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A review of high PV penetrations in LV distribution networks: Present status, impacts and mitigation measures

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ABSTRACT

The installed capacity of photovoltaic (PV) systems globally reached 177 GW at the end of 2014. The annual rate of installations, 38.7 GW in 2014, continues to increase. A large part of this is installed as residential systems connected to low voltage (LV) networks. The majority of the LV distribution networks are radial, unbalanced with respect to loads and feeder structures and have high R/X ratios. The large scale deployment of PV within the LV distribution networks is limited by voltage quality problems, particularly over voltages and unbalance. Development of proper mitigation techniques is essential to effectively and efficiently manage high penetration of PV within the LV distribution networks. A number of techniques have already been developed and implemented in LV distribution networks to alleviate those problems. This paper provides an extensive review of the present status, impacts and technical challenges of PV penetration in LV distribution networks. In addition, the review comprehensively examines the commercially available and emerging mitigation methods and provides a framework that systematically explores the full range of technical methods and limitations for PV impact mitigation. These will provide a useful framework and strong point of reference for the researchers working further in this field.

Contents

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1. Introduction

The global demand for electrical energy is constantly growing. The dominant energy supply since the industrial revolution, fossil fuels, is still relatively plentiful but environmental concerns have been one factor driving a growing interest in renewable energies internationally. Among a variety of renewable energy sources, PV is one of the major sources of distributed renewable energy [1] that has no supply limitations and is predicted to become the biggest contributor to electricity generation among all renewable energy candidates by 2040 [2]. Along with large scale PV installation, residential customers are also showing great interest in small scale installations in the form of roof-top domestic systems. Presently, single phase rooftop PVs are being increasingly installed by the customers at their premises that are interconnected with the LV distribution networks. As a result, the level of PV penetration is rapidly increasing in LV distribution networks each year. The European Photovoltaic Industry Association (EPIA) reported that the total cumulative installed PV capacity in the world exceeded 138 GW in 2013 [3] and reached 177 GW at the end of 2014 [4]. Recently, the Australian Clean Energy Regulator (ACER) published a report showing the total small scale installed capacity of PV in Australia exceeded 3.5 GW in 2014 [5,6]. However, the possibility of large scale PV in the LV distribution networks was not considered when the networks were constructed. Such high levels of PV penetration in LV distribution networks may alter the normal operational behaviour of distribution networks. The majority of LV distribution networks are radial. The operating assumption is that power flows from upstream high voltage networks to downstream low voltage networks. Due to the increased level of PV penetration in LV distribution networks, the demand upon the distribution feeders reduces because a significant portion of power is locally supplied by the installed PV. This causes significant voltage variation in LV distribution networks which is not desirable. In some cases, the generation of PV may exceed the feeder loads, producing the possibility of reverse power flow within LV distribution networks [7]. Changes of network voltage profile and reversal of power flow direction are the most significant power quality issues that may appear in LV distribution networks with the inclusion of distributed generation [8]. Voltage unbalance will occur for unbalanced current flows due to either load or generation, or from unbalanced impedances in the untransposed distribution networks. An unexpected effect of impedance unbalance and reverse power flow is the possibility for two phases to rise in voltage while the third drops, which is potentially damaging for electric appliances [9]. Positive sequence overvoltage is observed in LV distribution networks with high penetration of residential roof-top PV during periods of light load and high solar generation. Such high solar generation may cause inverter tripping which results in the loss of solar generation. Grid connected PV encounters those problems which may require imposing limits on the level of photovoltaic penetration or renewable generation within LV distribution networks. Some regulatory devices are essential in LV distribution networks to manage the network voltage to alleviate those problems. A review of recent papers indicates that interest is mainly focused on the PV output characterisation, voltage quality issues caused by the intermittent nature of PV and impacts of voltage issues in LV distribution networks, but a topology study of different mitigation techniques to alleviate voltage problems has not been conducted [10–15].

This paper seeks to provide a comprehensive topology study of different mitigation methods proposed in recent publications. As a part of this review, the present status and impacts of high PV penetration in LV distribution networks are also examined in this paper. A thorough discussion of the various topologies is provided and the favourable features of each method are clearly identified as a sound foundation for future applications. Finally, a possible future direction of research to further improve the voltage issues in LV distribution networks with high PV penetration is also presented.

2. Recent historical advancement of cumulative PV installation

2.1. Global PV scenario

The global PV market has grown rapidly over the past decade at a steadily increasing rate which will lead to PV becoming one of the major sources of power generation for the entire world [3]. The global PV market had a record year in 2014, installing more capacity than any other renewables after hydropower while exceeding wind power [16]. Fig. 1 shows the progress of cumulative installed PV capacity in the world over the period 2000–2014. A major portion of the total PV capacity is integrated with LV distribution networks in the form of rooftop domestic systems. According to the EPIA report, rooftop PV installations were more than 23 GW in 2013 which exceeded the utility scale installations significantly [3].

Table 1 presents numerical data for actual cumulative PV installed capacity by region with global market share in 2013, and forecasts of those numbers for 2018. Europe is the world's leading region in terms of cumulative installed capacity with 81.5 GW as of 2013 that represent about 59% of the world's cumulative PV capacity. However, the global market share of PV capacity in Europe is slightly down in 2013 from 70% in 2012 and about 75% of the world's capacity in 2011. Asia Pacific countries are also still growing fast, having about 21.9 GW of cumulative PV installed capacity representing 16% of the world's capacity in 2013. China is in the top rank within the Asia Pacific countries, recording 18.6 GW of cumulative installed capacity with 13% of market share in 2013. The Americas is improving its position compared to other countries in respect of cumulative installed capacity. The Americas achieved 13.7 GW cumulative installed PV in 2013 which was a global market share of 10%. Several countries from large Sunbelt regions like Africa, the Middle East, South East Asia and Latin America are on the brink of starting their development. For example, the cumulative installed capacity outside Europe was 30 GW in 2012, but doubled during 2013 to reach 60 GW. This indicates the ongoing rebalancing between Europe and the rest of the world and closely reflects changing patterns in electricity consumption [3]. The share of PV installations outside Europe can only increase, ensuring the ongoing development of the PV market globally.

The combination of declining European markets and the possibility of establishing durable new markets in developing countries could cause this market to boom. As a result, the Asia-Pacific