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Review

Overview of technical specifications for grid-connected photovoltaic systems☆

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ABSTRACT

Numerous countries are trying to reach 100% renewable penetration. Variable renewable energy (VRE), for instance wind and PV, will be the main provider of the future grid. Cost reduction of accelerates the large scale VRE deployment around the world. The efforts to decrease the greenhouse gases are promising on the current remarkable growth of grid-connected photovoltaic (PV) capacity. This paper provides an overview of the presented techniques, standards and grid interface of the PV systems in distribution and transmission level. This paper compares the different review studies which has been published recently and provides an extensive survey on technical specifications of grid connected PV systems. Moreover, the adopted topologies of the converters, a thorough control strategies for grid connected inverters, as well as their applications in PV farms has been studied. This study will help researchers and industry users to establish their research based on connection requirements and compare between different existing technologies.

1. Introduction

It has been very clear from recent studies and documentations the fossil fuels would last only a few more decades. The cost of fossil fuel has become a major challenge for all of human kind. Not only the economic value but the environmental impacts of fossil fuels have clearly made us move toward alternatives [1–3]. The greatest alternatives that can really make a difference for sustainability, such as reducing green-house gases and long term economics, are the renewable energy sources (RES) like wind and solar power. Solar photovoltaic (PV) industry is the dominant type of RES technology integrated to power grid systems as its cost reduces over the next ten years, while deployment of PV systems continues to increase quickly. As penetration of PV on the grid grows, finally reaching hundreds of gigawatt (GW) interconnected capacity, a diversity of methods require to be taken into account and also implemented at various scale, for reliable and cost-effective connection into the power grid [4].

Since many PV interconnection applications involve high penetration scenarios, the process needs to allow for a sufficiently rigorous technical evaluation to identify and address possible system impacts. Thus, except of reducing the PV cost installation, others issues such as standardization, simple improvements in design, better power electronics, and simplified procedures for grid integration are already improving the economics of PV systems.

They are many review studies on grid connected PV systems in the literature. The comparison of the most recent review papers in the literature is present in this part. In [5] authors studied the current trend of PV power plants development in the world, comparison of grid codes for fault ride through (FRT), voltage, frequency, active power, and reactive power was analyzed. After that, voltage stability, frequency stability, active power regulation, and reactive power regulation was studied. At last, the compliance technologies were investigated. Authors of [6] reviewed the technical requirements of PV systems with microinverters by analyzing the U.S. National Electrical Codes, standards and utility grid-interconnection application, Michigan state requirements, barriers and solutions for plug-and-play Photovoltaic systems, and advantages of microinverters. Ref. [7] studied the ratio between load and PV power, possible complications associated with high penetration PV into the grid, grid-connected inverters, and islanding detection methods. In [8] standards and specifications of grid-connected PV inverter, grid-connected PV inverter topologies, Transformers and types of interconnections, multilevel inverters, soft-switching inverters, and relative cost analysis have been presented. [9] did a review on prospects and challenges of grid connected PV systems in Brazil. [10] mostly focused on the techno- economic analysis of the grid connected PV system for building application. [11] reviewed the technical barriers of PV system development. The authors did a survey on categorizing the grid-connected and stand-alone PV systems, energy policy, a number of

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technologies implemented in PV cells, maximum power point tracking (MPPT), energy management, energy optimization, issues related to storage of energy in PV systems, hybrid PV systems, environmental and economic concerns, operation and maintenance issues. Ref. [12] provided analysis, explanation, and introduction on typical distributed MPPT and centralized MPPT. In [13] guidelines and standards of the grid connected PV generation systems, effects of large PV integration into the power grid, power quality requirements, protection methods, and control capabilities have been investigated. As it can be seen each paper mostly focus on only limited aspects of PV technical specification, and there is no comprehensive review on this topic.

In this paper a handy extensive investigation on grid connected photovoltaic system is conducted. The outline of the rest of the paper is as follows. Section 2 analyses the challenges of photovoltaic integration into the grid. Some integration solutions are also presented in this section. In Section 3 the standard requirements and grid codes for PV integration are studied. Section 4 analyses the power electronic inverter topologies for Photovoltaic interconnection to the grid. Most popular three phase inverters are investigated in Section 5. Most implemented control algorithms for PV systems are presented at Section 6. Future applications of PV are studied in Section 7. Finally, the paper is concluded in Section 8.

2. Challenges to integrate solar photovoltaic

In spite of all advantages of PV, it might make some potential adverse effect on the present power grid. Solar is known as non-dispatchable resources. There is no control over the input these kinds of energy resources for later use when desirable [14]. The lack of control over the input has a direct relationship with unpredictability of the output power injected to the grid [15]. The incapability of generating on-demand power triggers stability and reliability concerns to the power system [14,16,17]. Some of the challenges that come along with using renewable energies are depicted in Fig. 1 [18].

