, most of them are in the US, Japan, Europe, and China.

At present in Bangladesh, the cost of diesel-based electric power generation is about BDTk 15.80/kWh [10]. The PV is now becoming competitive with power generated from diesel-based systems. The solar home system (SHS) of Bangladesh is one of the fastest growing solar PV power promotion program in the world. In average 2000 SHSs are installing every day in Bangladesh. Beside a number of

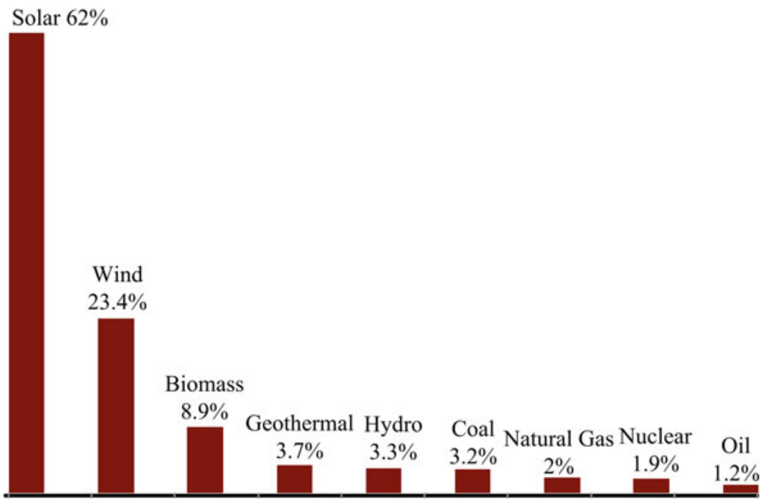

Fig. 3 World annual growth of energy use by source (2008–2013)

developed countries many developing countries have also set their target to generate electricity from renewable sources. The developing country, Bangladesh has set a target to generate 10 % of their total electricity from renewable energy sources by 2020, which is in terms of capacity of 2000 MW.

The first 1 MW_p PV power station was installed in 1982 at California by Arco Solar. In 1984, a 5.2 MW_p PV power plant was installed in Carrizo Plain. Since then, multimegawatt PV power plants have attracted great attention and now power plants of more than 500 MW_p in capacity have thereby become a reality. As of 2015, the Charanka Solar Park, Gujarat is one of the world's largest operating PV power plant and having a capacity of 600 MW_p. Italy, Germany, China, the US, France, and Japan are the leading countries in terms of installation of PV modules and systems. Up to 2014, about 1600 installations worldwide with a combined capacity of 22,500 MW_{AC} were PV power plants larger than 4 MW. Of these plants, several hundred plants have been installed in Germany and Spain, each plant generating an output of more than 1 MW_p. Of which 60 plants in Spain and 50 in Germany generating an output of more than 10 MW_p. Figure 4 shows the world cumulative and annual solar photovoltaic installations [4]. The number of PV power plants will continue to rise. Several hundred PV power plants will be installed within the next few years. Future PV power plants will have higher power capacity. Indeed, some of them will exceed 1000 MW. More than 90 % of the installed capacity consists of grid-connected systems.

The module efficiency is one of the important factor in selecting solar PV technology for installation. Crystalline silicon (c-Si) and the thin-film (TF) technologies dominate the global PV market. There are three types of c-Si-based solar PV technology, i.e., monocrystalline silicon (mono-c-Si), multicrystalline silicone (multi-c-Si), and ribbon-sheet grown silicon. Currently, crystalline silicon PV

