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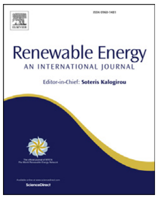

Assessing distribution network sensitivity to voltage rise and flicker under high penetration of behind-the-meter solar

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ABSTRACT

Behind-the-meter solar photovoltaics (PV) have the ability to impact the distribution system due to the significant fluctuations in energy production and potential reverse power flow. While these phenomena are well understood, this research will investigate the level of solar penetration at which voltage rise and flicker are observed on a real-world distribution network. Using solar power data measured at four second intervals from the Renewable Energy and Smart Grid Laboratory at Louisiana State University alongside detailed feeder data provided by a local utility, we investigate the impact of increasing levels of solar PV penetration on voltage rise and long-term flicker. Results suggest that feeders can handle up to 10% of customers installing 7-kW behind-the-meter solar systems before voltage rise and flicker are observed. For levels above 30% penetration, feeders experience significant power quality issues. We find that the safe penetration level of a specific feeder depends on the system's topology.

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1. Introduction

Behind-the-meter solar PV ("rooftop solar" of "solar PV") growth has been considerable in the United States over the past decade. As of 2017 there is estimated to be more than 15,000 MW of net metered solar capacity over more than 1.7 million rooftops across the country.[1] Much of this solar growth has been spurred by state and federal policies. As will be the focus of this analysis, Louisiana has had some of the more generous policy regimes for rooftop solar over the past decade.

In 2008, the Louisiana Legislature adopted a series of income tax incentives directly aimed at increasing rooftop solar: a 50% state income tax credit in addition to the 30% federal income tax credit; which on a combined basis and depending on a homeowner's tax situation, amounted to up to an 80% credit on all Louisiana solar installations less than \$25,000 in total value. In addition, solar customers also had access to full 1:1 retail net metering (hereafter referred to as "net metering"); that is, when solar production exceeds the household's load, the solar customers can push their power to the distribution grid and receive full retail rate. Average wholesale rates in Louisiana are about 2.5¢/kWh while retail rates are around 10¢/kWh. Thus, when a homeowner is at work during the day (using little power) and the solar irradiation is at high levels, they are able to in effect sell this excess power back to the grid at the full retail rate while a utility scale solar farm selling into the same market would receive the wholesale rate.[2] Given these policies, Louisiana experienced significant growth in rooftop solar. In 2008, Louisiana had essentially zero rooftop solar, but by the end of 2016, more than 140 MW of solar was installed on over 24,000 households [36].

Rooftop solar PV systems have the potential to provide a number of environmental and economic benefits in an electric power system. For instance, solar can abate the usage of fossil fuels avoiding environmental externalities associated with both localized air pollution[3] and CO_2 emissions that can impact global climate.[4]

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[1] EIA 861.

[2] This example is only illustrative. Wholesale rates vary by location and time. In addition, retail rates differ across utilities and typically have fixed and variable components.

[3] There is a vast literature identifying environmental externalities associated with localized air pollution. See Schlenker & Walker (2016), Knittel, Miller & Sanders (2016), Currie et al. (2014), Heutel & Ruhm (2016) for a few examples.

[4] See Tol (2014) for a synopsis of this literature.

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Rooftop solar can also create benefits for the electric grid itself. Because the generation is produced at the point of consumption, line losses associated with utility scale generation can be avoided. Further, if enough PV systems are installed, potentially the peak demand that needs to be met by the utility might decline therefore reducing the need for investments in the generation, transmission, and distribution networks. These economic benefits have been studied extensively [4,6,7,10,36]. Additionally, rooftop solar systems might impose costs on the electrical system. This paper will focus on two of the potential problems that might emerge in distribution feeders with high rooftop solar penetration; namely voltage rise and voltage flicker.

Voltage rise can occur when behind-the-meter solar generation pushes significant amounts of power back to the electric grid during relatively low demand time periods. Peak solar penetration occurs in the early afternoon in Louisiana (while varying over the time of year), whereas peak residential load occurs in the early evening when homeowners return home from work. This discrepancy of solar generation and demand creates the potential for voltage rise on the distribution grid. Specifically, voltage rise can occur when there is a reversed flow of power at the Point of Common Coupling (PCC) where the solar PV is connected to the grid. The excessive flow of current at the inverter's output causes an increase in voltage (a negative voltage drop between the inverter and PCC).

The second challenge considered in this analysis is the voltage flicker. Voltage flicker has to do with the variability of PV generation. Unlike other sources of energy, high levels of variability are inherent in PV because of no rotating mass (like a synchronous generator) and therefore no inertia exists in the electricity generating process. Therefore, any changes in the radiation and/or temperature will immediately impact power output. As a result, fast voltage variations during transient cloud cover can result in emergent flicker. For high solar penetration levels, this flicker can become visible creating changes in the brightness of lights. Incandescent lamps, for instance, exhibit particularly noticeable flicker. Voltage flicker is quantified based on the number and the magnitude of changes in the voltage over a specific period of time using IEEE 1453 Standard.

Voltage rise and flicker on the distribution grid are just two examples of challenges associated with incorporating intermittent renewable energy sources into a power system. While we will not provide an exhaustive review, we will broadly discuss where this research fits into this growing literature.

At the utility scale, large scale intermittent renewable integration can create challenges associated with unit commitment, economic dispatch, stability and reliability [1,14,39]. Significant investments in transmission have been made to allow for the incorporation of higher renewable penetration. For example, Texas' "Creating Renewable Energy Zones (CREZ)" transmission project was needed to incorporate the significant investment in utility scale wind generation; CREZ cost over $7 billion.[5] More broadly, twenty-nine states have passed mandates for renewable energy. States with these Renewable Portfolio Standards (RPSs) have been found to experience electricity price increases by approximately 10% relative to states with similar economic, political, and renewable energy potential [15,33,34] and the cost of these standards are estimated to be approximately twice as costly as the equivalent least-cost portfolio for achieving CO_2 reductions [40].

In addition, large numbers of intermittent power generation sources might reduce electricity production simultaneously when the weather changes, such as increases in cloud cover or localized precipitation [19]. Distributed solar installations may also dramatically increase electricity production on sunny days leading to excess power that is pushed onto a local electric distribution grid, potentially leading to undesirable overvoltage situations [23]. The mildest effect of these solar-induced power production surges includes voltage flicker and subtle power quality degradation [17]. More severe cases of excess and concentrated solar electricity production can include widerspread voltage instability and localized system collapse [32]. The power generated by solar energy can cause excessive reverse power flow that in turn interferes with the protective mechanisms and may cause overload or unexpected circuit disconnections and voltage instability [38].

At the bulk power system level renewable energy generation will offset power generation from conventional resources which, in turn, can lead to various thermal efficiency losses depending upon the marginal resource impacted by the incremental solar generation increase [5,30]. In addition, due to the solar generation intermittency, adequate power reserves are required to balance generation and demand and control system frequency. This can be a significant challenge for the grid when the renewable penetration is high [16].

The engineering literature largely has focused on theoretical systems, as analysis of real-world systems in the academic literature is more difficult to come by, likely for two reasons. First, obtaining data on either a distribution grid or transmission and generation grid can be challenging, as it requires an industry partner willing to share sensitive engineering data about their systems. Second, running load flow (and other) analysis on a real-world system increases the computational burden significantly due to both the size and layout of the systems. These real-world systems are not as "clean" as a theoretical system and, in our experience, modeling requires significant communication with the data provider with questions about the system.

In this analysis, a Louisiana distribution utility has provided specific data on three feeders within its distribution system including synthetic geographical coordination of buses, resistance (R), capacitance (C) and reactance (X) of all line segments along with the phase configuration for all distribution lines, conductor types, and nameplates of active and reactive powers of all nodes. Additionally, 15-min load profiles for each of these feeders was provided. This is the first analysis of which we are aware that tests for voltage rise and flicker in real-world distribution systems.

So, while many of the engineering challenges addressed in this research have been studied on theoretical feeders [2,12,20,23,37], the specific level of solar penetration that is needed on a distribution grid before significant problems begin to arise is needed. While running a theoretical model on a theoretical system is good for identifying areas of concern for utilities, these analyses are unlikely to yield results that are useful for making specific planning decisions for a specific part of a utility's grid. Furthermore, the threshold at which problems might begin to arise will likely vary from area to area even within the same geographic region and utility. Thus, it is not clear that a "one size fits all" approach that sets some specific limits on the solar penetration will be sufficient to achieve acceptable power quality in distribution feeders. For this reason, there is great opportunity for analyses of voltage rise, flicker, and potentially other engineering concerns associated with increased behind the meter PV penetration on actual distribution systems. Such analysis will be important for policy makers looking to guide policies aimed at increasing rooftop grid solar. This analysis aims to contribute to this effort.

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[5] Texas is the leader in wind penetration with more than 21,000 MW of installed capacity.

Table 1
Nine clusters of representative days for yearly power flow analysis.

	Net Load with Solar Categories								
	High Load			Medium Load			Low Load		
Variability	High	Medium	Low	High	Medium	Low	High	Medium	Low
January	3	2	11	1	2	5	0	1	2
February	3	3	3	2	1	7	3	2	5
March	0	0	0	3	1	2	10	6	8
April	0	0	0	5	1	0	8	8	8
May	2	1	0	6	6	0	6	3	0
June	10	10	0	3	5	1	0	1	0
July	12	14	4	0	0	1	0	0	0
August	9	3	4	5	5	5	0	0	0
September	6	8	2	1	8	3	1	1	0
October	0	0	0	2	7	9	4	4	5
November	0	0	2	2	1	1	8	8	8
December	0	2	5	4	4	6	4	4	2
Total	45	43	31	34	41	40	44	38	38

Note: Categories are based on load and variability of changes in solar. Load is simply defined as the sum of total MWhs consumed in the feeder over the day. Variability of changes in solar is based on the difference in solar penetration in time *t* and *t*-1. The standard deviation of the change between 4-s intervals is used. “High”, “medium” and “Low” are based on the 33rd and 66th percentile of each respective metric.

