Chapter 1
Introduction

1.1 Background

Nowadays, the most critical issue in the entire world is to meet the permanent growth of the energy demand. Some projections indicate that the global energy demand will almost triple by 2050 as in [1]. Moreover, the rapid depletion of the conventional power sources and their adverse impacts on the future of the planet has necessitated imperative researches for the renewable energy sources as alternative sources of energy. Also, the use of renewable energy sources is desired to improve energy efficiency which is essential to sustainable economic development. Furthermore, the use of renewable energy sources also reduces combustion of fossil fuels and consequent CO_2 emission which is the principal cause of greenhouse effect/global warming [2]. Among the renewable sources of energy, the PV energy and the wind energy have attracted great attention and can be considered as the most promising power technologies to generate the electricity. The PV energy and the wind energy are alternative to each other which will have the actual potential to be integrated with the electrical grid and satisfy the load dilemma to some degree. Also, the wind energy can be captured using large generators to generate great power capacity. Hence, the increased penetration of the wind energy generation systems is evident since it is clean, global, and having minimal operating cost requirements. On the other hand, the PV energy has shown great potential as another promising power technology to generate electricity since it is clean, global, and free and can be harnessed without emission of pollutants. In addition, the distributed PV systems, in contrast to the other renewable energy sources such as wind power generators, are more easily integrated into the electrical utility grids at any point. Therefore, the installation of PV systems has been growing rapidly in the last decades [3]. However, the PV energy and the wind energy are not entirely trustworthy, and they have some demerits such as their unpredictable nature and dependence on the environmental conditions such as the variations of the solar irradiance and the wind speed. Furthermore, the PV energy can be utilized only during the daylight

A. A. Elbaset et al., *Performance Analysis of Photovoltaic Systems with Energy Storage Systems*, https://doi.org/10.1007/978-3-030-20896-7_1

[4]. Both (if used independently) would have to be oversized to make them completely reliable, resulting in a higher total cost. Therefore, a merging of PV energy and wind energy into PV/wind hybrid generating system can attenuate their individual fluctuations, increase overall energy output, and generate more reliable power with higher quality to the electrical grid and the rural areas.

1.2 Photovoltaic Power Generation

Nowadays, the PV energy source has been one of the fastest growing renewable energy sources, which has annual growth rate around 55% over the last decade [2, 5]. The PV power generation utilizes the solar cells which convert the solar energy directly into electricity. At the heart of the PV systems is the PV cell, a semiconductor device which produces an electrical voltage and/or current when exposed to the sunlight [6]. Also, the PV cell generates a specified power according to its current-voltage (I-V) and power-voltage (P-V) characteristics. Therefore, the PV cells must be aggregated together to generate enough current and voltage for practical applications. In this regard, a PV module is formed by connecting several PV cells in series; the PV modules are connected in series to form a PV string to provide a greater output voltage. Then, the PV strings, in turn, are connected in parallel to form a PV array to increase the output current and generate enough power to be synchronized with the electrical grid. However, the incident solar irradiance on the PV array varies due to various reasons such as the variation of time in a day, the atmospheric effects such as clouds, and the latitude of the location. Therefore, the MPPT technique is implemented to regulate the output voltage and output current of PV array for extraction of the maximum power from the PV system during variation of the solar irradiance. Therefore, the PV system is equipped with a DC/DC boost converter to implement the MPPT technique and a three-phase voltage source inverter to be synchronized with the electrical grid [7].

