Solar Energy 159 (2018) 538–547

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

Fast Quasi-Static Time-Series (QSTS) for yearlong PV impact studies using vector quantization

Jeremiah Deboever[a,*], Santiago Grijalva[a], Matthew J. Reno[b], Robert J. Broderick[b]

[a] Georgia Institute of Technology, 777 Atlantic Drive NW, Atlanta, GA 30332-0250, USA
[b] Sandia National Laboratories, P.O. Box 5800, Albuquerque, NM 87185-1033, USA

ARTICLE INFO

Keywords:
Photovoltaic systems
Power system simulation
Quasi-static time-series
Voltage control

ABSTRACT

The rapidly growing penetration levels of distributed photovoltaic (PV) systems requires more comprehensive studies to understand their impact on distribution feeders. IEEE P.1547 highlights the need for Quasi-Static Time Series (QSTS) simulation in conducting distribution impact studies for distributed resource interconnection. Unlike conventional scenario-based simulation, the time series simulation can realistically assess time-dependent impacts such as the operation of various controllable elements (e.g. voltage regulating tap changers) or impacts of power fluctuations. However, QSTS simulations are still not widely used in the industry because of the computational burden associated with running yearlong simulations at a 1-s granularity, which is needed to capture device controller effects responding to PV variability. This paper presents a novel algorithm that reduces the number of times that the non-linear 3-phase unbalanced AC power flow must be solved by storing and reassigning power flow solutions as it progresses through the simulation. Each unique power flow solution is defined by a set of factors affecting the solution that can easily be queried. We demonstrate a computational time reduction of 98.9% for a yearlong simulation at 1-s resolution with minimal errors for metrics including: number of tap changes, capacitor actions, highest and lowest voltage on the feeder, line losses, and ANSI voltage violations. The key contribution of this work is the formulation of an algorithm capable of: (i) drastically reducing the computational time of QSTS simulations, (ii) accurately modeling distribution system voltage-control elements with hysteresis, and (iii) efficiently compressing result time series data for post-simulation analysis.

1. Introduction

Interconnection of emerging technologies into the electricity grid such as solar PV, wind, and electrical vehicles are changing the power system energy mix and impacting the way distribution systems are being planned and operated. Specifically, distributed solar PV systems can affect the distribution feeder and impact the operation of controllable elements on the circuit. The conventional steady state scenario-based power flow modeling is not sufficient to study the impact of distributed PV because it cannot capture time-dependent effects of controllers with delays and deadbands. Specifically, voltage regulators and capacitor banks with local controls may be significantly affected by power injection variation that can cause rapid voltage changes on the circuit. Therefore, chronological, time series power flow simulations provide a more detailed understanding of the impact of distributed PV interconnections on distribution feeders, as recently discussed in IEEE standard P1547.7 D110 (IEEE P1547.7 D110, 2013). Quasi-Static Time-Series (QSTS) studies can simulate a feeder over a period of time and capture the impacts that distributed PV and load variations can have on a realistic system, which is something that scenario-based analysis cannot capture.

Due to decreasing prices of solar photovoltaic (PV) and more ambitious renewable penetration targets, the analysis of distributed PV systems becomes a key focus. Formerly, integration of solar PV was based on power flow studies performed for worst-case scenarios, e.g. when the system experienced peak load or back-feeding. However, solar PV as an intermittent resource introduces variable current injections to the circuit, which in certain conditions can reverse the flows and cause intermittent operational violations including over- and under-voltages, thermal limit violations, back-feeding, or excessive controller actions (e.g. tap changes) over a period of time. Although some impacts can be approximated with scenario-based simulations (Cohen et al., 2016), it may not be possible to simulate all scenarios a feeder will experience in a year and, more importantly, impacts on the daily operation of the feeder cannot be accurately assessed. Therefore, a comprehensive impact study requires a yearlong simulation at a 1-s granularity (Reno et al., 2017) to represent both the seasonal variation of the load and the high-frequency fluctuations of distributed PV. This

* Corresponding author.
E-mail address: jeremiah.deboever@gatech.edu (J. Deboever).

https://doi.org/10.1016/j.solener.2017.11.013
Received 15 June 2017; Received in revised form 24 October 2017; Accepted 7 November 2017
Available online 20 November 2017

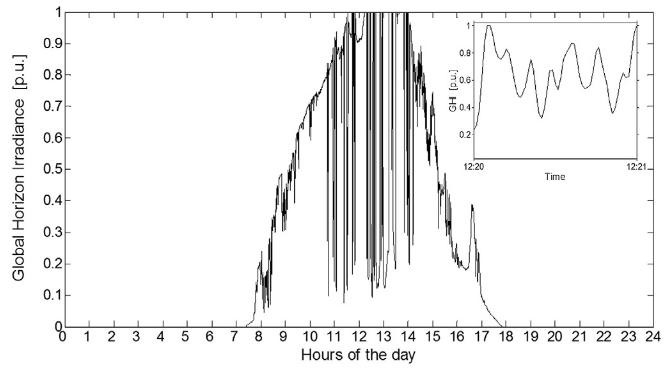

Fig. 1. Normalized global horizon irradiance over one day displaying the fluctuation due to clouds.

represents running 31.5 million chronological power flows for 10–120 h on conventional computers, depending on the complexity and size of the circuit, which is far too slow for PV interconnection impact studies. The computational burden associated with running QSTS simulation is one of the reasons why it has not been widely used by the industry. Reducing the computational time of the simulation will provide a new tool for system planners to perform accurate PV interconnection studies, allowing high penetrations of solar energy to be connected on the distribution system.