The second contribution of the current analysis is the granular four second (4-s) time resolution. Using more granular time durations can be important when studying power quality factors, in particular, voltage flicker that occurs in a matter of seconds [13]. The temporal resolution in prior analysis has varied from a few seconds to one-hour intervals; however, one-hour time interval data is becoming more prevalent due to detailed spatial data [24], while obtaining second-to-second variation in solar generation is less common. Several important analyses, though, have shown that this time granularity is important for understanding the real-world implications of growing intermittent renewable energy sources on the electric grid. Cao & Sirén [26] utilize energy matching indices and compare results from simulations with time resolutions ranging from 1-minute to 1-hour. Considerable differences in results are observed with 1-hour resolution compared to 1-minute resolution. While the importance has been documented, though, lack of available data and computation burdens have made this level of granularity difficult to incorporate in many analyses. Related, Beck et al. [3] examine the impact of the time resolution on self-consumption and battery sizing by changing the time step size from 10-seconds to 15-minutes. Related to this analysis, Ferdowsi, Mehraeen, & Upton [36] also examine the sensitivity on one of the distribution grids in this analysis to voltage rise and flicker observed with ten (10) different time steps ranging from a few seconds to several minutes. Results show that flicker measurement within the network is highly sensitive to the time resolution of analysis. This can have implications for the economics of systems [28] depending on a local utility’s rate design for distributed solar customers.

This study quantifies the level of solar penetration on three real-world distribution feeders where voltage rise and flicker exceed acceptable levels set by ANSI–C84.1 standard (voltage) and IEC–61000-4-15 standard (flicker). While voltage rise and flicker have been studied, generally, we contribute to this literature in two main ways. First, we consider three real-world distribution feeders all powered by the same utility company and in the same geographic region to show the potential differences in the safe penetration level before power quality issues emerge. Second, we consider a 4-s time-granularity typically not considered in other analyses. Specifically, we model three 24.9 kV distribution feeders owned and operated by the Southwestern Electric Power Company (SWEPCO). SWEPCO is located in northwestern Louisiana and serves about 225,000 customers in 13 parishes and is owned by American Electric Power (AEP), one of the largest public utilities in the United States. For these three sample feeders the steady-state voltage and the long-term flicker are considered. We provide specific estimates of the level of penetration that power quality might start to decline due to rooftop solar. In Section 2, solar generation measurement and load data are discussed, the configuration of the feeder is analyzed and an OpenDSS model is described. The results are discussed in Section 3 for different penetration levels of rooftop solar. The conclusion is presented in Section 4.

2. Methodology

2.1. Data

Data on solar generation comes from the Renewable Energy and Smart Grid Laboratory at Louisiana State University (30°24′38.2″N 91°10′49.5″W). The solar panel is installed on the Electrical Engineering building’s roof on LSU’s campus in Bton Rouge, Louisiana. The solar panel records the voltage each time a change occurs, with a minimum time between observations being four seconds. For instance, in the middle of the night (with no solar production), data will not be recorded for hours. But during the day, there will often be an observation every four seconds. We aggregate this data into 21,600 four second intervals throughout a day. We scale the size of our solar panel (which is a 140 W system) to a 7-kW unit, a typical size for a residential system.

Next, we merge solar generation with a residential load profile. The utility provided 15-minute load data for a one-year period for the distribution feeders being considered. We linearly extrapolated residential load to 4-s intervals. We then scaled this feeder level load data to the size of a typical household based on the average kWhs of usage for a residential customer in Louisiana.[6]

We then match the 4-s interval solar generation data with the linearly extrapolated load data.[7] The result is linearly extrapolated load data matched with the 4-s solar generation data for a

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[6] According to EIA, the average Louisiana resident consumes 15,435 kWhs of electricity per year. (U.S. Energy Information Administration).

[7] Specifically, we scale the total load by the number of nodes on the system to get the average household load.

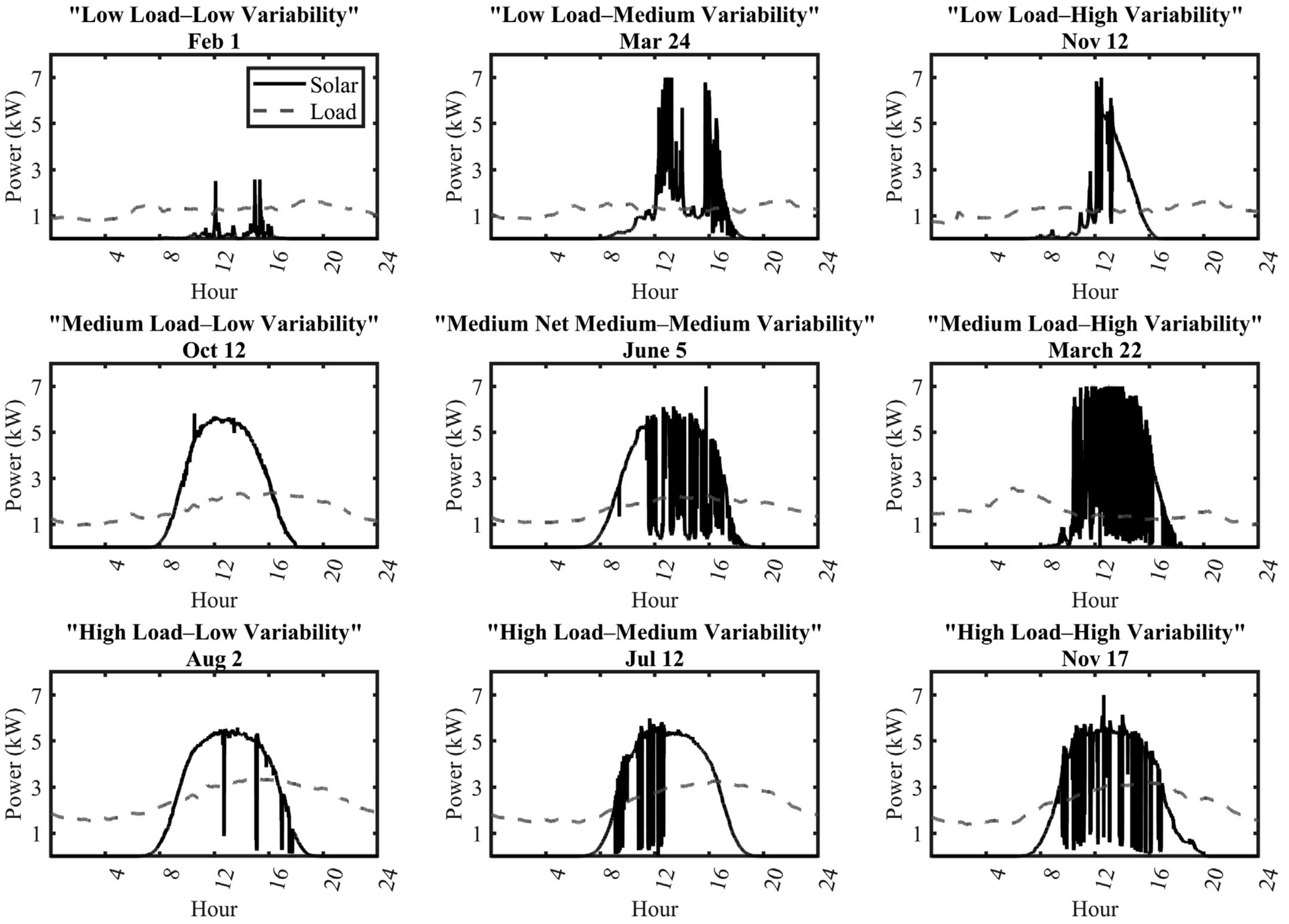

Fig. 1. Solar patterns along with load profiles corresponding to nine representative cluster.

representative household with a behind-the-meter solar system.[8]

2.2. Representative days for load flow analysis

Next, we choose a representative sample of days for analysis. Due to computation burden, it is not feasible to run the load flow analysis for all 365 days of the year. Therefore, we categorize each day of the year based on the (a) load and (b) variability of solar production.

For load, we sum the total kWhs of electricity consumed for the residential load profile provided by the utility. We then calculate the 33.3rd and 66.6th percentile days by total kWhs consumed and categorize each day into “high”, “medium”, or “low”. For variability, we subtract the solar generation from the four second interval solar data between each time step, $\Delta s_t = s_t - s_{t-1}$, where s_t is the solar power (W) in time t. We take the standard deviation of Δs_t and again categorize each day into “high”, “medium”, or “low” variability based on the 33.3rd and 66.6th percentile day. Using a random number generator, we randomly choose one day from each of the nine categories as a representative day to run power flow analysis. The categories and the number of days by month in each category are listed in Table 1.[9]The load profiles and solar generation for these representative days are shown in Fig. 1

2.3. Feeder modeling

Three 24.9 kV distribution feeders that are currently in operation today are used for analysis. Data on the feeders’ load profiles along with lines, transformers and the nameplate of active and reactive power of nodes are loaded into OpenDSS.[10] OpenDSS is an

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[8] We should note that this method will create two sources of potential bias to our variability of net load (i.e. household load less solar production). On one hand, scaling up data from a 140 W research rooftop solar panel to a 7 kW system might overestimate the variability of the solar production data. For instance, a cloud might pass over just a part of the panel or move across the panel over the course of several seconds mitigating the variability. We have corroborated that utility scale systems might have less variability from second to second due to this aggregation. Further, larger utility scale systems have lower second to second variability than smaller utility scale systems. On the other hand, though, we smooth the load data considerably as we only have the load for the entire feeder on a 15-min interval—not each house. Thus, the variability is underrepresented due to two reasons. First, actual variability from house to house will be more than the aggregate of all houses on the feeder. Second, linearly extrapolating this 15-min load into 4-s intervals further smooths this data. We are unable to comment on the net effect of these two sources of bias.