1.2.1 Worldwide Annual Growth of PV Generation

The worldwide annual growth of the PV systems has the shape of an exponential curve during the period from 2007 to 2017, as illustrated in Fig. 1.1. For several years, the growth of PV systems was mainly driven by Japan and pioneering European countries. As a consequence, the cost of PV system installation has declined significantly due to the improvements in technology and design. Historically, the United States was the leader of installed PV systems for many years, and its total capacity amounted to 17 GW in 1996, more than any other country in the world at the time. Then, Japan was the world's leader in producing solar electricity until 2005, when Germany took the lead, and by 2016 it had a capacity of over 40 GW. However, in 2015, China became the world's largest producer of PV power. China is expected to continue its rapid growth and to triple its PV capacity to 70 GW by 2018 [8, 9]. Figure 1.1 shows the cumulative PV generation capacity in the world. By the end of 2016, the global cumulative PV generation capacity has increased from 30.3 GW in 2007 to roughly 306 GW, sufficient to supply between 1.3% and 1.8% of the global electricity demand. Then, the global cumulative PV generation capacity has reached about 401.5 GW in 2017 [10]. Moreover, the global cumulative PV generation capacity is projected to be more than 500 GW during the period from 2017 to 2020. By the end of 2050, solar power is anticipated to become the world's largest source of electricity, with concentrated solar power contributing 11%. Also, the global cumulative PV generation capacity is expected to grow to 4600 GW by the end of 2050 [11].

1.2.2 Photovoltaic Power Generation in Egypt

Egypt possesses an abundance of land, sunny weather, and high wind speeds, making it a prime location for utilization of the renewable energy sources. Egypt intends to supply 20% of the electricity demand from the renewable energy sources by 2022, with wind providing 12%, hydropower 5.8%, and solar 2.2%. Egypt's Solar Atlas states that Egypt is considered a "Sun Belt" country with 2000–3000 kWh/m^2/year of direct solar irradiation. In addition, the sun shines 9–11 hours a day from north to south in Egypt with few cloudy days. Therefore, the solar energy plan aims to install 3.5 GW by 2027, including 2.8 GW of PV and 700 MW of concentrated solar power. Historically, the first solar thermal power plant was built at Kuraymat in 2011; it has a total installed capacity of 140 MW. Also, a 10 MW power plant has been operated in Siwa since March 2015, and the remaining plants are expected to be implemented and operated in 2018. Recently, Egypt has embarked on an ambitious project to build the biggest solar PV plant in the world at Benban, Aswan. The

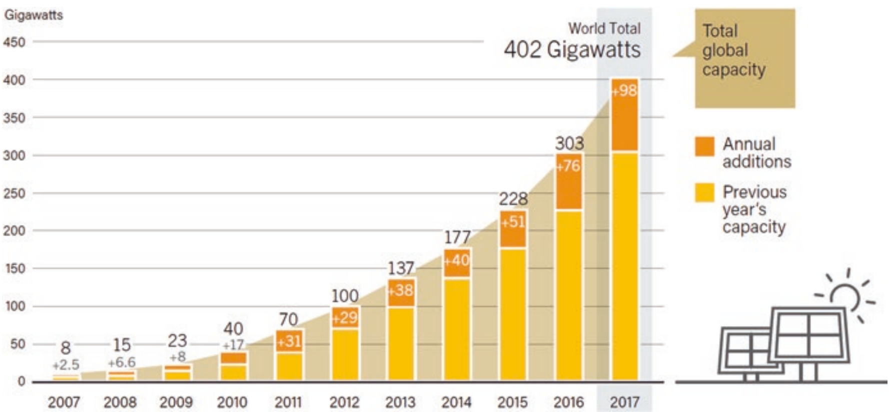

Fig. 1.1 Global PV generation capacity and annual additions, 2007–2017 [12]

PV station Benban project locates in the south of the Egyptian territory; the project has an estimated total cost of up to US$ 4 billion and will produce 1.8 GW of power when operational. The project site consists of a 37 km^2 plot divided into 39 projects of approximately 50 MW each [13].

1.3 Basics of Solar Cell

A PV system is made up of several PV solar cells, as illustrated in Fig. 1.2. An individual small PV cell can generate about 1 or 2 W of power approximately, depending on the type of material used. For higher power output, PV cells can be connected together to form higher power modules. In the market the maximum power capacity of the module is 1 kW; even though higher capacity is possible to manufacture, it will become cumbersome to handle more than 1 kW module. Depending upon the power plant capacity or based on the power generation, group of modules can be connected to form an array [14].