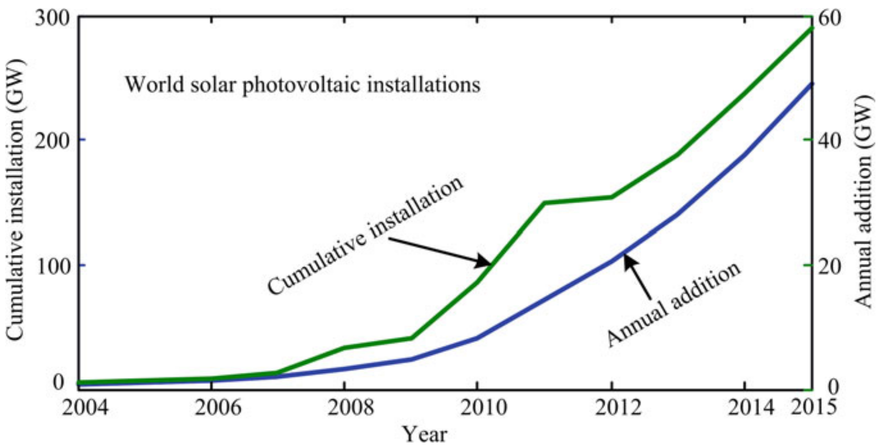

Fig. 4 World cumulative and annual solar photovoltaic installations

Table 1 Performance of commercial solar PV technologies

PV technology		Module effic. (%)	Record lab effic. (%)	Record commercial effic. (%)	Area/kW (m^2/kW)	Lifetime (Years)
c-Si	Mono-c-Si	13–19	24.7	22	7	25
	Multi-c-Si	11–15	–	20.3	8	25
TF	a-Si	4–8	10.4	7.1	15	25
	a-Si/μc-Si	7–9	13.2	10	12	25
	CI[G]S	7–12	20.3	12.1	10	25
	CdTe	10–11	16.5	11.2	10	25

technology dominates about 85 % of the PV market share. Although, TF solar PV is cheaper than c-Si-based solar PV, but TF solar PV is significantly less efficient and requires more surface area for the same power output. The TF solar PV technology can also be divided into four basic types, i.e., amorphous silicon (a-Si), amorphous and micromorph silicon multi-junction (a-Si/μc-Si), copper-indium-[gallium]-[di]-sulfide (CI[G]S), and cadmium telluride (CdTe). Crystalline silicon (c-Si) cells have reached a record efficiency of around 25 %. The highest efficiency of commercial modules recorded at 20 % with a lifetime of about 25 years. Maximum 12 % efficiency recorded for commercial TF modules. It is predicted that the maximum efficiency of c-Si-based and TF-based commercial modules will increase to 23 and 16 % by 2020. Performance of commercial PV technologies is tabulated in Table 1 [9].

Since multimegawatt PV power plants require large areas of land, they are usually installed in remote areas, far from cities. For example, the 10 MW grid-connected solar PV power plant in Ramagundam, India, occupied over 50 acres of land [11]. Ramagundam's plant installed about 44,448 PV modules with a total of 1852 strings. For power transmission, a medium voltage network is commonly used. A 33 kV transmission grid is used to transfer power from Ramagundam plant to utility grid. Figure 5 shows the architectural layout of 10 MW solar PV power plant in Ramagundam, India [11]. However, the intermittent nature of solar energy source, in terms of the output voltage and power, is a major challenging issue for grid integration.

On the other hand, when PV arrays are used to harvest solar energy, high cost and low energy conversion efficiency are two important factors that could limit the implementation of PV power plants. In PV systems, the PV array represents about 30–50 % of the total cost of the system, and the remaining costs include the installation, the energy storage, balance of system, control circuit, and the power electronic components. The battery storage corresponds to about 20–30 % of the system cost. The inverters and maximum power point tracker (MPPT) contribute to only 7 % of the total system cost. Due to the low conversion efficiency and high cost of solar array, it is very desirable to operate the PV panel at the maximum

