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Assessment techniques of the impact of grid-tied rooftop photovoltaic generation on the power quality of low voltage distribution network - A review

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ABSTRACT

Many countries have experienced a surge in the level of the penetration of solar PV systems in the last decade. A huge portion of the newly deployed PV systems are connected to low voltage Grid. High Penetration of PVs at this level could potentially disrupt the normal operation of distribution network. A major concern is the impact of these units on power quality indices. Namely, photovoltaic panels could increase the level of voltage and current unbalance, deteriorate harmonic distortion and cause the voltage rise. These concerns may prohibit higher pentation levels of PVs. Thus, proper assessment techniques are vital for network operators for the planning and decision-making process. On the other hand, many characteristics of PV system are inherently uncertain. These uncertainties should be properly modeled in assessment framework. The main effort of research communities is to propose new methodologies that could model the uncertainty of solar power generation and stochastic assessment methods that could accurately estimate the state of the operation of the network with different levels of penetration of solar photovoltaics. This paper provides a comprehensive review of recent publications and trend of research activities regarding methods of representing uncertain variables and stochastic assessment techniques for power system quality analysis.

1. Introduction

Electricity generation from Photovoltaic (PV) systems has had the highest increase among other renewable energy sources in recent years [1]. According to the International Energy Agency (IEA), the total capacity of installed photovoltaic panels reached 500 GW worldwide by 2018 with 98 GW installed only in 2018 [2] (Fig. 1). Fig. 2 depicts the total growth of PV capacity in Australia in the last decade and distinguishes the growth rate of the PV industry based on the size of the installation. Although the growth rate is higher for utility-scale PV systems, commercial and residential small-scale rooftop PVs encompass a large portion of solar PV capacity. According to the report by the Clean Energy Regulator [3], up to 65% of homeowners have installed PV panels in some suburbs in Australia. The high penetration level of small scale PV systems in Low Voltage (LV) grid creates new technical challenges for the network operators [4]. Voltage stability and protection problems due to reverse power flow as well as network congestion and excess loading of transformers are the main technical challenges exerted to the distribution networks. Additionally, rooftop PVs are normally connected to the network through converter based technologies, and most of the rooftop residential PVs have single phase connection. This type of connection will create power quality problems such as increasing voltage unbalance rate and injecting harmonic distortions. These technical challenges may limit the capacity of the power system to support the higher integration of PVs if proper mitigation techniques are not devised [5]. In many countries, the hosting capacity of renewable sources especially rooftop PV panels are limited by regulations and grid codes [6]. Many measures have been taken by DNOs in different countries to increase the capacity of the grid. In Ref. [7], the author has interviewed the German DNOs' representative and has summarized their actions to empower the low voltage grid to mitigate these technical challenges. Most of the DNOs have run investigations on two issues of exceeding permissible voltage limits and thermal rating of equipment.

Among technical challenges caused by rooftop PVs, their impact on power quality indices of LV networks such as voltage unbalance and harmonic distortion has rarely been considered as a major challenge by DNOs. However, at a higher penetration level, the occurrence of power

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List of abbreviation:

ANSI	American National Standard Institute
ARMA	Auto Regressive Moving Average
BESS	Battery Energy Storage System
CATHPF	Complex Affine Arithmetic Three Phase Harmonic Power Flow
CDF	Cumulative Density Function
CIGRE	Council of Large Electric System
DER	Distributed Energy Resource
DHLF	Decoupled Harmonic Load Flow
DPC	Direct Power Control
DNO	Distribution System Operator
EPRI	Electric Power Research Institute
ESS	Energy Storage System
FI	Feeding Index
HB	Herman Beta
HLF	Harmonic Load Flow
HPD	Harmonic Producing Devices
HDF	Harmonic derating Factor
IEA	International Energy Agency
LHS	Latin Hypercube Sampling
LV	Low Voltage
LVUR	Line Voltage Unbalance Ratio
MC	Monte Carlo
MPPT	Maximum Power Point Tracking
MV	Medium Voltage
NEMA	National Electric Manufacturer Association
OLTC	On-Load Tap Changer
PBI	Power Balance Index
PCC	Point of Common Coupling
PDF	Probability Density Function
PEM	Point of Estimation Method
PLF	Probabilistic Load Flow
PoC	Point of Connection
PV	Photovoltaic
ROOFTOP PVS	Photovoltaic Distributed Generation
RPF	Reverse Power Flow
RPFCI	Reverse Power Flow Contribution Index
RPIVI	Reactive Power Impact on Voltage Index
SGU	Small-scale Generation Unit
SQP	Sequential Quadrature Programming
SSBI	Single Stage Boost Inverter
SVR	Step Voltage Regulator
THDI	Total Harmonic Distortion of Current
UPQC	Unified Power Quality Conditioner
VR	Voltage Rise
VUR	Voltage Unbalance Ratio
VU_{TD}	Voltage Unbalance True Definition

