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A comprehensive review on large-scale photovoltaic system with applications of electrical energy storage

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ABSTRACT

In order to mitigate energy crisis and to meet carbon-emission reduction targets, the use of electrical energy produced by solar photovoltaic (PV) is inevitable. To meet the global increasing energy demand, PV power capacity will be expanded ranging from large-scale (from ten to several hundred MWs) PV farms at high and medium voltage level to kilowatt residential PV systems at low voltage level. It is expected that the PV penetration will increase in power systems with the retirement of traditional carbon-emission emitting power plants. Solar energy is diurnal in nature and in practice, it is highly uncertain due to various perturbation effects. With the recent technological advancements and rapid cost reductions in electrical energy storage (EES), EES could be deployed to enhance the system's performance and stability. This paper presents a comprehensive review on the emerging high penetration of PV with an overview of EES for PV systems. The crucial element, the building block of solar panel and the solar cell are reviewed. The emerging cell technologies are presented. A study of solar power forecasting techniques, an important tool for the successful operation and planning of PV and EES is included. A selection of EES is presented and studied for PV system purposes. Future research and areas for improvements in recent works and related areas are identified.

1. Introduction

Renewable energy has been used by humanity for several millennia. In fact, hydro, wind, solar and biofuel power were the only available energy sources during the ancient times. The Industrial Revolution in the 18th century has opened a new era of energy production and consumption methods. This has a tremendous positive effect to the development and advancement for civilization. However, the significant environmental adverse impacts are noticeable in the last several decades. Carbon dioxide has been emitted from burning fossil fuels, i.e. coal, oil and gas. The consequences of generating fossil fuel based power are global warming due to carbon emission and a significant increase in the environmental pollution levels. In recent decades, governments from several countries realized the severe issues. There is a need to reassess the ways in which energy is generated and consumed in order to minimize pollution from emission, planetary global warming rate, and mitigate the nuclear accidents risks.

The renewable industry has experienced a boom in the recent years. There is an increase in the penetration of renewable energy in the energy mix of developing and developed countries [1]. Such increase can bring the grid to economic and technical challenges due to the connection of intermittent renewable energy sources. There is a motivation in the development of improved operational strategies for securing the reliability and secure operation of high penetration of renewable based power systems. This is mainly due to the non-dispatchable nature and the inability to control of these renewable resources. This requires a revolutionary change in modern power systems development, which needs to incorporate energy storage, intelligent communication networks, power electronic converters, demand response, and advanced controllers.

Solar energy is a sustainable and clean source of renewable energy. With clear sky irradiance assumptions and available land area, the maximum potential annual solar energy amount reaches the earth's surface before energy conversion was estimated to be 50 ZJ [2]. This is significantly larger than the total annual world energy consumption in 2012, which was 376 EJ [3]. The global solar energy production is significantly greater than the global energy demand [4]. However, due to the diurnal and stochastic nature of solar energy, there are

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challenges to integrate solar power into the power system.

Solar power generation is directly proportional to the solar irradiance. This signifies that there is a requirement to adjust the power output of dispatchable generators, e.g. coal fire or gas power plant regularly to avoid the fluctuations [5]. As a result, it causes challenges in determining adequate system reserve economically for secure and reliable operation. When photovoltaic (PV) systems take a larger share of generation capacity i.e. increase in penetration, increasing system flexibility should thus become a priority for policy and decision makers. Electrical energy storage (EES) may provide improvements and services to power systems, so the use of storage will be popular. It is foreseen that energy storage will be a key component in smart grid [6]. The components of PV modules, transformers and converters used in large-scale PV plant are reviewed in [7]. However, the applications of storage have not been mentioned and studied in the paper.

This paper provides a comprehensive review on the recent and future developments in large-scale and high penetration solar PV renewable systems, with an emphasis in the potential contributions of EES. Section 2 reviews the PV system global development. In order to achieve the target, it is essential to have the required technology and Section 3 talks about the PV cell technology. Due to the high penetration of PV, the solar intermittency introduces instability to power network. Section 4 explains the integration solution to reduce such an effect. For better PV-EES system planning and operation, Section 5 compares the solar irradiance forecasting methods to have a better prediction of PV output. Section 6 demonstrates how EES storage system need to be used for power system operation, management and control. Sections 7 and 8 provide the discussion and conclusions.

