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Local steady-state and quasi steady-state impact studies of high photovoltaic generation penetration in power distribution circuits

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ABSTRACT

Both steady-state and quasi steady-state impact studies in high Photovoltaic (PV) penetration distribution circuits are presented. The steady-state analysis evaluates impacts on the distribution circuit by comparing conditions before and after extreme changes in PV generation at three extreme circuit conditions, maximum load, maximum PV generation, and when the difference between the PV generation and the circuit load is a maximum. The quasi steady-state study consists of a series of steady-state impact studies performed at evenly spaced time points for evaluating the spectrum of impacts between the extreme impacts. Results addressing the impacts of cloud cover and various power factor control strategies are presented. PV penetration levels are limited and depend upon PV generation control strategies. The steady state and quasi steady-state impact studies provide information that is helpful in evaluating the effect of PV generation on distribution circuits, including circuit problems that result from the PV generation.

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1. Introduction

Photovoltaic (PV) generation is one of the most rapidly growing renewable energy sources, and is regarded as an appealing alternative to conventional power generated from fossil fuel [1]. This is leading to significant levels of distributed PV generation being installed on distribution circuits. Although PV generation brings many advantages, circuit problems are created due to the intermittency of the PV generation, and overcoming these problems is a key challenge to achieving high PV penetration. Without addressing these technical issues properly, PV generation can be limited from injecting more active power into a distribution network [2,3].

It is necessary for utilities to understand the impacts of PV generation on distribution circuits and operations. An impact study is intended to quantify the extent of the issues, discover any problems, and investigate alternative solutions. Researchers and systems operators will need to evaluate the impact of PV generation on system operation characteristics, such as voltage profile, power losses, stability, and reliability [4–6].

An impact study can be divided into two categories; system wide and local [7]. A system wide study addresses growth impacts of new technologies on the circuit, including Plug-in Hybrid or Electric Vehicles, Distributed Energy Resource (DER) generation, and energy storage systems. This study deals with the uncertainties and effects of new technology, including location, size, and operating characteristics [8,9].

On the other hand, local impact studies address expected impacts of new technologies on a distribution circuit as it exists today. The native loading and PV generation data are available along with the location and characteristics of the PV generation. A local impact study is presented in this article.

The potential impact of PV generation on power systems has been discussed in many articles. An extensive literature search is conducted to address potential problems associated with high penetration levels of PV generation in [10,11]. Furthermore, the impact of increased penetration of PV generation in the transmission system is studied for both steady and transient stability. The analysis with and without the existence of the PV generation is studied and compared to identify improvements or adverse effects of PV generation on the system [12].

The effects of the integration of distributed PV generation into distribution systems are examined in [13–20]. It is becoming apparent that local voltage issues are likely to precede protection, load, fault, harmonic, and stability issues as penetration increases. In addition, reverse power flow can negatively affect protection coordination and operation of voltage control and regulation equipment. Furthermore, PV generation introduces changes in the circuit loss and also imbalances of voltages and power flows. Barriers to the successful integration of DER generations into microgrids, including power quality, protection, and stability, are addressed in [21–23].

In this article both local steady-state and quasi steady-state PV impact studies are presented. The steady-state impact study investigates impacts at extreme circuit conditions and the quasi steady-state represents a series of steady-state studies over a set of time varying values. Thus, the quasi steady-state study evaluates a spectrum of impacts. In addition, PV generation power factor control for mitigating voltage variation problems is investigated.

This article is organized as follows. In Section 2 the most common expected impacts of PV on the distribution circuit are discussed. Section 3 presents simulation strategies addressing the impacts discussed in Section 2. In Section 4 the results obtained from existing circuits with individual customers modeled are presented. Finally, findings of the study are summarized in Section 5.

2. PV impact study

Some of the impacts from high PV penetration which should be considered in steady-state and quasi steady-state PV impact studies are discussed in this section.

2.1. Steady-state PV impact study

A steady-state PV impact study seeks to discover the worst case, or extreme impacts, on the distribution circuit. Circuit conditions that are considered include maximum loading, maximum PV generation, and maximum difference between PV generation and circuit load. The objective is to analyze extreme impacts by comparing circuit conditions before and after a change in PV generation. In these studies the effects of control actions are very important. Solar generation transients can be so rapid that traditional utility control devices cannot act sufficiently fast to correct circuit problems caused by the rapidly varying generation.

2.1.1. Customer voltage variation

Among the various technical challenges under high PV penetration, voltage variations caused by the intermittency of the PV generation are among the foremost concerns. The need to limit voltage variations resulting from rapidly varying PV generation can limit the amount of PV generation in the distribution circuit. The typical allowed variation in voltage is $\pm 5\%$ from a nominal voltage, but other concerns, such as causing excessive control motion of utility equipment, may place tighter restrictions on the allowable voltage variation [24].

It is important to maintain the voltage within allowable ranges at all components in the circuit. Many distribution circuits are radial and the voltage is controlled by automated devices (voltage regulators, switched capacitor banks, load tap changing transformers). Solar generation can vary rapidly up and down as clouds pass over, creating many voltage transients at the automated control devices. If typical utility control equipment attempts to