[9] It should be noted that days of year do not add up to 365 because some days of solar generation data contained error and were therefore purged from the data. Some days technical errors occurred in the lab due to the computer freezing up, a student unhooking the panel accidentally, etc. In total we have sufficient data on 354 days of the year, thus are missing just 11 days associated with data issues.

[10] The utility used a commercial software application for their load flow modeling, but this software did not allow us to run sequential 4-s interval analysis needed for the flicker analysis in particular. For this reason, we ran the load flows in the commercial software that the company commonly uses and corroborated these results with results from OpenDSS to ensure consistency across models.

Table 2
Feeders summary statistics.

Feeder	Nodes (Counts)	Load Bus (Counts)			Power Delivery Lines (Counts)
		1-phase	2-phase	3-phase	
Feeder A	2,776	576	9	10	2,793
Feeder B	2,484	806	12	10	2,503
Feeder C	1,663	381	5	98	1,669

open-source program produced by the Electric Power Research Institute (EPRI) with the capability of simulating unbalanced and single-phase networks. OpenDSS performs distribution system load flow analysis by employing the fixed-point iteration technique which is a special case of Newton's method. OpenDSS forms the Y-bus matrix of the network using the primitive Y matrices of power delivery components (lines and transformers). The primitive Y matrix of a power delivery line is described in equation (1). Parameters R, X and B are resistance, reactance and susceptance of the segment between bus i and bus i'. Loads are modeled by a shunt current source along with the primitive Y-bus matrix while the Norton equivalent of voltage sources (generators) is taken into the power flow model. Therefore, equation (2) can be formed using the primitive Y matrices, equivalent current sources and voltage at all buses. Finally, currents can be replaced by powers (either load or generation) given in equations (4) and (5) using equation (3). Equations (4) and (5) represent the active and reactive power balance at each node. P_i and Q_i are the algebraic summation of the active and reactive powers injected to nodes i and i'. θ_i and θ_j represent the voltage angles measured at bus i and bus j while the θ_{ij} is the angle of phasor Y_{ij} in the network's Y-bus matrix.

$$\begin{bmatrix} I_i \\ I_i' \end{bmatrix} = \begin{bmatrix} \dfrac{1}{R+jX}+jB & -\dfrac{1}{R+jX} \\ -\dfrac{1}{R+jX} & \dfrac{1}{R+jX}+jB \end{bmatrix} \begin{bmatrix} V_i \\ V_i' \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_n \end{bmatrix} = \begin{bmatrix} Y_{ii} & \cdots & Y_{in} \\ \vdots & \ddots & \vdots \\ Y_{ni} & \cdots & Y_{nn} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_n \end{bmatrix} \tag{2}$$

$$I_i = \frac{P_i - Q_i}{V_i^*} \tag{3}$$

$$P_i = |V_i| \sum_{j=1}^{n} |Y_{ij}||V_j| \cos(\theta_i - \theta_j - \theta_{ij}) \tag{4}$$

$$Q_i = |V_i| \sum_{j=1}^{n} |Y_{ij}||V_j| \sin(\theta_i - \theta_j - \theta_{ij}) \tag{5}$$

We link OpenDSS with MATLAB to simulate distribution networks with fluctuating load and solar penetration. The open-source property of OpenDSS allows for utilizing the program into the target study in conjunction with the solar and load time series data. The Flowchart shown in Appendix Figure A–1 depicts the interaction between the OpenDSS and MATLAB. The FW vector shown in the algorithm is the Flicker Window in which values are updated at each iteration; however, the length of the window remains unchanged as the long-term flicker (P_{lt}) is calculated over a 2-hour period. TS represents the time-step; 4-s in this analysis. Summary statitics on feeders analyzed are shown in Table 2 and the topology of each radial feeder is depicted in Fig. 2.

For purposes of this analysis, we will define "solar penetration" as the percentage of load buses with a 7kW rooftop solar system. For instance, for a feeder with 500 load buses, 10% penetration means that 50 of these load buses contain rooftop solar. For each simulation, we randomly assign the solar to load buses.[11]

To investigate the impact of solar on the network operation, the power flow program is run for each 4-s interval to acquire the time series of voltages at all buses in the network. This allows for the steady-state voltage to be monitored as soon as the power flow calculation is completed for each interval. In order to obtain flicker, voltage data is stored in an array that is imported to the flicker computation unit which calculates the long-term flicker (Plt) every 120 minutes based on the IEEE standard#1453 (adopted from IEC#61000-15-4) [22].[12] According to the standard, the long-term flicker (P_{lt}) is calculated based on the short-term flicker (P_{st}). Short-term flicker of 1 represents a point at which 50% of people are irritated by the flicker. P_{lt} is defined as the irritations over a long period of time caused by irregular flicker. The short-term and long-term perceptibility of flicker are quantified in equations (6)–(8) where P_x, is the flicker exceeded for x% of the observation period. P_{lt}, is calculated based on 12 P_{st} readings over a two hour period as shown in equation (8) .

$$P_{st} = \sqrt{0.0314P_{0.1} + 0.0525P_{1s} + 0.0657P_{3s} + 0.28P_{10s} + 0.08P_{50s}} \tag{6}$$

$$\begin{cases} P_{1s} = \dfrac{P_{0.7} + P_1 + P_{1.3}}{3} \\ P_{3s} = \dfrac{P_{2.2} + P_3 + P_4}{3} \\ P_{10s} = \dfrac{P_6 + P_8 + P_{10} + P_{13} + P_{17}}{5} \\ P_{50s} = \dfrac{P_{30} + P_{50} + P_{80}}{3} \end{cases} \tag{7}$$

$$P_{lt} = \sqrt[3]{\frac{\sum_{i=1}^{12} {P_{st}}_i^3}{12}} \tag{8}$$

The flowchart in Fig. 3 shows a step-by-step layout of the simulations. *Pen*, *j*, *i*, and *F* represent (1) thesolar penetration level, (2) the number assigned to each representative day, (3) the sample number and (4) the long-term flicker time factor respectively. Penetration begins with 10% and it increases by 10% to 100%. The

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[11] In real-world systems, there is likely special correlation between solar installations. Spatial clustering will likely exacerbate voltage rise and flicker, thus, this is likely a conservative approach. Although, future research might investigate the importance of considering spatial clustering.

[12] We consider long-term flicker (in lieu of short-term flicker) as this is the relevant power quality issue in this context. For instance, short-term flicker is mostly used for product standardization Spring (2013) where the fluctuation of voltage is monitored in 10-min time windows.

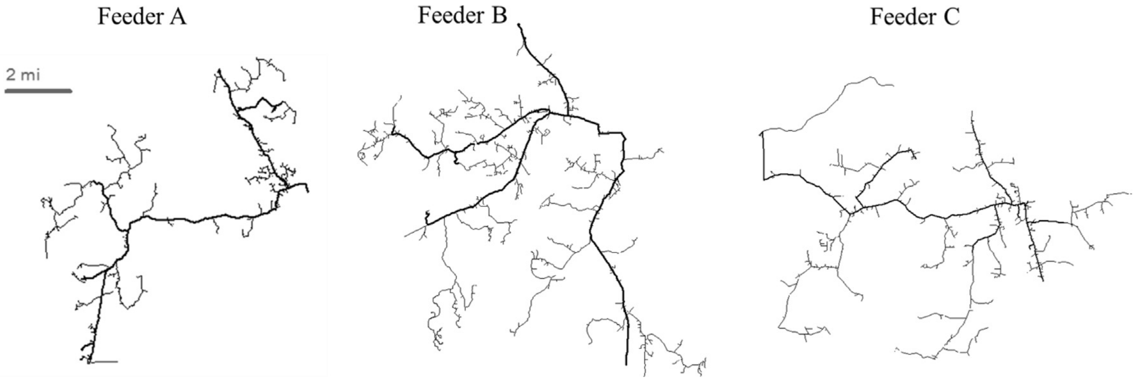

Fig. 2. Layout of radial distribution systems powered by SWEPCO.