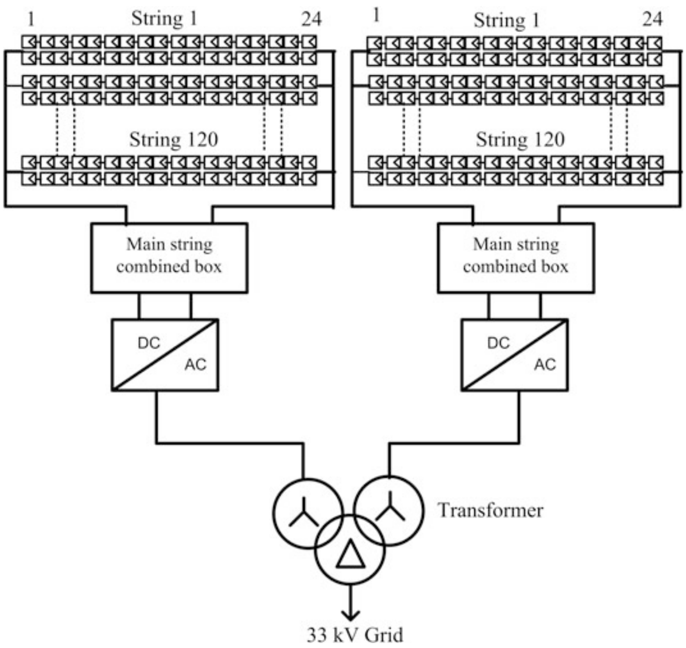

Fig. 5 Layout of 10 MW solar PV power plant in Ramagundam, India

power point (MPP). ASEA Brown Boveri (ABB) and Siemens are the leading manufacturers of PV inverters. Most of the inverters convert the DC power generated by PV arrays into single or 3-phase AC power with a voltage rating of 300–400 V [12]. The power converter topology, system stability, and control of grid-connected PV power plants have attracted considerable interest in recent years, as the existing technologies are not suitable for large-scale PV power plants yet. In the last two decades, extensive research has been carried out in proposing new inverter topologies, e.g., inverters with or without high-frequency transformers, with common DC or magnetic links, and with multilevel concepts [7, 13–15]. Beside the development of inverter topologies, considerable research efforts have also been directed toward the progress of MPPT algorithms, e.g., particle swarm optimisation, line search, chaos search, and simulated annealing. Recently, pumped hydro and compressed air energy storages other than traditional batteries have been developed specially for utility-scale energy storage systems. At the end of lifetime, the recycling of PV modules is necessary for environmental and economic purposes. It is estimated that about 800 metric tons of waste will be produced from 10 MW PV modules. A solar module is full of numerous encapsulating plastic materials, such as ethylene vinyl acetate and polyvinyl fluoride. Research is needed to push these technologies to solve two enormous challenges, i.e., energy and environment by replacing conventional power plants with solar PV power plants.

2 Major Objectives of the Book

The main objective of the book is to present the design and implementation process of large-scale solar PV power plants. The chapters are prepared and arranged in such a way that the book provides a consistent compilation of fundamental theories, a compendium of current research and development activities as well as new directions to overcome some critical limitations of the existing grid integration technologies. It is expected that the contents of this book will have great useful for future renewable power plants and smart grid applications.

3 Organization of the Book

For grid integration of PV system, either compact high-frequency transformer or bulky low frequency transformer is employed in the dc- or ac-side of the PV inverter, respectively, to step up the low output voltage of the PV modules to the grid voltage. Galvanic isolation is provided and the safety is assured with the use of transformer. Because of the high cost and significant loss of the transformer, the PV inverter becomes expensive and poor efficient. To mitigate these problems, the transformer is removed from the PV inverter. The transformerless PV inverter is smaller, cheaper, and higher in efficiency. Various transformerless PV inverter topologies, with different circuit configuration and modulation techniques, have been developed recently. The operating principle and the converter structure are evaluated in Chap. 2. It is expected that the transformerless PV inverter would have great potential for future renewable generation and smart micro grid applications.

Tracking the maximum power of the PV arrays at real time is very important to increase the whole system performance. In the past decades, there are a large number of maximum power point tracking (MPPT) methods have been proposed for PV system, such as constant-voltage tracing method (CVT), perturbation, and observation method (P&O), incremental conductance method (INC), curve fitting method, look-up table method, and so on. Actually, these conventional methods can track the MPP. But these methods have some drawbacks, like oscillation, miscalculation, poor accuracy, unimodal *P–U* curves only. To overcome the limitation of these methods, some advanced MPPT methods are introduced in Chap. 3. In Chap. 4, the criteria for assessing the performance of MPPT methods are defined followed by a complete description and discussion of both techniques designed for uniform environmental conditions and those designed for nonuniform environmental conditions.

Most of the conventional MPPT algorithms are incapable to detect global peak power point with the presence of several local peaks. A hybrid particle swarm optimization and artificial neural network (PSO-ANN) algorithm is proposed in Chap. 5 to detect the global peak power. The performance of the proposed algorithm is compared with that of the standard PSO algorithm. The proposed algorithm is tested and verified by hardware experiment. The simulation and the experimental results are compared and discussed in the Chapter.

Accuracy in prediction of global horizontal irradiance is vitally important for photovoltaic energy prediction, its installation and pre-sizing studies. A change in the solar radiation directly impacts the electricity production and in turn, the plant economics. Hence employing a model possessing improved prediction accuracy significantly affects the photovoltaic energy prediction. Furthermore, monthly mean data is required for prediction of long term performance of solar photovoltaic systems making the same to be concentrated for the present contribution. The available models for prediction of irradiance and energy unlike physical and statistical models depend on input parameters whose availability, assumption, and determination is difficult. This finally creates complexity in predicting the desired response. Hence empirical models are chosen preferable over physical and statistical based models. Empirical models correlate only the available input atmospheric parameters affecting solar irradiance and energy, thereby reducing the complexity experienced by physical and statistical model. Yet, the reliability or accuracy of model varies with location. The reliability of an empirical model depends on the incorporation of input's and data set (training set) for its formulation. Thus, the consideration of significant input factors lies to be a persistently prevailing challenge driving the need for an improved prediction model delivering irradiance and energy. In Chap. 6, an empirical model is proposed for prediction of irradiance and energy. The incorporated input factors for the formulation of energy prediction model is emphasized by performance and energy analysis of solar photovoltaic systems. The proposed model hence combines the thermal and electrical aspects of photovoltaic systems gaining reliability and limiting the dependence toward real time measured input factors.

