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Minimizing the steady-state impediments to solar photovoltaics

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A R T I C L E I N F O

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A B S T R A C T

The main objective of this paper is to determine which voltage regulation strategies best allow grid-tied Photovoltaic (PV) Systems to be integrated into distribution networks. More particularly, this involves performing a literature review on the negative impacts of grid-tied PV systems on distribution networks, and also the current and proposed voltage regulation methods available. The next step is to assess, through simulation, which strategies allow the greatest amount of PV to be integrated with minimal effect on power quality. This will be done by simulating various Medium Voltage (MV) and Low Voltage (LV) radial feeders under varying load conditions and changing solar irradiance levels. Real network data will be incorporated with an accurate model for PV output power to accurately model high penetrations of PV. Our research highlights the necessity of reducing peak loadings through strategies such as energy storage, off-peak loading methods, and reactive power control of inverters to decrease the voltage deviations. It has been shown that voltage rise and reverse power-flows can and should be avoided on distribution feeders. Voltage unbalances can also be easily avoided by following the simple steps outlined in this paper. Now, a proactive approach should be taken by Governments, Distribution Networks System Providers, and customers with PV to ensure that as penetrations increase, Power Quality is not diminished.

1. Introduction

Photovoltaic systems are a technology with great potential, which has been realized by those who have already invested in Rooftop Solar panels. There are several benefits to our society from integrating Solar Photovoltaic's into the power grid. Firstly they can alleviate the pressures of increasing demand on Transmission and Distribution networks. Also, they reduce the negative impacts of our society's use of electrical energy derived from carbon-emitting coal-fired generators, which are the dominant source of electrical power in Australia. However, they also have several problems associated with their use. The negative impacts relate to the effects Photovoltaic's have on Power Quality and Reliability. Several works have been done to reduce the side effects of PVs on distribution networks.

This project aims to find the optimal method for operating Distribution Feeders with high penetrations of Photovoltaic systems. Various methods, which could be used by Power Distributors, for maintaining the expected quality of electricity supply in the presence of Photovoltaic's have been examined and recommendations have been made.

1.1. Literature review

In references [1], a review of existing and future standards that addresses the technical challenges associated with the growing number of grid-connected PVs is presented. Then, in grid-connected PVs, it has suggested the use of inverters that support ancillary services like power control, frequency regulation, and energy storage. The reference [2] has summarized all possible approaches that can be used to improve and optimize the utilization of renewables. Another interesting work in [3] presents a detailed analysis of various multilevel multifunctional configurations for 1-phase and 3-phase systems and control strategies to compensate the different power quality problems. The issues like different islanding techniques; remote and local techniques and their advantages and disadvantages on utility's stability with high penetration of PVs discussed in reference [4]. The reference [5] reviews the dynamic model of large-scale PV for stability studies as well as the grid codes for large-scale PV integration into the system. The paper summarizes the research findings about the technical solutions to overcome the power system stability challenges regarding the large-scale PV integration into the electrical networks. The reference [6] has

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investigated negative impacts of PVs to the power networks. It has studied the performance of artificial intelligence (AI) and conventional methods in mitigating power quality event. From this study, power system monitoring, inverter, dynamic voltage regulator, static synchronous compensator, unified power quality conditioner and energy storage system are able to compensate power quality events, also AI methods usually outperform conventional methods in terms of response time and controllability. With a very short-term (15 s) PV power forecasts, the paper [7] proposes a local voltage regulation technique to circumvent imminent upper voltage limit violation or an overvoltage scenario. A hybrid forecasting method is formulated based on the Kalman filter theory, which applies physical PV generation modeling using high-resolution data from on-site measurements. The paper [8] has studied voltage issues in a cloudy country (Malaysia) and compared it with other countries by extracting probability density of voltage rise and voltage unbalances from measurement data. The paper [9] has proposed a new comprehensive taxonomy for off-grid systems for rural electrification. Then it has classified the rural off-grid systems to five areas: Technology: layout and components; Models and methods for simulation and sizing; Techno-economic feasibility analyses and sustainability analyses; Case studies analyses; Policy analyses. The reference [10] has tested ten different commercially available inverters in a Federal Laboratory. Then it has modeled mathematically the power factor and total harmonic distortion in current curves as a function of relative power in order to be used in computer simulation of photovoltaic systems. Some other papers have reviewed the situation of grid-connected PVs in a specific country. They have discussed the industrial trends, governmental policies, economical considerations, technological problems, environmental conditions, and limitations in the India [11], Kenya [12], USA [13], Lebanon [14], Pacific Island Countries [15], and Malaysia [16].