As per the statistics, the solar PV module world market is steadily growing at the rate of 30% per year. The reasons behind this growth are that the reliable production of electricity without fuel consumption anywhere there is light and the flexibility of PV systems [15]. Also, the solar PV systems using modular technology and the components of solar PV can be configured for varying capacity, ranging from watts to megawatts. Earlier, large variety of solar PV applications is found to be in industries, but now it is being used for commercial as well as for domestic needs.

One of the hindrance factors is the efficiency of the solar PV cell; in the commercial market, a cell efficiency of up to 18.3% is currently obtained, depending on the technology that is used. When it is related to the module efficiency, it is slightly lower than the cell efficiency. This is due to the blank spaces between the arrays of

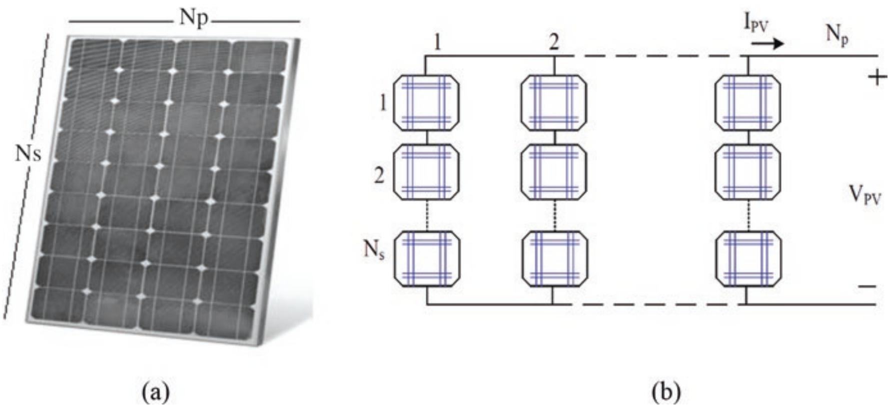

Fig. 1.2 PV module constructions and its circuit [14]. (**a**) Construction of PV module. (**b**) Circuit of PV module

solar cells in the module. The overall system efficiency includes the efficiency and the performance of the entire components in the system and also depends on the solar installation. Here there is another numerical drop in value when compared to the module efficiency, this being due to conductance losses, e.g., in cables. In the case of an inverter, it converts the DC output from the solar PV module to the AC grid voltage with a certain degree of efficiency. It depends upon conversion efficiency and the precision and quickness of the MPP tracking called tracking efficiency. The MPPT which is having an efficiency of 98–99% is available in the market; each and every MPPT is based on a particular tracking algorithm [16].

1.4 Types of PV with Storage Installations

Based on the electric energy production, PV modules can be arranged into arrays to increase electric output. Solar PV systems are generally classified based on their functional and operational requirements and their component configurations. There are three main types of solar PV and storage systems: grid-connected, PV-hybrid, and stand-alone solar PV system. They all have their advantages and disadvantages, and it really comes down to the customer's current energy supply and what they want to get out of the system. It can be classified into grid-connected and stand-alone systems [17].