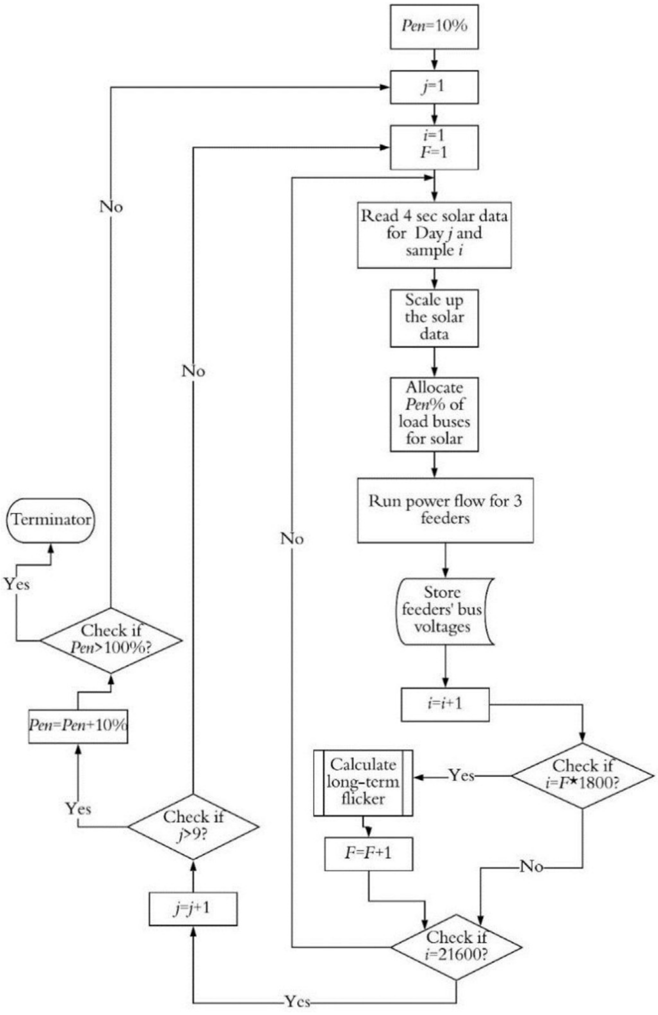

Fig. 3. Voltage rise and high flicker detection algorithm for nine representative days and three feeders.

number assigned to each day starts from 1 representing the first representative day and increases until it reaches 9 which means the last representative day. The sample number starts from 1 and ends with 21,600 covering one day considering the sampling rate of 4-sec. The variable *F* represents the timing horizon factor over which the long-term flicker is calculated which is 2 hours. The flowchart runs the power flow for all three feeders considered for 9 representative days and 10 different solar penetration levels. The flicker computation unit and the interaction between MATLAB and OpenDSS is shown in the appendix.

Finally, we run the load flow (make a consistent selection load flow or power flow) analysis on the nine representative days of the year at 10 different levels of penetration, varying from 10% to 100%. Combined, we run the load flow analysis for 90 scenarios across 21,600 four-second intervals. We store the long-term flicker at a sample bus alongside the resultant voltage (from the load flow solution) across all nodes and all phases.[13]

3. Results and discussion

The results for voltage rise and flicker are presented in Tables 3 to 5 corresponding to feeders A, B and C respectively.

The first row at each penetration level indicates the percent of voltage readings outside of the ANSI standard (+- 5%) for all buses over a 24-hour period (21,600 samples). Voltage violation is considered as voltage rise indicating poor power quality. The second row represents the maximum long-term flicker (Plt) observed at the sample bus. In different sets of literature, different limits on Plt are recommended for power distribution systems that vary from 0.25 to 0.7 depending on the feeder voltage level and the utility's conservativeness [11,22,25]. In this study, the high flicker threshold is assumed to be 0.5 which is near the middle of the upper and lower limits found in different technical reports.

Two results are notable. First, we detect no occurrences of voltage rise or flicker exceeding permissible ranges for the 10 to 20% penetration levels. This is good news, suggesting that low levels of penetration are unlikely to cause significant distribution grid reliability issues. On the other hand, these results suggest that if an area pursues the goal of achieving a significant share of the state's electricity being met by behind-the-meter solar PV, specific feeders will certainly need to exceed these thresholds.

Second, these results verify that these problems arise primarily on days of higher solar variability. On days of low variability, we do not expect significant problems with flicker outside of the permissible range, and estimate that voltage rise will not occur until penetration levels above 60% are reached in Feeders A and B. Results are also presented in Fig. 4 and Fig. 5 for voltage rise and flicker and correspond directly to numbers presented in Table 3. The voltage rise and flicker corresponding to Table 4 and Table 5

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[13] OpenDSS does not have the ability to monitor voltage flicker at all nodes unless monitors are manually defined for every single node but does have the ability to monitor voltage level at each node bus. For this reason, flicker is calculated at samples nodes.

Table 3
Flicker and voltage rise for different solar penetrations and clusters, Feeder A.

Penetration Level	Power Quality Parameters	Low Load			Medium Load			High Load		
					Variability					
		Low	Medium	High	Low	Medium	High	Low	Medium	High
10%	Voltage Rise	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Flicker	0.02	0.01	0.02	0.16	0.01	0.18	0.03	0.08	0.02
20%	Voltage Rise	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Flicker	0.02	0.07	0.09	0.16	0.07	0.4	0.03	0.08	0.09
30%	Voltage Rise	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Flicker	0.02	0.15	0.2	0.16	0.16	0.61	0.03	0.14	0.19
40%	Voltage Rise	0%	0.57%	0.44%	0%	0%	3.04%	0%	0%	0%
	Flicker	0.03	0.25	0.33	0.16	0.26	0.77	0.03	0.22	0.31
50%	Voltage Rise	0%	2.04%	2.74%	0%	0%	12.72%	0%	0%	0%
	Flicker	0.05	0.37	0.47	0.16	0.39	0.98	0.05	0.34	0.45
60%	Voltage Rise	0%	3.16%	6.65%	0%	0%	20.72%	0%	0%	0%
	Flicker	0.06	0.46	0.58	0.16	0.49	1.04	0.06	0.43	0.56
70%	Voltage Rise	0%	4.88%	12.55%	2.69%	2.27%	24.62%	0%	0%	0%
	Flicker	0.11	0.77	0.93	0.16	0.79	1.32	0.11	0.74	0.9
80%	Voltage Rise	0%	6.93%	16.70%	4.93%	3.88%	27.09%	0%	0%	0%
	Flicker	0.13	0.87	1.06	0.16	0.89	1.41	0.13	0.85	1.02
90%	Voltage Rise	0%	8.74%	18.78%	20.09%	15.48%	29.88%	0%	0.05%	0.01%
	Flicker	0.19	1.22	1.51	0.16	1.23	1.68	0.18	1.23	1.38
100%	Voltage Rise	0.01%	10.51%	20.81%	29.62%	23.39%	31.98%	0.29%	2.26%	1.66%
	Flicker	0.19	1.24	1.52	0.16	1.21	1.69	0.18	1.23	1.31

Note: Voltage rise shows the percent of voltage readings outside of the ANSI standard. Flicker is shown as the per-unit flicker voltage where one per-unit is noticeable and annoying light flicker perceived by 50% of the human population. PV penetration level defined as the percent of nodes within the feeder that have a 7-kW behind-the-meter solar system. The solar penetration level is based on the number of load buses. For instance, in a feeder with 500 households, the penetration of 20% means 100 households have installed rooftop solar PV.

Table 4
Flicker and voltage rise for different solar penetrations and clusters, Feeder B.

Penetration Level	Power Quality Parameters	Low Load			Medium Load			High Load		
					Variability					
		Low	Medium	High	Low	Medium	High	Low	Medium	High
10%	Voltage Rise	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Flicker	0.02	0.03	0.04	0.19	0.04	0.28	0.04	0.09	0.04
20%	Voltage Rise	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Flicker	0.02	0.12	0.16	0.19	0.15	0.55	0.04	0.14	0.2
30%	Voltage Rise	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Flicker	0.03	0.26	0.32	0.19	0.3	0.78	0.04	0.29	0.39
40%	Voltage Rise	0%	0.84%	0.67%	0%	0%	4.61%	0%	0%	0%
	Flicker	0.06	0.43	0.52	0.19	0.51	1.01	0.06	0.52	0.61
50%	Voltage Rise	0%	2.91%	3.64%	0%	0%	20.14%	0%	0%	0%
	Flicker	0.08	0.52	0.63	0.19	0.61	1.1	0.08	0.63	0.7
60%	Voltage Rise	0%	4.55%	10.12%	0%	0%	22.55%	0%	0%	0%
	Flicker	0.15	0.87	0.96	0.19	0.97	1.39	0.17	1.11	1.04
70%	Voltage Rise	0%	6.38%	16.99%	1.41%	0.75%	28.32%	0%	0%	0%
	Flicker	0.16	0.91	1	0.19	1.03	1.43	0.19	1.21	1.06
80%	Voltage Rise	0%	8.93%	20.36%	14.90%	12.18%	31.71%	0%	0%	0%
	Flicker	0.16	0.91	1	0.19	1.03	1.43	0.19	1.21	1.06
90%	Voltage Rise	0%	10.92%	22.49%	30.45%	23.84%	34.46%	0%	0.23%	0.03%
	Flicker	0.21	1.12	1.21	0.19	1.21	1.57	0.26	1.5	1.18
100%	Voltage Rise	0.01%	12.51%	23.73%	40.95%	31.76%	36.18%	0.00%	1.03%	0.23%
	Flicker	0.27	1.34	1.38	0.19	1.36	1.68	0.32	1.83	1.12

Note: Voltage rise shows the percent of voltage readings outside of the ANSI standard. Flicker is shown as the per-unit flicker voltage where one per-unit is noticeable and annoying light flicker perceived by 50% of the human population. PV penetration level defined as the percent of nodes within the feeder that have a 7-kW behind-the-meter solar system. The solar penetration level is based on the number of load buses. For instance, in a feeder with 500 households, the penetration of 20% means 100 households have installed rooftop solar PV.

Table 5
Flicker and voltage rise for different solar penetrations and clusters, Feeder C.