The information collected from an extensive survey on literature shows that the PV output power fluctuation due to solar irradiance intermittency is the most important problem of PV grid integration. Thus, large scale integration of photovoltaic system into the distribution grid introduces corresponding problems such as voltage regulation problem, harmonics, reactive power compensation, synchronization, energy storage, forecasting and scheduling, and load demand management systems. A classification of technical challenges of large-scale PV in the distribution systems are presented in Table 1.

Distributed system protection coordination in a feeder with high PV integration using widespread distributed feeder measurement and utilizing OpenDSS has been studied by [19]. Short circuit detection technique for the PV inverter by valuating the magnitude and slope (d/dt) of the PV inverter current is introduced in [20]. In order to prevent any contrary effects of the short circuit current, the proposed system either disconnects the inverter or transfers the inverter to a PV dynamic reactive power compensator (STATCOM).

Higher solar integration requires implementation of battery (and super-capacitor) energy storage systems to compensate high energy

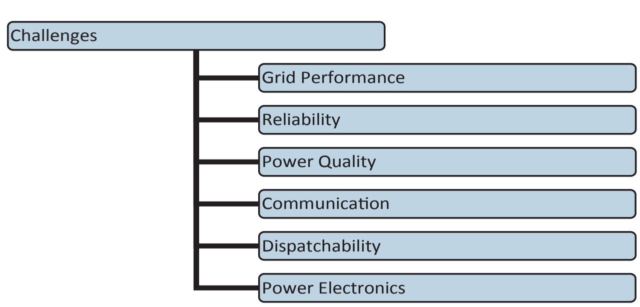

Fig. 1. Challenges that arise when integrating renewable resources into the smart grid.

(and high power) fluctuations caused by stochastic nature of renewable resources [21]. Different methods for calculating the battery energy capacity to accommodate a specific PV penetration level with minimum cost has been studied in the literature [22,23]. Increased use of renewable energies, especially PV, has resulted in bigger implementation of battery system in LV grid [24,25]. Large scale integration of PV energy sources has a number of complications that need to be overcome as PV begins to compete and in time replace more traditional means of energy generation, i.e. coal, natural gas, and oil power plants.

There are various types of energy storage systems (ESS) that can be used in conjunction with PV each of which has their uses in the electric grid. Examples of these ESS are: pumped hydro energy storage (PHES) [26–28], compressed air energy storage (CAES) [29–32,32], flywheel energy storage (FES) [33–35], battery or electrochemical energy storage (EES) [36–40], flow battery energy storage (FBES) [41], superconducting magnetic energy storage (SMES) [42–49], and supercapacitors or dual layer capacitors (DLC) [50–55].

The success of alternative energy is dependent upon the engineering equipment and infrastructure which it is based upon and its ability to capture and convert this energy [15]. The availability of solar power is dependent upon the position of the sun, angle at which the sun-rays fall upon the surface of the earth, and cloud location [18]. The places at which these renewable resources are available are typically far from their intended population areas. This would require extensive investment in transmission infrastructure in order to insure the proper and secure transfer of energy produced. For the promise of alternative energy to be achieved, the following goals shown in Table 2 must be met [56].

Similarly, for the success of renewable energy, proper technology must be available for implementation [18]. Most researched technologies take anywhere between twenty to twenty-five years to demonstrate the feasibility and large-scale commercialization before they are implemented outside of the laboratory. The reason is that many of the processes for these technologies must be perfected and optimized for different operating environments. Apart from the optimization, all of the technologies must also be patented, tested, safety evaluations must be conducted, land procurement must be acquired, the financial analysis must be conducted, along with several other studies must take place before such technologies can be seen to commercial use.

2.1. Present usage of PV generation

Currently, it seems impossible that todays power grid could run on simple renewable resources unless there is a major advancement in energy conservation and improved energy efficiency.

One way to overcome this while using the available technology is to use other dispatchable renewable resources which can be kept running in reserve modes. Examples of some dispatchable renewable resources are [15]: Hydroelectric, Biomass, Geothermal.

Some of the other solutions that have been looked at is the solution of using compressed air storage, batteries, and the use of molten salts in appropriated solar thermal plants [57]. Some of the downsides from these approaches include losses in the process of energy storage, transfer and usage along with the limited density of energy that these systems are capable of storing with todays available technologies [58].

The inability to produce on-demand real and reactive power, in a way that generators have spinning reserve can be compensated by using energy storage systems. Therefore, the power generated by renewable energy resources like solar and the wind could be stored and then later used in order to abide by the load balancing act and available energy [59]. In todays society, pumped hydro devices almost dominated large-scale energy storage system in the USA [60]. However, some battery energy storage System also known as (BESS) are installed [61].

Application of energy storage has been known for their ability to provide many of the auxiliary functions such as load leveling, peak shaving, voltage regulation, VAR support, frequency control, spinning