1.4.1 Grid-Connected PV System

Grid-connected PV systems are usually installed to enhance the performance of the electric network by reducing the power losses and improving the voltage profile of the network. However, this is not always the case as these systems might impose several negative impacts on the network, especially if their penetration level is high [18]. A grid-tied system is a basic solar installation that uses a standard grid-tied inverter and does not have any battery storage, as illustrated in Fig. 1.3. This is perfect for customers who are already on the grid and want to add solar to their house. These systems can qualify for state and federal incentives which help to pay for the

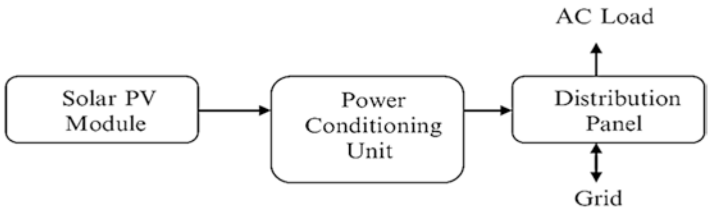

Fig. 1.3 Bock diagram of grid-connected PV system [14]

system. Grid-tied systems are simple to design and are very cost effective because they have relatively few components. The main objective of a grid-tied system is to lower your energy bill and benefit from solar incentives.

One disadvantage of this type of system is that when the power goes out, so does your system. This is for safety reasons because linemen working on the power lines need to know there is no source feeding the grid. Grid-tied inverters have to automatically disconnect when they don't sense the grid. This means that you cannot provide power during an outage or an emergency and you can't store energy for later use. You also can't control when you use the power from your system, such as during peak demand time.

But if a customer has a basic grid-tied system, they are not out of luck if they want to add storage later. The solution is doing an AC-coupled system where the original grid tied inverter is coupled with a battery back-up inverter. This is a great solution for customers who want to install solar now to take advantage of incentives but aren't ready to invest in the batteries just yet.

A customer can benefit from net metering because when the solar is producing more than they are using, they can send power back to the grid. But in times when the loads are higher than what the solar is producing, they can buy power from the utility. The customer is not reliant on the solar to power all his or her load. The main takeaway is that when the grid goes down, the solar is down as well and there's no battery backup in the system.

1.4.2 Grid-Tied System with Battery Backup

The next type of system is a grid-tied system with battery backup, otherwise known as a grid-hybrid system. As shown in Fig. 1.4, this type of system is ideal for customers who are already on the grid who know that they want to have battery backup. Good candidates for this type of system are customers who are prone to power outages in their area or generally just want to be prepared for outages.

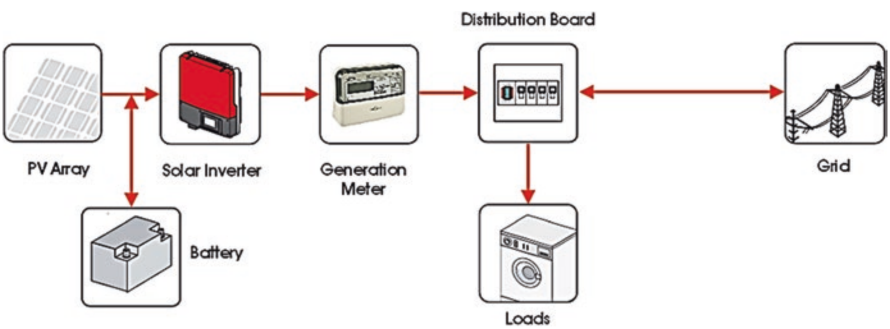

Fig. 1.4 Block diagram of grid-tied system with battery backup [19]

With this type of system, you get the best of both worlds because you're still connected to the grid and can qualify for state and federal incentives while also lowering your utility bill. At the same time, if there's a power outage, you have backup. Battery-based grid-tied systems provide power during an outage, and you can store energy for use in an emergency. You are able to back up essential loads such as lighting and appliances when the power is out. You can also use energy during peak demand times because you can store the energy in your battery bank for later use. Cons of this system are that they cost more than basic grid-tied systems and are less efficient. There are also more components. The addition of the batteries also requires a charge controller to protect them. There must also be a subpanel that contains the important loads that you want to be backed up. Not all the loads that the house uses on the grid are backed up with the system. Important loads that are needed when the grid power is down are isolated into a back-up subpanel [19].