Penetration Level	Power Quality Parameters	Low Load			Medium Load			High Load		
		Variability								
		Low	Medium	High	Low	Medium	High	Low	Medium	High
10%	Voltage Rise	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Flicker	0	0.01	0.02	0.03	0.01	0.17	0.01	0.01	0.01
20%	Voltage Rise	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Flicker	0	0.03	0.04	0.03	0.03	0.27	0.01	0.02	0.04
30%	Voltage Rise	0%	2%	2%	0%	0%	10%	0%	0%	0%
	Flicker	0.01	0.08	0.1	0.03	0.08	0.42	0.01	0.06	0.09
40%	Voltage Rise	0%	4.50%	11.79%	0%	0%	25.26%	0%	0%	0%
	Flicker	0.01	0.1	0.13	0.03	0.1	0.48	0.01	0.08	0.12
50%	Voltage Rise	0%	7.50%	18.63%	9%	7%	29.89%	0%	0%	0%
	Flicker	0.03	0.25	0.32	0.03	0.24	0.76	0.03	0.22	0.28
60%	Voltage Rise	0%	10.35%	21.95%	32%	25%	33.87%	0%	0%	0%
	Flicker	0.04	0.31	0.4	0.03	0.3	0.85	0.03	0.27	0.34
70%	Voltage Rise	0%	14.15%	24.77%	45.54%	35.08%	37.25%	8%	14%	14%
	Flicker	0.03	0.25	0.33	0.03	0.25	0.77	0.03	0.22	0.29
80%	Voltage Rise	0%	17.55%	27.25%	54.64%	43.22%	40.10%	17%	28%	26%
	Flicker	0.05	0.34	0.44	0.03	0.33	0.9	0.04	0.3	0.37
90%	Voltage Rise	0%	20.98%	29.24%	59.17%	47.07%	42.31%	35%	44.74%	42.92%
	Flicker	0.08	0.61	0.77	0.03	0.57	1.19	0.07	0.52	0.57
100%	Voltage Rise	0.18%	23.90%	30.48%	62.95%	50.37%	43.95%	49.31%	54.12%	51.67%
	Flicker	0.11	0.83	1.05	0.03	0.75	1.38	0.1	0.68	0.72

Note: Voltage rise shows the percent of voltage readings outside of the ANSI standard. Flicker is shown as the per-unit flicker voltage where one per-unit is noticeable and annoying light flicker perceived by 50% of the human population. PV penetration level defined as the percent of nodes within the feeder that have a 7-kW behind-the-meter solar system. The solar penetration level is based on the number of load buses. For instance, in a feeder with 500 households, the penetration of 20% means 100 households have installed rooftop solar PV.

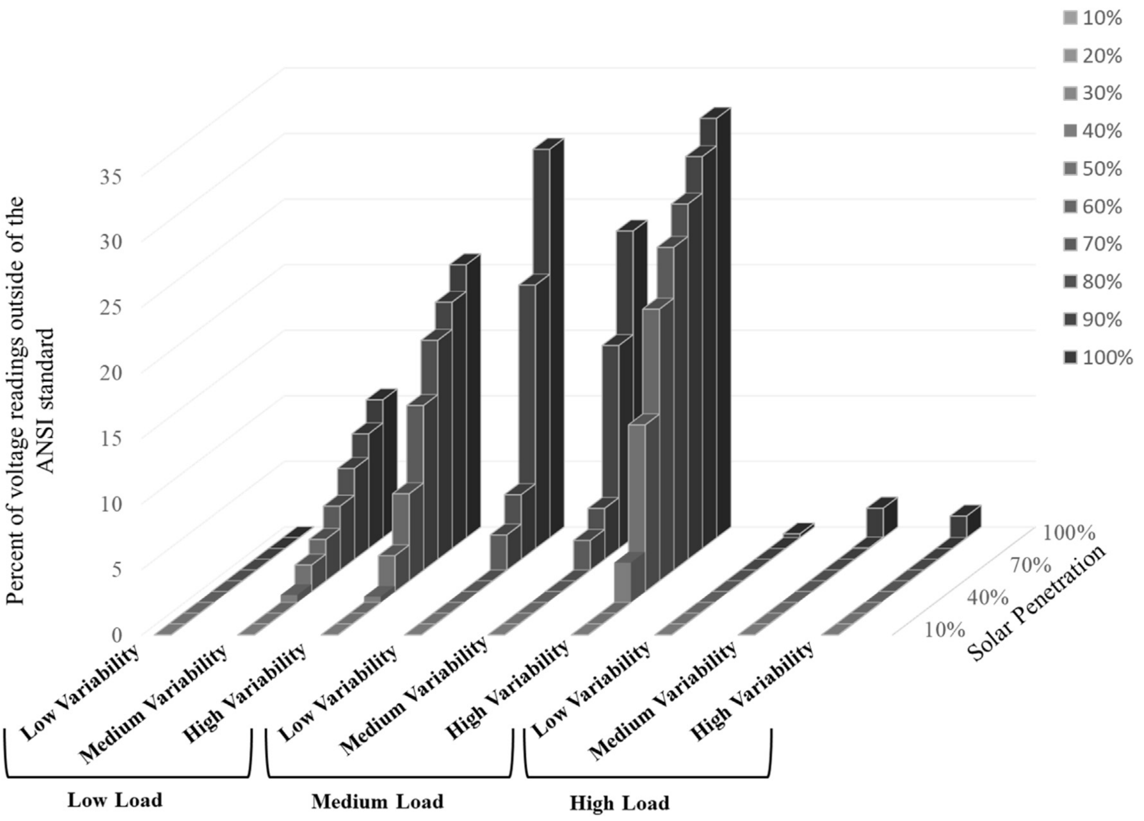

Fig. 4. Percent of voltage violations, Feeder A.

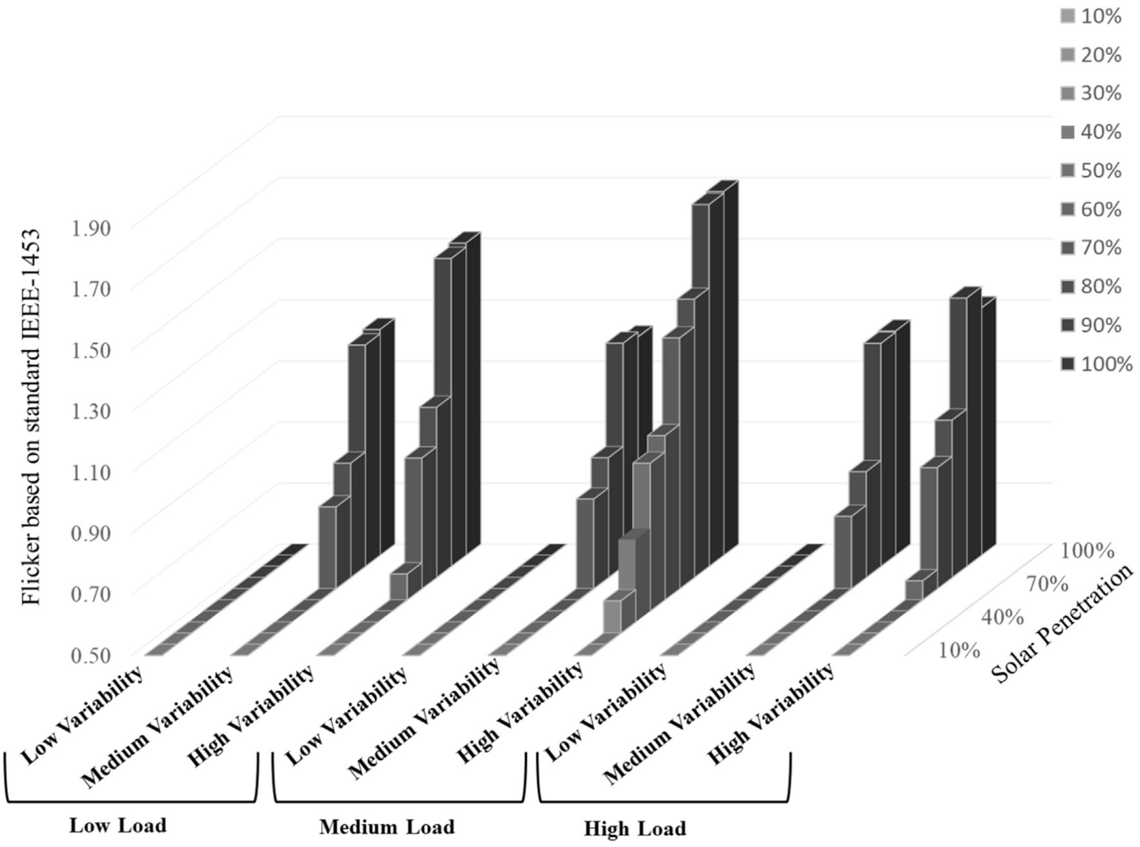

Fig. 5. Maximum long-term flicker at a sample bus.

are presented in Figure Figs A– 2 to A– 5 in the appendix. Feeder B experiences flicker between 10 and 20% penetration levels on days with low load and high variability. Voltage rise does not begin to be detected until penetration levels between 30 and 40%. After the 40% threshold is met, the distribution grid experiences significant occurrences of voltage rise and flicker in six of the nine categories of load and variability. For Feeder C, voltage rise begins between 20 and 30% and begins on days of high variability and medium load. But on Feeder C, we do not begin to see problems associated with flicker until between 40 and 50% penetration. The impact of solar power on distribution feederslikely depends on the network's topology (i.e. radial, parallel, ring main and meshed), level of interconnectivity within the grid and the length of the feeder. For instance, for long feeders with residential loads at the end of the feeder voltage rise is not expected even at high solar penetrations due to the severe voltage drop in power delivery lines.