According to [17], the number of PV systems in New South Wales has increased from 2900 in December of 2008, to over 50000 by November 2010. This rapid increase has been due predominately to the NSW government's Solar Bonus Scheme, which is a generous electricity buy-back tariff of $0.6/kWh [17]. This tariff has since been reduced to $0.2/kWh for new connections [18].

Typically, on an MV distribution, voltage Rise results from the current flowing in the reverse direction along the feeder. This is a direct result of power being injected into the network [20]. Therefore reverse power flows and voltage rise are closely linked to each other. PV systems are able to inject power into the network, so they can cause the voltage to rise. If voltages violate the limits, some circuits will begin to trip off, potentially leading to instability on the network. Hence a limit of 30% penetration is recommended [20].

For [21], a penetration of 100% of houses with a small 1 kW_p is suggested to be the most ideal compared to having 2 or 3 kW_p systems. This is because, at a level of 1 kW_p per household, there is the ability to mitigate small voltage drops and reduce losses without causing reverse power flows. The authors of [22] suggest that a penetration equivalent to 60% of the capacity of the transformer that the feeder originates from is the limit to prevent unacceptable voltage rise.

One difficulty with reviewing the outcomes of each of the papers is that the feeders under study for each paper are different. Different assumptions are made and the acceptable penetration levels are expressed in a variety of ways. In Table 1 below the recommended PV penetration levels are summarized:

Table 1
Suggested maximum PV penetrations.

Paper	Percentage of transformer capacity	Percentage of households	Notes
[17]	50%	-	-
[18]	-	30%	1.8 kW_p/household
[20]	20%	–	Above this controlled loads are used
[23]	60%	–	Above 60% extra voltage regulation required
[25]	–	100%	I kW_p/household

It is evident from the table that there are large discrepancies between each of the values. This suggests that finding an acceptable PV penetration value is dependent on a range of different factors that will be different for each feeder considered.

1.2. Reverse power flows

As stated before Voltage Rise and Reverse Power-flows are closely linked. This situation is made more likely since the peak load periods and peak PV generation periods tend not to match up for most networks around the world [20]. Generally, peak PV power output will occur during the middle of the day when solar irradiance is highest. Peak loads usually occur in the evening or mid-morning [23]. These characteristics of load and PV generation are quite inflexible, leading to what could be described as a 'worst case' situation [21].

From the papers under review, there are several reasons given why Reverse Power-flows are to be avoided. Firstly in [24] the reason given for avoiding the situation on Japanese distribution networks is that it is simply illegal. In [22], a paper focused on Canadian networks, the authors are bit more specific. The reason they give for avoiding Reverse Power-flows is that current procedures used by the Utilities for guaranteeing Power Quality and Reliability become less effective under these conditions [22]. Hence Canadian Electricity Utilities have adopted conservative limits as to how much DG can be placed on their Distribution networks without performing a detailed study.

Distribution feeders are often radial in their layout, and so are designed for transmitting energy in one direction only, towards the customer. Hence the voltage regulation equipment and protection devices are not normally set up to cope with power flowing away from the customer [21]. This can cause these devices to operate in unpredictable ways.

1.3. Voltage fluctuations

Voltage Fluctuations can occur on distribution grids with high penetrations of PV systems [25]. The reason behind this is that the power output of PV systems can change quickly in reaction to changes in solar irradiance levels. Changing cloud cover will change the local solar irradiance levels very quickly. The result can be changed in voltage of around 3–4% [25]. These changes can be very significant, as they happen quickly and are in addition to the wide range of voltages that can be present on distribution feeders. Voltage regulating Transformers do not react quickly enough to counter the effects of such variations [26].

Thomson and Infield [20] note the effects of cloud cover on the voltage profiles produced by their simulations. They include the effects of cloud cover from the measured solar irradiance profiles that were used as the input data for calculating the PV power output. They collected data for several summer and winter days that match with load data they already possessed. In [25] the data is produced in a similar fashion, from a sensor measuring global irradiance (the sum of direct and diffuse irradiance) for 365 days of a year. This data was used to calculate the mean clearness index K_T, a number that is proportional to cloud cover at that time.

1.4. Phase imbalance

Phase Imbalance is characterized by the voltage and current magnitudes between different phases in a polyphase system becoming unequal. For a three-phase system, the phase shift between phases may also differ from 120 degrees, which is the phase shift for a balanced system [27]. If a three phase Distribution feeder has voltages or