1.4.3 Off-Grid System

Off-grid systems are great for customers who can't easily connect to the grid. This may be because of geographical location or high cost of bringing in the power supply. In most cases, it doesn't make much sense for a person connected to the grid to completely disconnect and do an off-grid system. The block diagram of stand-alone PV system with battery storage is shown in Fig. 1.5.

The benefits of an off-grid system are that a person can become energy self-sufficient and can power remote places away from the grid. You also have fixed energy costs and won't be getting a bill from your energy use. Another neat aspect of off grid system is that they are modular, and you can increase the capacity as your energy needs grow. You can start out with a small, budget-conscious system and add on over time.

Because the system is your only source of power, many off-grid systems contain multiple charging sources such as solar, wind, and generator. You have to consider weather and year-round conditions when designing the system. If your solar panels

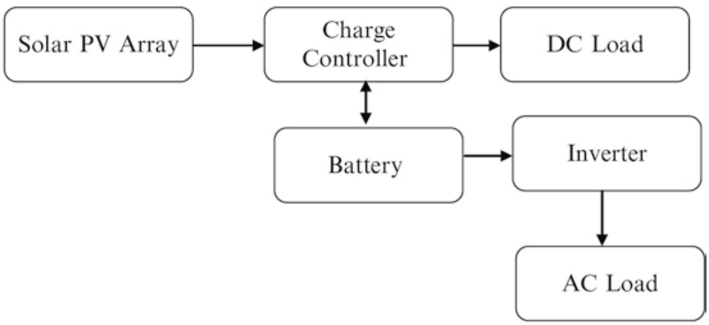

Fig. 1.5 Block diagram of stand-alone PV system with battery storage [14]

are covered in snow, you need to have another way to keep your batteries charged up [20]. You also will most likely want to have a back-up generator just in case your renewable sources are not enough at times to keep the batteries charged. One disadvantage is that off-grid systems may not qualify for some incentive programs. You must also design your system to cover 100% of your energy loads and hopefully even a little bit more. Off-grid systems have more components and are more expensive than a standard grid-tied system as well.

1.4.4 PV-Hybrid Systems

Hybrid systems generally refer to the combination of any two input sources; here solar PV can be integrated with diesel generator, wind turbines, biomass, or any other renewable on nonrenewable energy sources as illustrated in Fig. 1.6. Solar PV systems will generally use a battery bank to store energy output from the panels to accommodate a pre-defined period of insufficient sunshine; there may still be exceptional periods of poor weather when an alternative source is required to guarantee power production. PV-hybrid systems combine a PV module with another power sources – typically a diesel generator but occasionally another renewable supply such as a wind turbine. The PV generator would usually be sized to meet the base load demand, with the alternate supply being called into action only when essential. This arrangement offers all the benefits of PV in respect of low operation and maintenance costs but additionally ensures a secure supply [21].

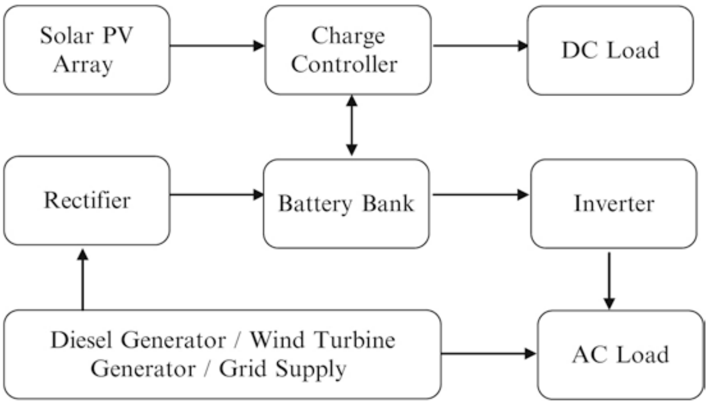

Fig. 1.6 Block diagram of photovoltaic hybrid system [14]

1.5 Energy Storage System

A fundamental characteristic of a PV system is that power is produced only while sunlight is available. For systems in which the PV is the sole generation source, storage is typically needed since an exact match between available sunlight and the load is limited to a few types of systems – for example, powering a cooling fan. In hybrid or grid-connected systems, where batteries are not inherently required, they may be beneficially included for load matching or power conditioning [22].