3.1. Vulnerability maps

It is important for utilities to detect vulnerable areas in a specific feeder when solar penetration increases. Vulnerable areas generally refer to buses which are more prone to power quality issues such as voltage rise, flicker and frequency distortion because of high penetration of solar within a feeder. Feeder vulnerability analysis helps electric power utilities to plan solar installations and the level of penetration more efficiently to avoid power quality issues. This becomes more important when there are some sensitive loads such as high-tech devices powered by a feeder. In this study, vulnerability maps for Feeder A are derived from the steady-state voltages in all nodes within Feeder A shown in Fig. 6. The intensity of the problem corresponds to the darkness of the feeder nodes in the figure.

4. Discussion and policy considerations

There are a few important policy implications associated with these results. First, we begin to see problems between these three feeders at levels exceeding 20% penetration. For one feeder, we observe problems between 10 and 20% penetration. As previously mentioned, penetration in this analysis is defined as the percentage of households that have installed a 7-kW behind-the-meter solar system on a feeder. Second, problems begin to arise, especially for flicker, on days of high variability, where problems with voltage rise primarily begin to arise on days of lower load. Third, different feeders see different problems. In particular, Feeders A and B in this analysis became susceptible to flicker problems before voltage rise. On the other hand, Feeder C became susceptible to voltage rise problems at relatively lower levels of penetration, while flicker problems were not observed until significantly higher penetration levels. For this reason, in the event that utilities do make distribution grid upgrades to accommodate higher levels of solar growth, the types of problems being mitigated, and therefore the type of investments needed, might vary. Thus, it is unlikely that a "one size fits all" approach will be sufficient for mitigating these problems. Special attention will need to be paid to the specifics of the feeder.

There are broadly two policy implications of this result. First, states with relatively small shares of households with rooftop solar are unlikely to experience wide-spread problems of voltage rise and flicker on their distribution grids. But, if these solar

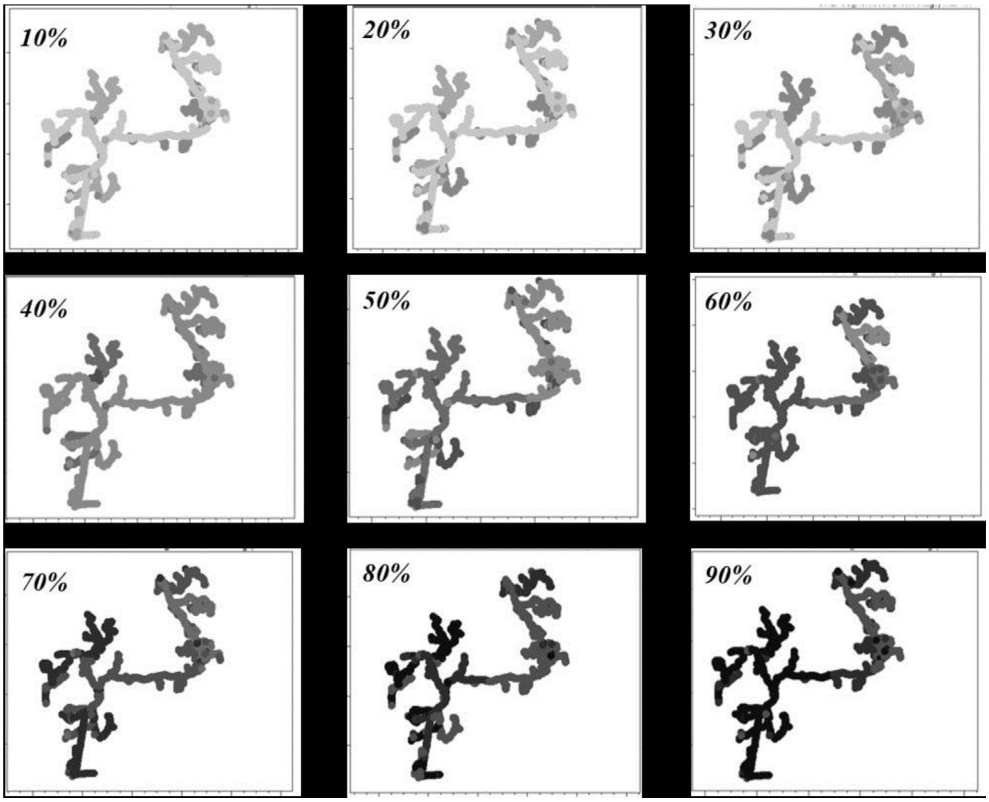

Fig. 6. Vulnerability map for feeder A.

installations are spatially concentrated, then it might be that specific feeders require investments in distribution grid upgrades to mitigate problems. But we recommend these localized issues should be investigated specifically. In addition, the study relies on the network physical properties and thus it may not be extended to feeders with different loading or topology. That is, individual studies are required for each circuit.

The second policy implication has to do with the types of investments that should be made. For two of the feeders considered, we see problems with voltage flicker before rise. While for the third feeder, we observe the opposite, where problems with voltage rise before flicker. Thus, the types of investments needed to mitigate the issues might depend on the feeder itself. Policy makers might take the granularity of this result into account when investing in distribution grid upgrades. Simply put, as penetration increases, the types of investment might differ from feeder to feeder as well.

This analysis also has potential policy implications for behind-the-meter batteries. If policies are set appropriately such that batteries are incorporated into rooftop solar, these batteries might shield the distribution grid from second-to-second variability and smooth the dispatch in a way that voltage rise problems are mitigated by dispatching batteries at high demand time periods. Thus, policy makers might be able to set policies that incentivize batteries to mitigate these issues through appropriate rate design policies.

5. Conclusions

This research investigates the impact of rooftop solar systems on power distribution networks. Three real-world 24.9 kV feeders are modeled using OpenDSS and MATLAB. We find that two of the three feeders begin to experience violations of voltage level or flicker between twenty and thirty percent penetration; however, one feeder begins to experience violations between ten and twenty percent. There is no standard way to predict the safe level of solar penetration for distribution systems and individual systems must be studied for this purpose. The safe penetration level depends on the feeder topology, load profile and solar/cloud patterns during the day. The maximum permissible share of solar is identified as the point where the voltage rise and/or flicker issues begin to arise. It is shown that this threshold depends on the topology of the feeder even for the same penetration level and the same weather condition. Therefore, the maximum permissible share of solar cannot be generalized for different distribution feeders unless a conservative threshold is considered. It is recommended that individual feeders be investigated for possible problems before high penetration of solar power is allowed. Granular data is also essential in determining the safe penetration level of solar power because fast dynamics in the solar profile producing flicker can be taken into account.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Technical Appendix

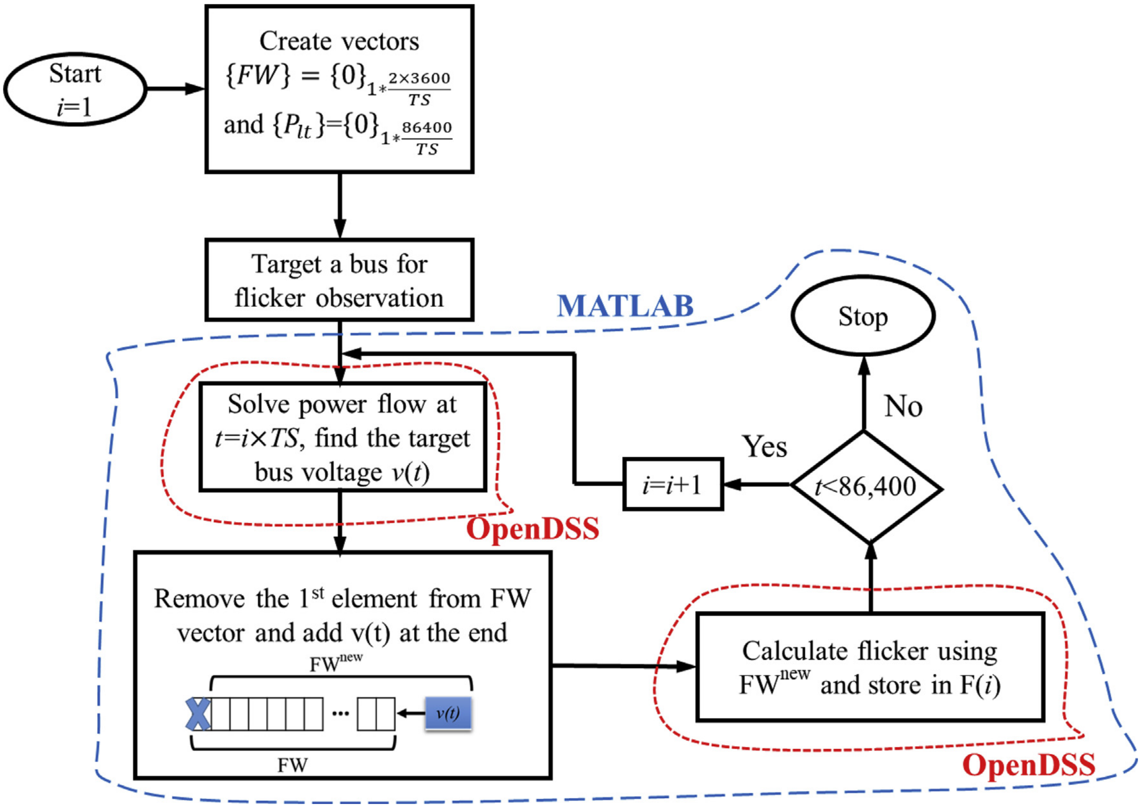

Fig. A1. OpenDSS and MATLAB interconnection for calculating the flicker.