Nomenclature

$\Delta\vec{U}$	Voltage drop across conductor
$\vec{U}_m$	Voltage at bus m
$\vec{U}_n$	Voltage at bus n
P_r	Reverse Active Power
Q_r	Reverse reactive Power
r	Resistance of the conductor
x	Reactance of the conductor

quality problems might increase significantly. Thus, it is vital for DNOs to have a vivid understanding of network operational conditions for very high penetration level of rooftop PVs.

The assessment methods of the impact of rooftop PVs on the distribution network have been the focus of the research community in recent years. The main challenge is to create a computational framework to deal with the uncertainty from PV system. The solar generation like many other renewable sources has an inherent intermittent behavior due to the intermittency of solar radiation. Moreover, since most of the rooftop PVs are privately owned, the DNOs have little or no control over where and with what capacity a rooftop PV would be integrated into the LV feeders. These characteristics introduce further uncertainty to the assessment of the grid. In a report from the Electric Power Research Institute (EPRI) [9], it has been recommended that stochastic assessment should be performed to determine the hosting capacity of the grid. It is vital to have an accurate model of uncertainties imposed by rooftop PVs to have a valid, reliable stochastic assessment.

Regarding the problems mentioned above, this paper provides a review of recent publications and research works focusing on assessment methods of the impact of high penetration of rooftop PVs on the quality of power of the distribution network. The technical challenges of high penetration of rooftop PVs have been previously reviewed in Refs. [10–12]. In Ref. [10], the mismatch of solar generation and load demand and the formation of the known duck curve is named as the major challenge of high penetration of rooftop PVs. In Ref. [11], voltage regulation and voltage unbalance problems and possible mitigation

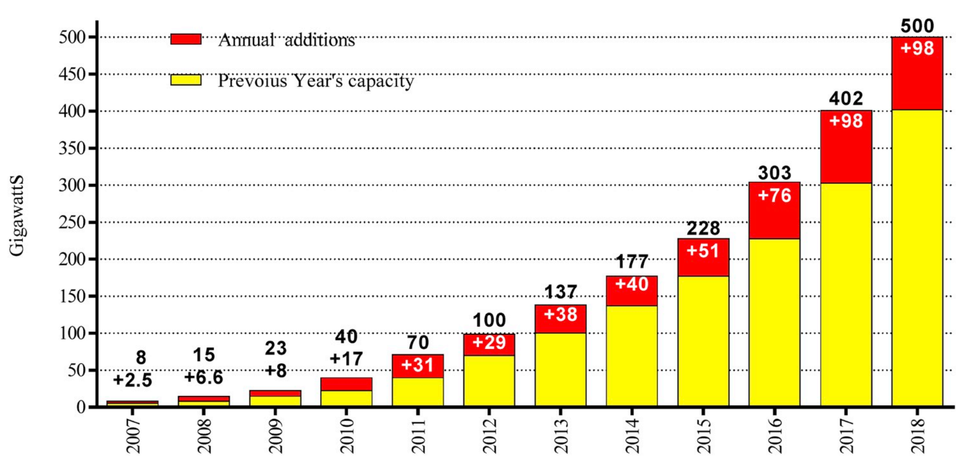

Fig. 1. Solar PV global capacity and annual additions, 2007–2018 [2].

techniques are mentioned. In Ref. [12], in addition to voltage regulation issues, a review on harmonic distortion issues is also provided. Although these publications expand on the nature of these issues, a comprehensive review of assessment techniques with a focus on the specific stochastic characteristic of rooftop PVs and uncertainty modelling techniques are still missing. The goal of this paper is to introduce and study the stochastic techniques to model the uncertainty from rooftop PVs and how these techniques have been employed to assess the impact of large penetration of rooftop PVs on power quality indices.

