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Trends and challenges of grid-connected photovoltaic systems – A review

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ABSTRACT

This paper presents a literature review of the recent developments and trends pertaining to Grid-Connected Photovoltaic Systems (GCPVS). In countries with high penetration of Distributed Generation (DG) resources, GCPVS have been shown to cause inadvertent stress on the electrical grid. A review of the existing and future standards that addresses the technical challenges associated with the growing number of GCPVS is presented. Maximum Power Point Tracking (MPPT), Solar Tracking (ST) and the use of transformless inverters can all lead to high efficiency gains of Photovoltaic (PV) systems while ensuring minimal interference with the grid. Inverters that support ancillary services like reactive power control, frequency regulation and energy storage are critical for mitigating the challenges caused by the growing adoption of GCPVS.

Contents

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1. Introduction

It is generally accepted in the scientific community that human activity is affecting climate change and that a majority of this impact comes from fossil fuel combustion caused by the electric utility industry [1]. In 2012, 32% of the total greenhouse gas emissions in the U.S. was from the electric power industry, the highest of all sectors [2]. Conventional fossil-fuel generating facilities have in past met the majority of global electrical energy demands. However, environmental and climate change implications of fossil fuel-based generation present serious challenges to society and the environment [3]. Distributed Generation (DG), particularly Photovoltaic (PV) systems, provides a means of mitigating these challenges by generating electricity directly from sunlight.

Unlike off-grid PV systems, Grid-Connected Photovoltaic Systems (GCPVS) operate in parallel with the electric utility grid and as a result they require no storage systems. Since GCPVS supply power back to the grid when producing excess electricity (i.e., when generated power is greater than the local load demand), GCPVS help offset greenhouse gas emissions by displacing the power needed by the connected (local) load and providing additional electricity to the grid. As such, during peak solar hours (maximum solar irradiance), fewer conventional generation plants are needed. In addition, GCPVS reduce Transmission and Distribution (T&D) losses. Although average T&D losses amounted to 5.7% in the U.S. in 2010, losses during peak hours are higher [4]. For example, the estimated T&D losses for Southern California Edison and Pacific Gas & Electric exceeded 10% in 2010 [5]. Locating DG assets close to loads can help to partially mitigate these losses.

In this paper, we focus our attention on the growing adoption of GCPVS and the technical challenges posed by the mass proliferation of these DG systems on the overall performance and reliability of the electric grid. A review of the standards governing the safe installation, operation and maintenance of GCPVS, and the known methods of improving efficiency of PV systems are presented. We also focus on the role of the inverter as an active grid participant. Inverters designed with the ability to support electric grid ancillary services will become the norm in the foreseeable future, especially in light of the growing number of small and large-scale GCPVS that are being brought on-line. The fresh wave of concerns of what appears to be the endless interconnection of new GCPVS and the threats they pose to the grid in the 21st century are a new territory to the electric utility industry. However, some electric utilities in the U.S. like the Hawaiian Electric Company (HECO) are at the forefront of addressing some of these challenges. Recently, HECO announced plans to support smart inverters that can ride through transient and rapid under (or over) voltage and frequency dips (or spikes) [6]. According to the company, it is working with several inverter manufacturers and national solar industry experts to address grid reliability and safe operation concerns.

This paper is organized as follows: Section 2 summarizes the current state and trends of the PV market. Section 3 discusses regulatory standards governing the reliable and safe operations of GCPVS. In Section 4 we discuss the technical challenges caused by GCPVS. Since there are a number of approaches for increasing the output power of PV systems, i.e., Maximum Power point tracking (MPPT), Solar Tracking (ST), a combination of both [7] or by using *transformless inverters*, Section 5 examines each method independently. We present evidence that these methods can indeed help improve the efficiency of GCPVS. In Section 6, we explore recent developments in inverter technology and conclude with the changing role of GCPVS inverters in Section 7.

2. The growing popularity of Grid-Connected PV Systems

The PV industry is expected to continue to grow due to several factors like the falling prices of silicon and PV modules, technological advancements in large scale manufacturing, many governmental incentives, maturation and proliferation of favorable interconnection agreements and continued technological improvement of power converter technologies. For example, the cost of manufacturing PV modules has reduced dramatically, from over 100 per watt in the 1970s [8] to less than 1.00 per watt in 2014 [9]. In fact, large-scale wholesale orders can result in prices below $0.60 per watt [10].

According to the Solar Energy Industry Association's (SEIA) 2013 annual review, the average PV system price was $2.59 per watt by the end of 2013 with the average price of PV panels dropping by as much as 60% [11]. Following Swanson's law, the cost of PV cells has fallen an average of 20% every time the global manufacturing capacity of solar has doubled [12], further reducing the overall system costs of PV systems. In 2013, at least 38 GW of solar PV systems were installed globally, up from 30 GW from the year prior and bringing the number of PVs installed worldwide to 139 GW [13]. In other words, the amount of PV installed globally in 2013 alone was 30% of the total capacity of PV installed since the commercial inception of solar PV technology between the 1970s and 2012. It is estimated that by 2018, the total amount of new PV installations could exceed 68 GW while the total cumulative global PV capacity installation may triple 2013's numbers [14].

Fig. 1 shows the amount of net generation of solar PV in the U.S. from 2004 to 2014. This figure backs the claims that the growing popularity of Solar PV is a trend that will continue to rise. Although our survey yielded mixed reports as to when PV solar will be at grid parity with traditional generation sources, a common underlying theme among many researchers is that this will likely happen sooner than later. The Rocky Mountain Institute recently released a report that suggests that grid parity will be achievable by 2030 [16]. Scientists at the Argonne National Lab in Illinois have argued that this may happen by 2025 while the National Renewable Energy Laboratory (NREL) have publicly suggested that due to the rapid growth of GCPVS, grid parity may even happen as early as 2017 [17].

In Fig. 2, the amount of electricity generated from solar PV in the U.S. in 2014 almost doubled that of the prior year [15]. Due to the many benefits associated with GCPVS, an overwhelming majority of PV systems are connected to the grid. Barbose et al. collected data on more than 200,000 residential, commercial and utility projects from 1998 to 2012 in the U.S. [18]. They reported that by the end of 2012, 72% of all the grid-connected systems in the U.S. were installed and commissioned between 1998 and 2012. In a survey of select International Energy Agency (IEA) member countries released in 2013, of the total installed PV systems, more than 99% were estimated to be grid-connected [19]. Utility-scale installations with large systems are beginning to make up for a sizable share of the PV market. In the U.S. alone, the utility sector was responsible for about two-thirds of the total new installations in the third quarter of 2014 [20].

Fig. 3 represents new solar PV installations capacity in the U.S. by market segment. For the first time, in 2013, by system capacity, utility-scale installations exceeded residential and commercial installations.

The rise in the number of GCPVS, especially from the utility sector, does not come as a surprise, especially given that many governmental and regulatory bodies tend to promote programs aimed at expanding DG resources like GCPVS [22]. In the U.S., the Clean Power Plan proposed by the Environmental Protection Agency (EPA) in June of 2014 will help reduce emissions by 30% below 2005 levels over a 15 year timeframe [23]. The EPA hopes to