For off-grid and critical applications, storage systems are required; the most common medium of storage is the lead-acid battery. Presently researches are going on in the field of Li-ion batteries to implement the concept of fuel cells in solar PV systems. One of the most expensive components in the PV system is the battery. Under sizing the batteries will become more costly as the battery life cycle is significantly reduced at higher depth of discharge (DOD%). At a higher DOD, expected average number of charge-discharge cycles of a battery reduced. Further, a higher current discharge than the rating will dramatically reduce the battery life. This can be avoided by carefully sizing of the battery according to the "C-rating" during the system design. It signifies the maximum amount of current that can be safely withdrawn from the battery to provide adequate backup without causing any damage. A discharge more than the C-ratings may cause irreversible capacity loss due to the fact that the rate of chemical reactions taking place in the batteries cannot keep pace with the current being drawn from them [23]. The de-rating factor of the balance of system plays a significance role in boosting up the overall efficiency of the solar PV system.

1.6 Book Objectives

The main objectives of this book are summarized as follows:

1. Apply the MPPT technique for the PV system in order to extract the maximum power during variation of the environmental conditions.
2. Analyze the performance of the PV system with battery storage during variations of the solar irradiance in order to evaluate the effectiveness of the implemented MPPT techniques and the employed control strategy.
3. Addressing the performance analysis for the stand-alone PV system under the effect of the entry and exit sudden electrical loads.
4. Structure and modeling of stand-alone PV system with BS-HESS to reduce the dynamic stress and peak power demand of the battery by employing the appropriate control strategy.
5. Experimental work for performance analysis of stand-alone PV system with battery storage energy under variable solar irradiation and load profile.

1.7 Book Organization

To achieve the above objectives, the present book is organized in seven chapters in addition to a list of references. The chapters are organized as follows:

- *Chapter* 1: The main aim of this chapter is to present an introduction to the PV power generation worldwide and in Egypt. Also it presents an introduction to the principles for the solar cell. In addition, the types of photovoltaic power systems and energy storage systems have been reviewed.
- *Chapter* 2: This chapter introduces the energy storage systems in PV systems and discusses the classifications and types of batteries. Also, the focus was on lead-acid battery, and some properties of supercapacitors were reviewed. Finally, it gives an overview of previous works and methods based on the PV system and energy storage systems.
- *Chapter* 3: This chapter discusses the modeling of the fundamental elements in the off-grid PV systems. In addition, it introduces a simulation of two MPPT techniques that is implemented in the PV systems.
- *Chapter* 4: This chapter investigates a dynamic modeling, simulation, and control strategy of the stand-alone PV system with BES under variable load profile. Moreover, this chapter discusses the performance comparison of PV stand-alone system with BES in two cases of operation. In the first case, the system operates without and with BES under constant solar irradiation. In the second case, the PV system is connected to a BES and operates under a variable in solar irradiation.
- *Chapter* 5: This chapter proposes an optimal control strategy for a stand-alone PV system with BS-HESS. The proposed control strategy comprises of a low pass filter and fuzzy logic controller. The performance of the proposed system is compared to the conventional systems by Simulink with the setup of rural household load profile and the actual solar irradiation profile of a rainy day.
- *Chapter* 6: In this chapter, the experimental setup along with its components is implemented in renewable energy laboratory, faculty of industrial education, Suez University. This chapter includes two parts: the first part presents the experimental setup of an off-grid PV system, and the second part contains the experimental results and discussion.
- *Chapter* 7: This chapter reports the main conclusions from the book and summarizes the future research topics related to bookwork.