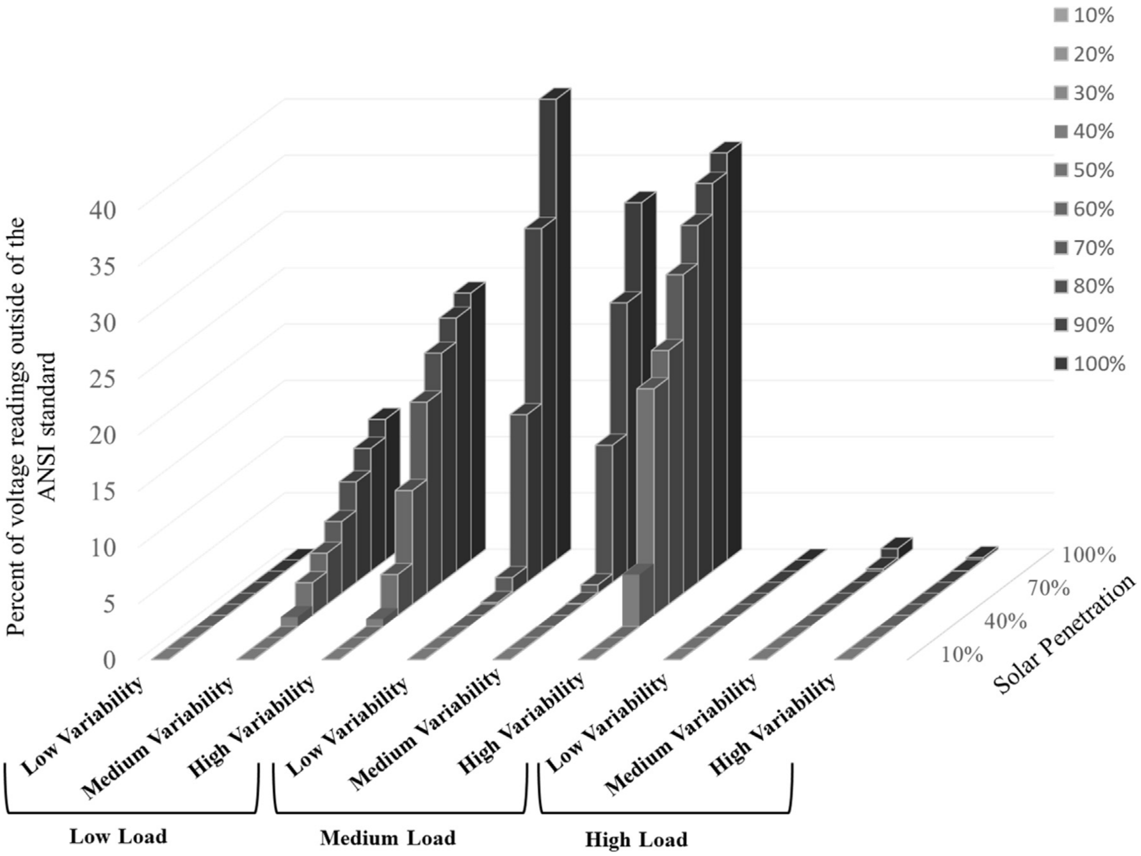

Fig. A2. Percent of voltage violations, Feeder B.

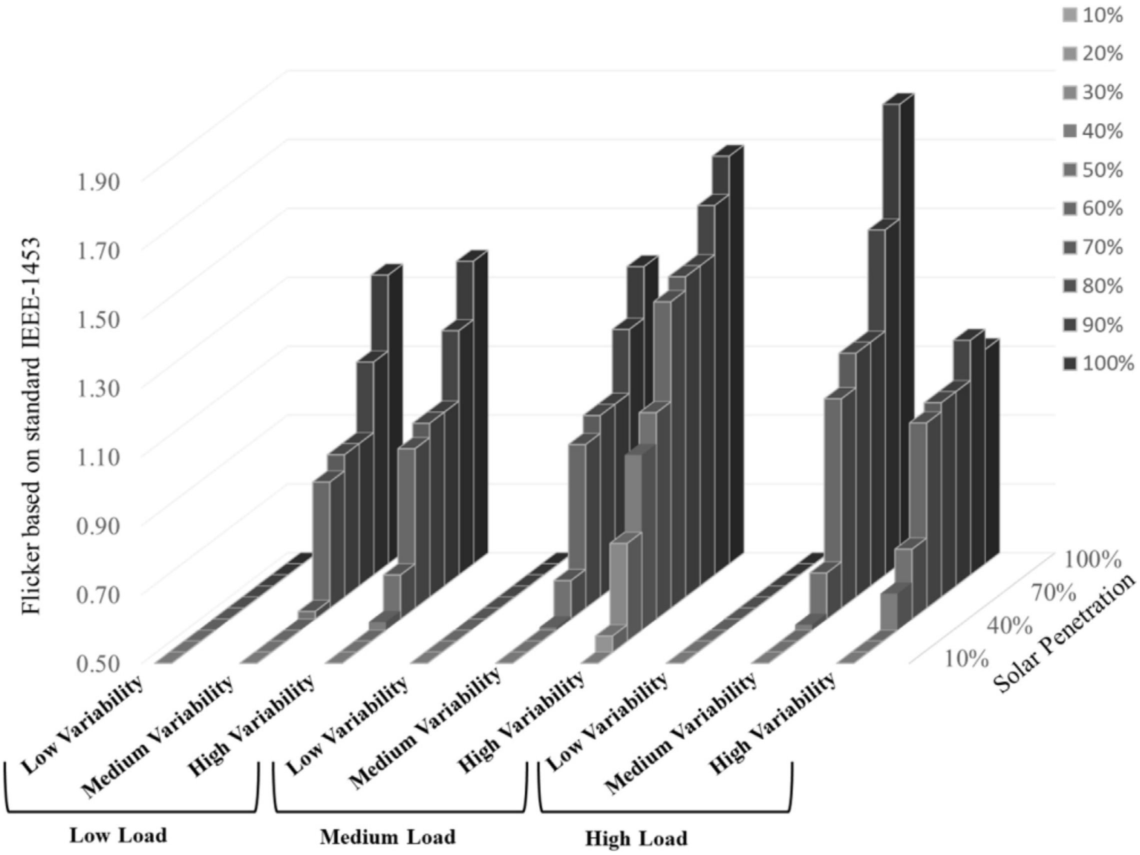

Fig. A3. Maximum long-term flicker at a sample bus.

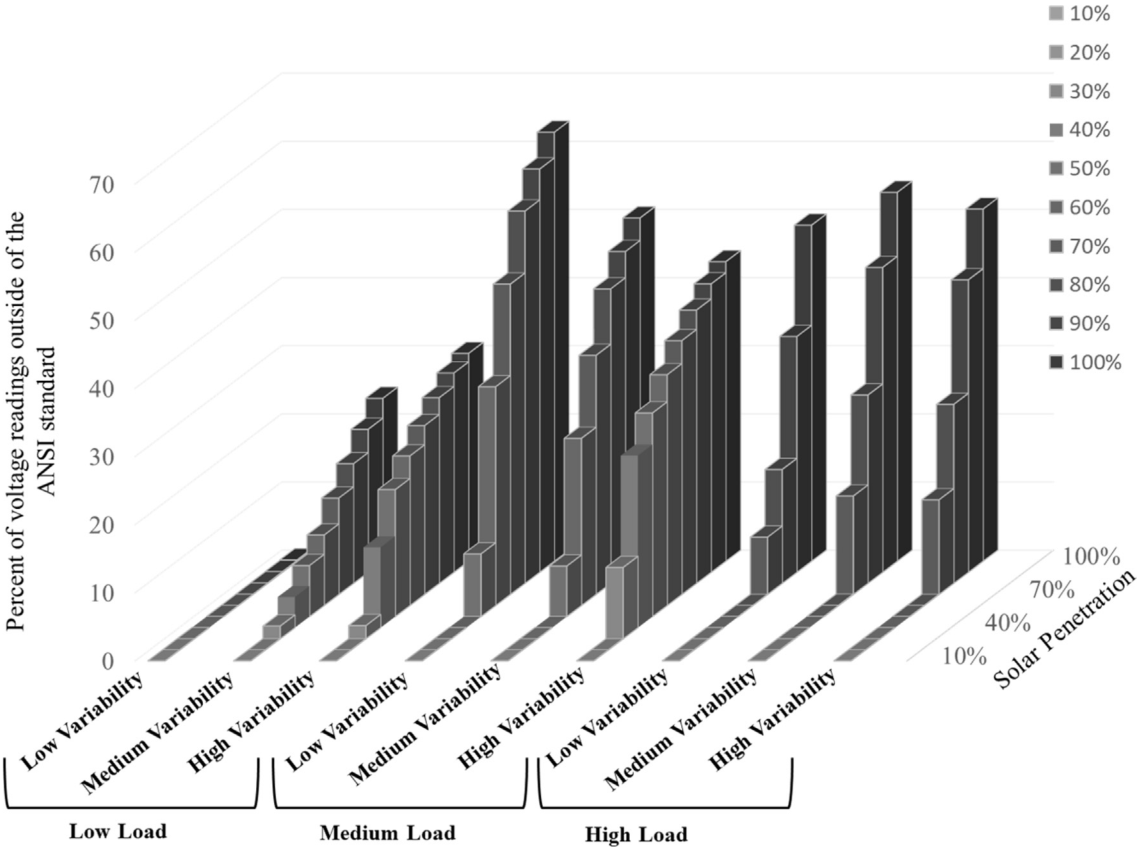

Fig. A4. Percent of voltage violations, Feeder C.