Chapter 7 reviews the recent trend and development of control techniques for islanding mode particularly for PV grid-connected systems. The fundamental concept and theory of operation of popularity used anti-islanding detection methods are described. In addition, the advantages and disadvantages of each control method have been highlighted. The operation characteristics and system parameters of each detection techniques are analyzed and discussed. Moreover, the comparison of islanding detection method based on various characteristics has been detailed. It can be concluded that anti-islanding detection methods are greatly governed by the nature of system application as well as the scale of the system. Finally, this chapter also explains construction of the simulation of the PV grid-connected anti-islanding detection method in MATLAB/Simulink simulation software.

Unlike conventional generating units, PV plants do not have inertias. Therefore, the increasing penetration of PV may impact a system's oscillations negatively as PV units add additional dynamics to power system. Therefore, it is essential to analyze a system's behavior before replacing conventional generators by large-scale solar PV units. Chapter 8 analyzes the impacts of increasing penetration of PV units on power systems. The effect of control mode of PV generator on the system's stability is investigated. Both static and dynamic stability analysis methods are conducted to find out the critical issues. The simulation results effectively identify the impact of high PV penetration on the stability of the studied system which show that voltage control mode of PV generator can improve the performance of a system. However, high penetration of PV can interact negatively with the system in certain cases.

The major disadvantage for use of solar technology is its intermittent and unpredictable nature. This influence the power quality and consistency of the power grid, particularly at large-scale solar energy systems. The variation of sun light may lead to overproduction of electricity at one time and lack of production at another time. The variable nature of solar power causes significant challenges for the electric grid operators. To smooth out the intermittency of solar energy production, electrical energy storage technology will become necessary. In order to increase the solar energy penetration with appropriate reliability, Chap. 9 presents a range of energy storage systems that could technically and economically be used in association with solar photovoltaic energy.

Superconducting magnetic energy storage (SMES) technology has been progressed actively recently. To represent the state of art SMES research for applications, Chap. 10 presents the system modeling, performance evaluation, and application prospect of emerging SMES techniques in modern power system and future smart grid integrated with photovoltaic power plants. A novel circuit-field-superconductor coupled SMES energy exchange model is built and verified to bridge the applied superconductivity field to the electrical engineering and power system fields. As an emerging SMES application case to suit photovoltaic power plants, a novel low voltage rated DC power system integrated with superconducting cable and SMES techniques is introduced and verified to implement both the high-performance fault current limitation and transient power buffering functions. Four principal SMES application schemes of a sole SMES system, a hybrid energy storage system (HESS) consisting of small-scale SMES and other commercial energy storage systems, a distributed SMES (DSMES) system, and a distributed HESS (DHESS) are proposed and compared for achieving efficient and economical power management applications in future photovoltaic power plants.

Although solar energy is a green energy, it can produce a significant amount of waste. Some types of solar cells use rare elements or precious metals as the component material. Therefore, the recycling of PV modules is necessary for environmental and economic purposes. The recycling process for PV modules includes chemical and physical treatment methods, which have been successfully used in other recycling industries, such as electronics or hardware recycling. The use of these mature technologies can decompose and recycle PV module materials. There are still some differences between PV module recycling and electronic recycling. A solar cell module contains several encapsulating plastic materials, such as ethylene vinyl acetate and polyvinyl fluoride. In recycling programs, removing the plastic materials is the first step. In Chap. 11, several types of recycling processes are introduced, which correspond to different types of PV modules. These methods have been validated and successfully implemented in PV module recycling plants.

4 Summary

According to International Energy Agency about 17 % of the global population did not have access to electricity in 2013. Every government has a vision to provide electricity to all of their citizens. Due to the geographical conditions, e.g., remote areas which are far away from existing grid line and sometime isolated from main land, it is very difficult to fulfill the vision in near future by grid power only. In this regard, renewable energy resource-based off grid electrification program could be a possible solution for remote areas. Solar energy is richly available in almost every country and now it is proven and well accepted all over the world. Solar energy technology is environment friendly and price of the solar module is decreasing day by day. Scientists worldwide are now trying to enhance the solar PV technology to mitigate the growing energy demands through solar PV power plants instated of conventional power plants. The book provides a consistent compilation of fundamental theories, a compendium of current research and development activities as well as new directions to overcome some critical limitations of the solar PV technologies for future solar PV power plants.

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