There are significant challenges in reducing the computational time of QSTS simulations (Deboever et al., 2017b). Namely, the size and complexity of the simulation can become especially challenging when considering the hysteresis within voltage-regulation controllers. However, it is extremely challenging to determine their state realistically with scenario-based analysis. Furthermore, it is challenging to model the interaction between controllers on a feeder without running a time series simulation. The daily operation of a load tap changer (LTC) regulating the voltage at the substation may be completely different based on the state of a capacitor bank on a feeder and their interaction can be challenging to accurately study without chronologically stepping through time. In this paper, we present a novel algorithm to speed up the QSTS simulations by taking advantage of the many similarities in power flow solutions in order to dramatically reduce the number of computed power flows. We demonstrate a vector quantization approach as a fast time-series approximation of the QSTS analysis that accurately models controllable elements on distribution feeders. The contribution of this work is in the formulation of an algorithm which: (i) drastically reduces the computational time of QSTS simulations, (ii) accurately models distribution system voltage-regulation controllable elements with hysteresis, and (iii) compresses time series data for memory management and efficient post-simulation analysis. The paper is structured as follow. A review of the literature and quantization theory are presented in Section 2. In Section 3, a vector quantization algorithm is proposed and its implementation is discussed. The simulation methodology is detailed in Section 4, and the algorithm is tested on a modified IEEE 13 test circuit with a large PV system in Section 5. The results are discussed in Section 6, and the impact of this work is addressed in the conclusion.

2. Background

2.1. Motivation for QSTS simulation

Time-series power flow simulations has been discussed in the literature for impact studies of PV (Baggu et al., 2014; Broderick et al., 2013; Mather, 2012; Nguyen et al., 2016; Quiroz et al., 2013; Smith et al., 2011), wind (Boehme et al., 2007), electrical vehicles (Aguero et al., 2012; Shao et al., 2013), and energy storage (Kleinberg et al., 2014). The common objective of these impact studies is to capture the effects of controller actions that would otherwise not be captured with steady state scenario-based simulations. The time horizon and time-step resolution of the QSTS simulation varies based on the type of analysis performed and the distributed energy resource (DER) studied. For example, an hourly resolution for energy impact analyses, minutes for steady-state overvoltage studies and seconds to minutes for voltage fluctuations is recommended in Smith et al. (2011). The need of high resolution (seconds) to study the impact of PV systems based on its high variability nature is described in Broderick et al. (2013). On the other hand, wind, EV and ESS impact studies listed above have a minutes-to-hour resolution due to the slower variations in power injections of wind farms and storage charging schedules. Accurate simulation of voltage violations or control actions requires that the time step between each static power flow is smaller than the minimum control delay and fast enough to resolve the fast power variation on the feeder (Paradis et al., 2013).

When studying the impact of solar PV, it is important to simulate the seasonal variations as well as the second to second power injection fluctuations in the feeder (Lave et al., 2015b). Large penetration of distributed or centralized PV introduces fast fluctuations of power flows (minutes to seconds) into the system based on changes in cloud speed and coverage. In order to capture these fast fluctuations, this paper uses the high-resolution (1-s) QSTS simulation and irradiance data. Fig. 1 illustrates a daily irradiance per unit profile, with an inset plot illustrating the fluctuation within 60 s. Feeders with high penetration levels can experience increased controller operations because of this type of fluctuations (Baran et al., 2012; Cohen et al., 2016; Nguyen et al., 2016).

2.2. Review of fast QSTS methods

A one-year simulation at one second granularity represents 31.5 million chronological power flows. The computational burden of this simulation limits the capability to rapidly simulate multiple PV sizes, locations or configurations onto a realistic feeder. A handful of publications specifically discussed shortening the QSTS analysis (López et al., 2015; Montenegro et al., 2015; Pagnetti and Delille, 2015; Pecenak et al., 2017) and computational time reduction can be achieved either by improving the speed of each power flow, or by reducing the number of power flows solved. As discussed in Deboever et al. (2017b), even if improvements are made to the iterative power flow solver, the simulation still requires to solve 31.5 million power flows. Thus, the work presented in this paper focuses on the reduction of the total number of power flow solved and does not change the speed of an individual power flow.

Reno et al. investigated reducing the resolution or length of the simulation as a mean to reduce the total number of computed power flows. The speed improvement was limited to ~80% by increasing the resolution of the simulation to 5 s but finer resolution was recommended because of the time delays in various controllers (Reno et al., 2017). Although time reduction is limited, simulation results showed that reducing the resolution provided better time reduction than reducing the time horizon of the simulation. Two other publications have investigated shortening QSTS simulations by reducing the number of computed power flows (López et al., 2015; Pagnetti and Delille, 2015). Non-uniform vector quantization of load profiles, PV profiles and slack voltage profile is investigated in López et al. (2015) to shortened time-series power flow simulation with time savings between 50% and 70% and accuracy of $R^2 = 0.97$ for power losses. Similarly, clustering of load and production profiles has been proposed in Pagnetti and Delille (2015) to reduce the number of load flow calculations. The reference discusses the integration of on-load tap-changers or storage but does not model them in the system and the voltage at the substation is modeled as a pre-determined time-series profile and not with discrete control algorithms. This omission does not allow the QSTS simulation to capture the operation of those controllable elements in response to the introduced DER on a feeder.

The novel vector quantization approach proposed in this paper