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A review of generation dispatch with large-scale photovoltaic systems

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ABSTRACT

This paper presents a detailed literature review on the issues and technical difficulties encountered in integrating large-scale photovoltaic (PV) systems to the grid and the role of generation dispatch in solving such challenges. It is observed that although there is a widespread adoption of stability (voltage, frequency and angle) strategies in dealing with intermittent nature of PV systems, generation dispatch techniques can equally be employed to overcome the challenges posed by large-scale PV systems. Hydro-electric generators equipped with automatic generation control and combustion turbines coupled to the grid are some of the best options in this regard. It is expected that utilities will not only fulfill their mandate of ensuring continuity of supply, but will also be able to cut costs through optimal generation dispatch. The greatest benefit is the self-reliance in terms of energy supply at all times, including night-time when ordinary photovoltaic systems are considered redundant.

1. Introduction

In developing countries, standalone PV systems are popular off-grid power supply solutions for homes in remote locations [1]. Meanwhile, in most developed countries, grid-connected PV systems feature prominently at low voltage distribution level [2–4]. In sparsely distributed population countries such as Namibia, PV systems at low voltage distribution are not feasible. In this case, large-scale PV system at transmission level could be the alternative. This requires improved understanding of control measures to deal with the challenges of large-scale PV systems. Various control strategies aimed at limiting the voltage rise as a result of increased local PV power feed-in at low distribution level have been discussed [2–5]. These include PV inverter control strategies as well as a distribution transformer with On-load Tap Changer (OLTC) and traditional grid reinforcement measures for grid-connected homes [4]. Other methods entail the use of combined PV inverter reactive power control strategies and battery energy storage systems [5].

However, none of these approaches have addressed the challenges of large-scale PV system in transmission and sub-transmission networks. There is relatively large amount of work on themes such as stability techniques and technical mitigation measures at low distribution level. However, there is a dearth of information on technical mitigation measures of dealing with large-scale PV systems coupled to transmission and sub-transmission networks. Consequently, the large-scale PV systems have not been fully explored as a part of sustainable energy options. Furthermore, among the solutions to large-scale PV systems challenges are the generation dispatch and spinning reserve methods [6]. This piece will discuss their application to mitigate the intermittency issues that arise as a result of grid-connected large-scale PV systems.

Research on the integration issues has mainly focused on distribution level PV systems [4] and very little attention has been paid to large-scale PV system [6]. With increased deployment of large-scale PV plants, new challenges and solutions need to be explored. This study will therefore present a detailed overview on the uniqueness of large-scale PV systems and grid integration technical concerns. It also covers mitigation strategies for increased deployment of large-scale PV systems and economic viability to both power utilities and customers.

A detailed review of existing generation dispatch and spinning reserve techniques with PV systems is carried out. Finally, this paper proposes a different approach to address the impact of large-scale PV systems on the transmission grid.

2. Overview of current literature

2.1. Impacts of large-scale PV systems and solutions

Besides the variability in solar irradiance and temperature, another unique cause of intermittency in PV generation output is the well-known shading effect caused by moving clouds [7,8]. This is noted to be one of the challenges posed by large-scale grid-connected PV generation which results from sudden change in PV generator output when an entire array is covered or uncovered by a large moving cloud. The

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resulting operational problem is comparable to the sudden load change in the power system. Measures and challenges involved in dealing with this kind of scenario are discussed as follows.

On one hand, the control measures to handle PV generation sudden changes are:

i. Automatic Generation Control (AGC),
ii. regulating conventional generation,
iii. scheduling of more units to regulating duty, and
iv. use of combustion turbines or combined cycle generating units that have very responsive gas or oil firing systems, which make these specific generators easily controllable.

On the other hand the challenges in handling PV generation sudden changes are listed as,

i. the ramping rate imbalance - the rate at which the PV generation drops (e.g. MW/min) may be faster than the rate at which the conventional generation is ramped up,
ii. conventional generation entrusted with compensating for lost PV generation may reach peak generation output before attaining desired load-generation balance,
iii. cost of fuel (oil or gas) in combustion generators and the scheduling aspect.

Other possible solutions to the challenges of sudden changes in PV output as a result of abrupt clouds cover lies in the averaging effect and wide-area geographic diversity factor concepts. In terms of shading effect caused by moving clouds, large-scale PV systems in transmission and sub-transmission are not severely affected as opposed to PV systems at distribution level. This is because large-scale PV systems are usually installed in a vast area [9], and the resulting drop in PV output is minimized by the averaging effect. On the other hand, the output of a PV module in distribution level systems can severely be reduced to below 50%. This is of course in contrast to PV arrays installed across a vast area where the averaging effect minimizes the impact of this phenomenon on the PV generation output [6].