2. PV system global development

Several countries are aiming to maximize their solar energy portfolios [8]. Greenpeace stated that it is possible to become 100% renewable by 2050 and therefore experiencing a very sharp increase in installations [9]. To provide a glance of the PV capacity significance in a power system, the term PV penetration is used. The PV penetration level is normally used to conduct various sensitivity analysis for power system with PV generator. This is the amount of power generated by PV with respect to the total power generated in a power system. The definition of PV penetration level has been discussed in [10,11] and is calculated with Eq. (1). It is worth mentioning that other definitions of penetration level for distributed generators were also defined, such as in [12] where the peak load of the system is used as the denominator.

$$\text{PV Penetration}(\%) = \frac{\text{Sum of PV generation}(\text{MW})}{\text{Sum of system generation}(\text{MW})} \quad (1)$$

Fig. 1 presents the trends for global power capacity of solar PV systems from different literatures and case scenarios. Greenpeace has provided a forecast of global PV penetration under two scenarios, namely the "revolution scenario" and "reference scenario". It is shown that there is a sharp linear growth in solar power capacity with respect to time.

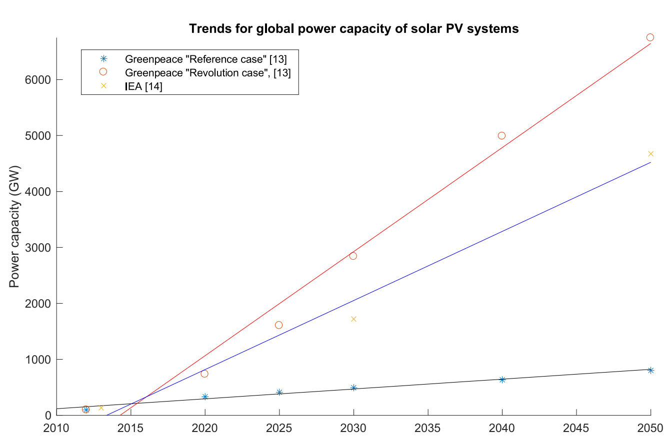

Fig. 1. Trends for global penetration of solar PV systems. [13,14].

2.1. USA

Solar energy holds the largest percentage in the renewable energy mix in the United States, with the possibility that solar energy generation can greatly be beyond the total electricity consumption [15].

According to the Solar Grand Plan, the country aims to meet 69% of the energy demand by 2050 with PV. This will contribute to 60% CO_2 emission reduction from 2005 levels. In a further perspective, it is expected that 250 GW and 2900 GW of PV capacity will be built by 2030 and 2050 respectively [16]. Other projects were developed recently to help achieving this goal. The SunShot initiative, launched in 2011 aims to make PV electricity to be grid parity by 2020 without the use of subsidies. Cost targets were set to \$0.09/kW h for residential PV, \$0.07/kW h for commercial PV and \$0.06/kW h for utility-scale PV systems. It has proved to be a success and five years after the establishment of the initiative, 70% of the progress has achieved for the 2020 goals [17]. More recently in November 2016, the SunShot 2030 was established to further reduce the cost of PV electricity. The cost targets are \$0.05/kW h, \$0.04/kW h and \$0.03/kW h for residential, commercial and utility-scale PV systems respectively [18].

2.2. China

China has abundant of solar energy. At present, solar energy is largely used in residential level for solar stoves, solar water heaters, and passive solar houses. The country is experiencing a rapid development in solar power generation technologies. According to [19], China has produced around 18% of the PV products globally, as a result from more than 400 Chinese PV companies' production. In 2012, six Chinese PV manufacture companies were in the list in the top ten global PV cell manufacturers. The manufacturers are Yingli Solar, Suntech, Trina Solar, Canadian Solar, JA Solar and Jinko Solar [20]. Still, the quantity of solar energy generated within the country is relatively little. Due to over production of solar modules and little installation of PV power plants, the solar PV manufacture industry in China has suffered. The production utilization rate of solar cells has surpassed the production utilization rate of polysilicon since 2011 and import of polysilicon is necessary. To make the situation worse, many polysilicon manufactures have closed down because of the price drop in polysilicon. The imbalance of polysilicon and solar PV cell production utilization rate is expected to be more severe with the years to come [21,22].

The strategic promotion of the PV industry based on comprehensive policy has been studied and discussed in [23]. Investment should be increased in technical research and development to control key techniques and manufacturing requirements. The plan from National Development and Reform Commission (NDRC) in 2007 has stated that the country hopes to have an installed PV capacity of 1.8 GW by 2020 [19]. The latest plan, the 13th Five-Year plan [24] mentioned that the country aims to achieve 110 GW of total installed solar capacity by 2020. This growth consists of 60 GW of distributed solar PV and 5 GW of thermal solar power. In 2015, the country has a total installed solar power capacity of 42 GW. By 2050, the renewable energy penetration will be at 85% and 2.7 TW of solar power will be installed with a total annual output of 9.66 trillion kWh, a contribution of 64% total power generation [25].

2.3. India

India also has an abundant of solar energy. Currently, solar energy is