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An approach for assessing high-penetration PV impact on distribution feeders

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ABSTRACT

The variability of solar power due to cloud shadows with high penetration levels can cause technical issues such as power fluctuation and voltage flicker in power distribution feeders. To help distribution planners better understand and predict these likely impacts on voltage quality and avoid overly conservative decisions on the amount of PV installed on a feeder, a comprehensive simulation method is needed to model and address these problems. To this end, this paper presents a simulation and analysis approach that uses a cloud shadow model to recreate the variable output power of both distributed and large centralized PVs at various locations on a feeder. Simulations are made on an actual EPRI test feeder. EPRI's OpenDSS distribution simulation program is driven through MATLAB. The feeder is monitored at all buses, and PV induced voltage quality issues are measured, including the dynamic reaction of voltage control devices. The example feeder illustrates the usefulness of the new evaluation method to address and quantify impacts of large amounts of PV systems on feeder steady-state over voltage, voltage fluctuation level and flicker, and voltage regulation device operation. Results for distributed PV show that PV levels as high as 50% can be tolerated.

1. Introduction

Over the past decade, utilization of solar energy for electricity generation has grown dramatically due to its economic benefits [1]. However, due to variable characteristics of PV generation, the integration of a large amount of PV in a close geographic region will have various negative effects on the operation of distribution feeders [2]. The most common potential concerns caused by solar power are steady-state overvoltage, issues with voltage regulating devices, impacts on system losses, protection, harmonics, and voltage flicker.

PV generated power fluctuates rapidly within a short period of time due to cloud movement. When an area with large numbers of PV is shaded by fast moving clouds the total solar generation drops to about 30% of full sun levels, causing voltage sags. Likewise exiting clouds may cause over voltage problems in a feeder whose regulator taps rise in response to voltage drop [3].

Solar PV integration impacts on distribution feeders may be in general classified into two types, steady-state and dynamic impacts [4]. Impact studies show that these effects are highly dependent on penetration level, location of PV installations, and topography of the feeder. Steady-state effects are assessed via circuit analysis tools, which provide snapshot power flow analysis at different feeder loading levels at one specific instant of time. Such studies are typically limited to analyzing only the worst-case conditions on distribution feeders. Considering fast-varying PV output due to cloud movements, dynamic studies over tens of minutes simulated in one-second time steps are intended to capture this time-dependent behavior and the possible interaction with automatic voltage regulation devices.

In the literature, PV cloud effects on distribution feeders have drawn concerns of researchers since the late 1980s [5–7]. Due to lack of high-resolution data, most of these early studies could not capture the dynamic behavior of PV generation over small time intervals. The well-known voltage fluctuation problem in high PV penetration feeders has been addressed in many recent publications implementing several voltage-control methods such as PV power curtailment [8], energy storage device integration [9,10], and inverter reactive power control [11]. Other investigations have focused on showing how time-varying PV power and its induced voltage fluctuation are not a severe issue [12,13]. Specifically, large-scale systems with well distributed PV units have been used to show that voltage variations are slow and smooth due to dispersion of PV generators [14,15].

Due to increasing PV penetration levels, and in order to avoid unnecessary feeder modifications and adding costly storage devices, there is a need in the power industry to develop a simple

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simulation approach method to predict the expected PV-induced voltage fluctuations and their impact on operation of feeder voltage control equipment. Time delay settings of control devices typically range from 30–90 seconds and for this reason, high resolution PV data is critical to evaluate the impact of PV power variability. Since the availability of such data can be problematic, prior studies have used low-resolution recorded PV data to produce realizations at a higher sampling rate [16,17]. There could be high-resolution solar measurements from locations close to feeder under study, but this surrogate data may not be helpful to utility planner whose feeder has PV sites of different sizes and locations dispread over a large area. In other words, different stations may have the same power profile, but they will not be time synchronized due to geographical separation. Assuming all PV stations varying simultaneously following the same PV variability profile will significantly overestimate PV variability impact on distribution feeders. Moreover, solar installations are often deployed in distributed sites that are hard to monitor collectively. The notable recent wavelet variability model (WVM) derived from [18,19] formed the input for in-depth studies of PV integration studies. According to [19], WVM method simulates area-averaged-irradiance using a single point sensor as input. For many studies, this method is limited by the need for a local sensor to derive correlation scaling coefficient.

In order to fully analyze these undesirable effects in either small or large-scales with different penetration levels during cloudy days, this paper describes an experimentally-based cloud model to recreate generated power by each PV unit at various locations over the distribution feeder with a time series load flow analysis using an actual EPRI feeder model. This cloud model, while simplified, facilities the analysis of various PV deployment scenarios from a single centralized plant to a fully distributed configuration.