A study funded by the U.S. Department of Energy investigated the role of wide-area geographic diversity factor in relation to cloud-induced short-term variability of solar power output [10]. It is noted that taking into account the potential role of diversity factor can greatly minimize the impact of short-term variability on the combined PV power output. In addition, the geographic diversity factor also holds the potential to reduce the resources and costs required to accommodate and manage the variability. The aforementioned additional resources and costs are directly associated with the system operator's reliance on the following resources and methods to maintain generation and load demand balance:

i. requirements to hold dispatchable resources in reserve in the form of spinning and non-spinning reserves,
ii. economic dispatch or load-following requirements, and
iii. unit commitment requirements.

This specific study also questions the conclusions of earlier studies that were mostly based on scaled PV plant data. One popular conclusion is that "the economic value of PV is significantly reduced at increasing levels of PV penetration due to the additional need for reserves [10]". The other conclusion is that "the high variability of PV and the limited ramp rates of conventional generation limit the feasible penetration of PV [10]". It was concluded that "the degree to which PV increases the demand for resources to balance the net load therefore depends on the amount of smoothing offered by geographic diversity". A similar study [11] aimed at determining what the actual barriers to the adoption of intermittent renewable energy resources attained a similar conclusion.

In an effort to make renewable energy resources more dispatchable and overcome the inherent challenge of intermittency, battery systems and other energy storage mechanisms are also engaged in an effort to attain firm power supply [12–15]. An investigation was carried out on the control strategy for a battery energy storage system (BESS) coupled to a PV system or a wind farm [13]. Through charging and discharging mechanism, the proposed rule-based control strategy for the BESS enables the volatile renewable energy resource to be dispatched on hourly basis similar to any other conventional generator. The BESS, connected to the point of common coupling via a converter, aids this process by compensating for the fluctuating power output of the PV system or wind farm.

Other storage mechanisms are also considered for the purpose of limiting PV output fluctuations caused by passing cloud cover [16,17]. The proposed method makes use of the ramp-rate control technique. The setup as involves an inverter power output P_{INV} obtained from the combined PV panel DC power output P_{DC} and compensation power output P_{COMP} from a storage device as illustrated in the following equation [16]:

$$P_{INV} = \eta_{INV}(P_{DC} + P_{COMP}) \quad (1)$$

where η_{INV} is the efficiency of the inverter. The inverter power output P_{INV} is kept constant by controlling the ramping rate of either P_{DC} or P_{COMP}. For instance, when the PV panel output power drops due to sudden cloud cover, the compensation power output is raised accordingly to compensate for the decrease in PV panel power output.

A recent review of the technical issues on the development of PV systems placed emphasis on the use of storage devices such as batteries in addressing the technical challenges caused by the intermittent nature of PV [18]. With regard to dispatch strategy of the stored energy, energy management techniques such as demand side management (DSM), scheduling techniques such as load forecasting, and a number of energy optimization methods were observed to be the effective means of deriving maximum financial benefits from PV-battery power systems. This is because certain loads are only brought online during off-peak demand period. In terms of time of use (TOU) tariff arrangement, off-peak demand period is also when the electricity charges are low. In addition, this is also the period when high energy consuming loads are off, thereby ensuring generation and load balance.

Besides the load following generation plants that help fulfill load following requirements, demand dispatch is also anticipated to play a complementary role in dealing with increased penetration of intermittent renewable energy resources such as large-scale PV systems [19]. This is a method in which generator outputs are adjusted and some loads are switched on or off to achieve generation – load balance as demand for electricity fluctuates. Widespread modern communication infrastructure such as internet are prerequisite to a successful demand dispatch technique.

The complementary hydro-PV power plant is a type of hybrid energy source consisting of hydro-power and PV power sources used together in a complementary operation mode. Longyangxia hydro-PV plant consisting of 850 MW PV arrays and 1280 MW hydropower units situated in north-western China is one of the popular case studies in this regard [20,21]. The key aim is the attainment of improved PV power quality as well as aiding the integration of large-scale PV in the power system [21]. The improvement in PV power quality is accomplished through tracking and compensation of random and intermittent PV power output using promptly-adjustable hydropower units. The other benefits lies in the ability to offset costly storage and spinning reserve requirements. There are also economic spinoffs based on local harnessing and deployment of complementary hydro-PV schemes in regions that are plentifully blessed with both hydro and solar energy.

2.2. Impacts of large-scale PV systems on the grid code and solutions

The integration of large-scale PV to the grid, like all other variable