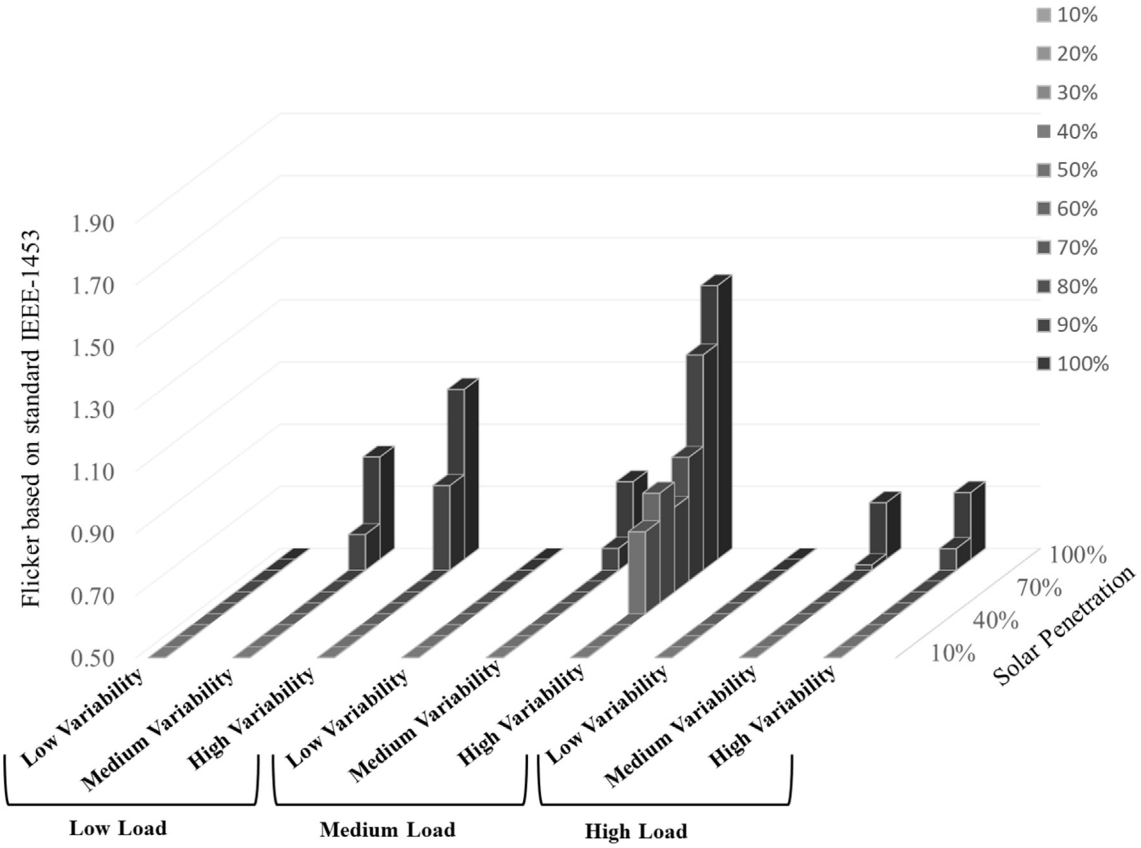

Fig. A5. Maximum long-term flicker at a sample bus.

References

[1] M. Alam, K. Muttaqi, D. Sutanto, A novel approach for ramp-rate control of solar PV using energy storage to mitigate output fluctuations caused by cloud passing, IEEE Trans. Energy Convers. 29 (2014) 507–518.

[2] O. Babacan, W. Torre, J. Kleissl, Siting and sizing of distributed energy storage to mitigate voltage impact by solar PV in distribution systems, Sol. Energy 146 (2017) 199–208.

[3] T. Beck, H. Kondziella, G. Huard, T. Bruckner, Assessing the influence of the temporal resolution of electrical load and PV generation profiles on self-consumption and sizing of PV-battery systems, Appl. Energy 173 (2016) 331–342.

[4] S. Borenstein, The Market Value and Cost of Solar Photovoltaic Electricity Production, Center for the Study of Energy Markets Working Paper Series. University of California Energy Institute. University of California Berkley, January 2008.

[5] B.H. Chowdhury, A.W. Sawab, Evaluating the value of distributed photovoltaic generations in radial distribution systems, IEEE Trans. Energy Convers. 11 (1996) 595–600.

[6] M.A. Cohen, D.S. Callaway, “Effects of distributed PV generation on California’s distribution system, Part 1: engineering simulations, Sol. Energy 128 (2016) 126–138.

[7] M.A. Cohen, D.S. Callaway, “Effects of distributed PV generation on California’s distribution system, Part 2: economic simulations, Sol. Energy 128 (2016) 139–152.

[10] David Dismukes, Estimating the Impact of Net Metering on LPSC Jurisdictional Ratepayers, Louisiana Public Service Commission, 2015.

[11] E. Compatibility, Part 3–3: Limits—Limitation of Voltage Changes, Voltage Fluctuations and Flicker in Public Low-Voltage Supply Systems, for Equipment with Rated Current# 16A Per Phase and Not Subject to Conditional Connection, IEC standard, 2005, pp. 61000–61003.

[12] J.H. Enslin, Network Impacts of High Penetration of Photovoltaic Solar Power Systems, 2010, pp. 1–5.

[13] Farzad Ferdowsi, Shahab Mehraeen, Gregory B. Upton Jr., Integration of behind-the-meter solar into distribution feeders: the importance of time resolution on model results, in: IEEE Green Technologies Conference Proceedings. April 2019, 2019.

[14] M. Farhoodnea, A. Mohamed, H. Shareef, H. Zayandehroodi, Power quality analysis of grid-connected photovoltaic systems in distribution networks, Przeglad Elektrotechniczny (Electrical Review) (2013) 208–213, 2013.

[15] Michael Greenstone, Ishan Nath, Do Renewable Portfolio Standards Deliver? University of Chicago, Becker Friedman Institute for Economics Working, 2019. Paper No. 2019-62.

[16] D.A. Halamay, T.K. Brekken, Monte Carlo Analysis of the Impacts of High Renewable Power Penetration, 2011, pp. 3059–3066.

[17] N. Hama, W. Kanokbannakorn, S. Sirisukprasert, An Evaluation of Voltage Variation and Flicker Severity in Micro Grid, 2017, pp. 1–4.

[19] C.A. Hill, M.C. Such, D. Chen, J. Gonzalez, W.M. Grady, Battery energy storage for enabling integration of distributed solar power generation, IEEE Trans. Smart Grid 3 (2012) 850–857.

[20] N.K. Kandasamy, K.J. Tseng, S. Boon-Hee, Virtual storage capacity using demand response management to overcome intermittency of solar PV generation, IET Renew. Power Gener. 11 (2017) 1741–1748.

[22] R. Langella, A. Testa, E. Alii, IEEE Recommended Practice—Adoption of IEC 61000-4-15: 2010, Electromagnetic Compatibility (EMC)—Testing and Measurement Techniques—Flickermeter—Functional and Design Specifications, 2011.

[23] Y. Liu, J. Bebic, B. Kroposki, J. De Bedout, W. Ren, Distribution System Voltage Performance Analysis for High-Penetration PV, 2008, pp. 1–8.

[24] M.A. Meybodi, L.R. Santigosa, A.C. Beath, A study on the impact of time resolution in solar data on the performance modelling of CSP plants, Renew. Energy 109 (2017) 551–563.

[25] Ric Austria, Power Quality Impacts and Mitigation of Distributed Solar Power, 2018, p. 23, 2016.

[26] S. Cao, K. Sirén, Impact of simulation time-resolution on the matching of PV production and household electric demand, Appl. Energy 128 (2014) 192–208.

[28] K.H. Solangi, M.R. Islam, R. Saidur, N.A. Rahim, H. Fayaz, A review on global solar energy policy, Renew. Sustain. Energy Rev. 15 (4) (2011) 2149–2163.

[30] N. Srisaen, A. Sangswang, Effects of PV Grid-Connected System Location on a Distribution System, 2006, pp. 852–855.

[32] Y.T. Tan, D.S. Kirschen, Impact on the Power System of a Large Penetration of Photovoltaic Generation, 2007, pp. 1–8.

[33] Richard S.J. Tol, The economic effects of climate change, J. Econ. Perspect. 28 (2014) 221–226. Number 2–Spring.

[34] Gregory Upton, Brian F. Snyder, Funding renewable energy: an analysis of renewable portfolio standards, Energy Econ. 66 (2017) 205–216.

[36] Gregory Upton, Farzad Ferdowsi, Kargarian Amin, Shahab Mehraeen, The future of solar in Louisiana. An analysis of the technical and economic implications of solar P.V. Growth on Louisiana's economy and electric grid, LSU Center for Energy Studies White Paper (2019).

[37] J. Wang, X. Zhu, D. Lubkeman, N. Lu, N. Samaan, Continuation Power Flow Analysis for PV Integration Studies at Distribution Feeders, 2017, pp. 1–5.

[38] A. Woyte, V. Van Thong, R. Belmans, J. Nijs, Voltage fluctuations on distribution level introduced by photovoltaic systems, IEEE Trans. Energy Convers. 21 (2006) 202–209.

[39] L. Xu, X. Ruan, C. Mao, B. Zhang, Y. Luo, An improved optimal sizing method for wind-solar-battery hybrid power system, IEEE Trans. Sustain. Energy 4 (2013) 774–785.

[40] D. Young, B. John, The costs and value of renewable portfolio standards in meeting decarbonization goals, Energy Econ. 73 (2018) 337–351.