The first half of this paper describes the cloud shadow model and the other half examines how this model assesses high-penetration PV impacts on distribution feeders. The remainder of the paper is arranged as follows: Section 2 introduces the cloud model used in this study. In Section 3, the configuration of the test feeder is described. The simulation approach to evaluate the impact of cloud transients using the cloud model is presented in Section 4. Section 5 demonstrates the simulation results for the feeder under study in order to evaluate cloud effects under different conditions. Section 6 provides conclusions.

2. Dynamic cloud model

System planners require in-depth investigation to accurately assess the dynamic effects of PV cloud impacts on a distribution feeder. Due to uniqueness of feeders under study, high resolution PV data on the order of seconds should be collected from all around the feeder and at each PV location by installing measurement equipment to compare with run time simulations. Such data are typically not available for most distribution feeders of interest and this emphasizes the need for a cloud model able to generate estimated PV power profiles for every utility feeder and all distribution scenarios.

In general, clouds can be classified into several major types with respect to their heights [20] and among them low altitude cumulus clouds with clear edge shadows account for the PV power ramps with highest frequency and magnitude [21]. To better understand the potential impact of output variability on the operation of the distribution system from a utility system operator prospective, this section details the proposed cloud shadow model. Due to irregular shape of cloud shadows, there is no general cloud pattern to exactly fit every real measured PV data. To this end, the proposed model is developed to reproduce PV power ramps similar to experimental data observed over many days. The objective is to develop a general model with primary focus to estimate the worst case realistic fluctuations caused by cumulus shadows in the change in output for PV systems ranging from a centralized power plant to regionally distributed PV (residential rooftop).

2.1. Distributed PV systems (residential rooftop)

PV power generation variability due to crossing of clouds changes from fast fluctuation to smoothed aggregate output once going from a single PV panel to large-scale power plant. In this section, the surface areas of distributed rooftop PV sites with a few kilowatts of power are considered to be small compared to the shadow size that is passing over and therefore their power output is calculated based on their location assumed as a point compared to the cloud shadow.

Any sudden change in irradiance hitting PV panels results in a change in output power of the PV arrays happening with almost the same pace [22]. On partly cloudy days the output of PV generators are reported to drop from 100% to 30% in 5–10 seconds [23].

The cloud model used in this study was first developed in [24] and is based on collected PV output data over many days using an *I–V* curve sweeper that measures maximum possible PV output in 1-second intervals. Fig. 1 shows results of a 130 W panel pair performance for a typical day with rapid cloud movements. Some interesting ramping trend was observed from study days with cloud speed of 10 m/s. Most of the extreme observed ramps occurred during 5 second transition intervals in which PV output varied between maximum and 30% of the available power. This transition mode is seen to be proportional to cloud velocity and is estimated to be 50 meters for days with cloud speed of 10 m/s.

Taking these and many similar observed days into account, as indicated in Fig. 2, the cloud shadow model is developed as a repeating pattern of cloud shadows moving on the ground at the rate of 10–20 m/s. Since large power fluctuations are of primary interest of this model, neglecting irregular shape and size of cloud shadows simplifies our cloud model to a pattern of circular shadows with the same size as shown in Fig. 2. First for each PV system, the clear sky maximum power, P_{Max}, is calculated for the given time of the day based on panel type, orientation, and azimuth and then, a cloud pattern of appropriate length and width is generated based on desired time interval (simulation interval), wind speed and direction, and size of the service area in which PV installations are spread. In order to simulate severe partly cloudy conditions, the model assumes a cloud cover factor of 0.5. The variation of the power in each PV system is then obtained considering the movement of cloud

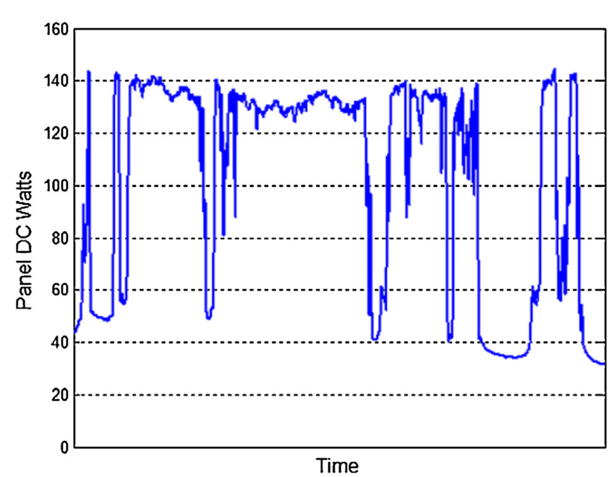

Fig. 1. Actual thirty-minute window of PV max power measurement for a 130 W PV panel pair with cloud shadow movement starting at 13:00.