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Evolution of dispatchable photovoltaic system integration with the electric power network for smart grid applications: A review

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A plug-and-play connection of spatially distributed microgrids with renewable and non-renewable energy sources is one of the proposed descriptions of the evolving smart grid. Moreover, there is a gradual shift on distributed generation (DG) over the years to focus more on renewable generation due to global incentivization, climatic issues (such as greenhouse gas emission), and energy market deregulation. This article places attention on photovoltaic (PV) system as an emerging power generation paradigm enabled by the evolving smart grid. One of the critical constraints in this game-changing technology is the high propensity for a mismatch between its power output and load profile characteristics, which could result into severe voltage violations, high losses and a larger reverse power during low load conditions. Consequently, the concept of dispatchability with load-following function for various PV deployment scenarios is crucial for the 21st century grid modernization. The dispatchable PV unit output is controllable when deployed with storage systems making it suitable for ancillary services and demand-side management application. Also, dispatchability implies the ability to remotely start and stop the operation of PV unit when needed to maintain grid reliability. This article presents various deployment scenarios of dispatchable PV units and their impacts on the evolving smart grid. Additionally, this paper reviews the evolution of control, monitoring and communication systems in the active distribution network, utility-interactive inverter technologies, dispatchable grid-connected hybrid system deployments, and communication network configuration for dispatchable distributed energy resource (DER) units integration into the electric power system (EPS).

Contents

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1. Introduction

Energy is one of the key factors that drives economic growth. Sustainable development is driven by sustainable energy [1]. Global electricity demand is estimated to rise by 43% through 2035 with a major upsurge from developing economies [2]. Consequently, there is a shift in paradigm with respect to power generation from fossil fuel to renewable sources. With the quest for sustainable energy for all being heralded by the United Nations, favourable policies are being made globally to increase renewable energy penetration into the global energy mix for obvious reasons such as green house gas emissions and local pollution reduction and increase in customers' participation [1,3]. Apart from environmental factors, social, operational and economic drivers are behind the recent evolution of power generation and transmission [4,5]. For instance, the total investment in power generation from renewable sources (wind, solar, biomass, waves) grew to $187 billion in recent times compared to $157 billion for natural gas, coal and oil [1]. As a result of the high rate of proliferation of these game-changing technologies, the evolving smart grid is envisioned to be a "plug-and-play" connection of spatially distributed microgrids with distributed energy resources as sources allowing for a bi-directional flow of power [6].

Distributed energy resources (DERs) technologies include photovoltaic (PV) arrays, gas-fired turbines, mircroturbines, wind turbines, fuel cells, reciprocating engines, conventional diesel and natural gas, and energy storage. These are broadly classified into rotating prime mover technologies (such as wind turbines, microturbines) and non-rotating prime mover technologies such as PV and fuel cells [7]. The localized grouping, coordination and control of DER units with controllable loads constitute a microgrid, which could operate autonomously or interconnected to the electric power system (EPS) [8–10]. The total capacity of microgrid as specified by IEEE Std 1547 is 10 MVA or less at the point of common coupling (PCC) interconnected to the area EPS [7].

The microgrid is becoming an invaluable energy system for improving the resilience of EPS in the face of frequent power outages as a result of severe weather conditions. This paradigm requires a new method of operation and planning the EPS to retain grid reliability [11]. Also, with forthcoming carbon taxes due to greenhouse gas emissions, countries around the world are introducing policies to encourage a large scale deployment of DERs in the electric power system [12,13]. For instance, the high penetration of PV systems in the German power system, with aggregate installed capacity of about 38.5 gigawatts (GW) in 2014, has been enabled mainly by favourable regulatory framework such as the feed-in tariff (FiT) [6]. The deregulation of the electricity market coupled with the recently launched sustainable development goals (SDGs) which laid emphasis on the increase of renewable energy resource in the global energy mix also serves as drivers for PV integration into the power system [14,3,15]. In [16,17], the solar power installed global capacity (GW) for top ten countries (shown in Fig. 1) depicts a gradual shift in market operations from Europe to United States and Asia region as these markets progress toward maturity and provide a platform for PV system to be cost-competitive with retail energy prices.

Additionally, there are two broad perspectives driving the PV system development, which are the end-users and public entities. The end-users are driven by network reliability, deregulation of energy markets, distribution level de-monopolization and profitability [18]. As for public entities, emergence of a new industry, reliability of the national energy and environmental consideration are the major drivers.

Consequently, the conventional power system is presently undergoing an evolution in terms of operations and architectural landscape. The traditional positive-sequence source, which follows from a centralized power generation with voltage ramped-up on the transmission line and stepped down to a consumable voltage at the distribution end for end-use loads, will experience a major transition in the next few decades. The distribution network which used to be a passive one is now active with the high penetration of DERs, introducing dispersed generation. The emerging electric grid (known as smart grid) is envisaged to allow for flexibility, scalability, resiliency in handling intermittency of some renewable resources without compromising power quality. PV inherent volatility, spatial distribution and a tendency to give rise to emergent behaviours [19], make solar PV integration and interoperability a major concern to authorities having jurisdictions (AHJs) over the grid and other stakeholders.

Despite the fact that the traditional power system has its own uncertainties, yet it is under intense pressure to bear with the variability and higher power quality requirements of DER sources such as the PV system. One of the major concerns of the utility in PV integration into the EPS is the high tendency for a mismatch between the PV output and load profile characteristics, which could result into severe voltage violations, high losses and a large reverse power during low load conditions. This variance could be as a result of cloud movements and hardware failures which

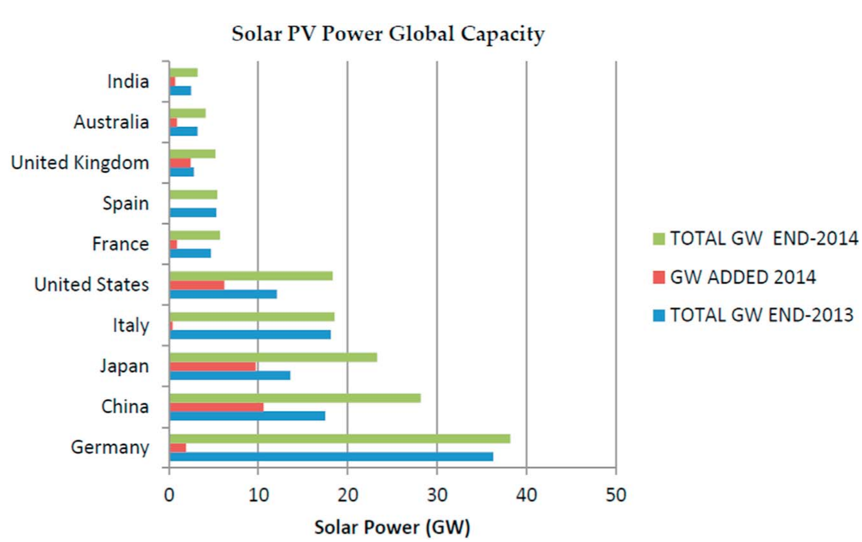

Fig. 1. Top 10 solar power global capacity.