The paper is structured as follows. Section 2 illustrates and compares the two deterministic and stochastic assessment methods. Various uncertainty modelling techniques and probabilistic computational tools are also introduced. Section 3 provides a comprehensive review of assessment techniques considering voltage unbalance, voltage rise, and harmonic distortion as common power quality issues. In this section, the relevant standards regarding the power quality indices are mentioned as well. Finally, section 4 presents the author conclusion.

2. Stochastic vs. deterministic assessment

Deterministic assessment methods, which are based on predefined values for systems' parameters, have been widely used for the analysis of operation and planning of power systems [13]. These methods evaluate the system in a scenario-based fashion and normally consider the worst-case scenario to assess the extreme impact of uncertain parameters. However, ignoring the inherent properties of uncertain variables may result in an inaccurate assessment and consequently overestimating or underestimating the impact of some uncertain variables. There exists a wide range of uncertain parameters in power systems that could be divided into two categories, technical parameters (e.g., load profile, photovoltaic generation, etc.) and economic parameters (e.g., the price of resources, Inflation rate, government incentives, etc.) [14]. The uncertainties from renewable sources originate from their dependency on intermittent climate conditions like solar radiation and wind speed. Another form of uncertainty, which is common with conventional Distributed Energy Resources (DER) units [15], originates from operational decisions of the DER's owners.

Uncertainty modelling techniques have been developed to offer a powerful tool to deal with the variability associated with renewable sources [16]. The main challenge is to calculate the impact of random input parameters and variables on the output variable of interest. In case of power quality assessment considering integration of PVs, the input uncertain variables are variability of PV output power and the output variables are power quality indices. The calculation of output necessitates suitable probabilistic analysis. The framework to achieve probabilistic analysis has three stages: (i) modelling of uncertain input variables (ii) using suitable probabilistic computational tool (iii) representing statistical output data [17]. Probabilistic input models are represented in form of probability distribution functions (PDF) obtained from historical data and measurements. Other approach of representing variability of input parameters is employing time series modelling techniques like Markov chain, Autoregressive (AR) Model, Autoregressive Moving Average (ARMA) and Artificial Neural Networks (ANN) [18]. For higher accuracy, it might be necessary to consider the correlation of input probabilistic variables. Section 2.1 provides a list of uncertain parameters related to PV systems and their modelling techniques. The computational tool is a probabilistic method that relates the uncertainty of input variables to power quality indices. Probabilistic power flow methods based on numerical or analytical methods are incorporated in power quality assessments (section 2.2). The probabilistic Output data are power quality indices from relevant standards, and they describe the impact of input uncertain parameters on these indices. Additionally, in many standards, the indices are coded based on statistical data to consider the chronological aspects of the probability of occurrence of values of the indices. The indices are indicated in the form of 99 and 95 percentile of yearly, weekly or daily statistical data, measured in very short-time (3s), short-time intervals (10min) or long-tern intervals (1 hour). The stochastic analysis which considers a wide range of scenarios of uncertain parameters of the inputs provides the statistical data of the output in the form of Probability Distribution Function (PDF) and Cumulative Distribution Function (CDF) which fit the format of indices defined in standards.

2.1. Uncertain parameters of PV systems

The main source of uncertainty in PV systems is the variability of solar irradiance due to climate conditions [18]. This uncertainty is normally incorporated in modelling PV active (and reactive) injected power. Also in literature, some studies have modeled climate related uncertainty in detail by modelling the uncertainty of diffuse fraction and sky clearness indexes. Other uncertain parameters pertaining to PV systems are number, size, and location of PV system in distribution network. Table 1 lists uncertain parameters related to PV systems.

2.2. Probabilistic computational methods: probabilistic techniques are generally divided into two categories: numerical and analytical techniques

2.2.1. Numerical methods

The most common numerical method is Monte Carlo (MC) [32]. MC is an iterative algorithm that generates the PDF of the output variables by running the deterministic experiment many times using randomly generated samples of the inputs from their PDFs. The strength of this method is its ability to deal with the nonlinearity of the system with no need to devise a complex linearization procedure. In other words, it

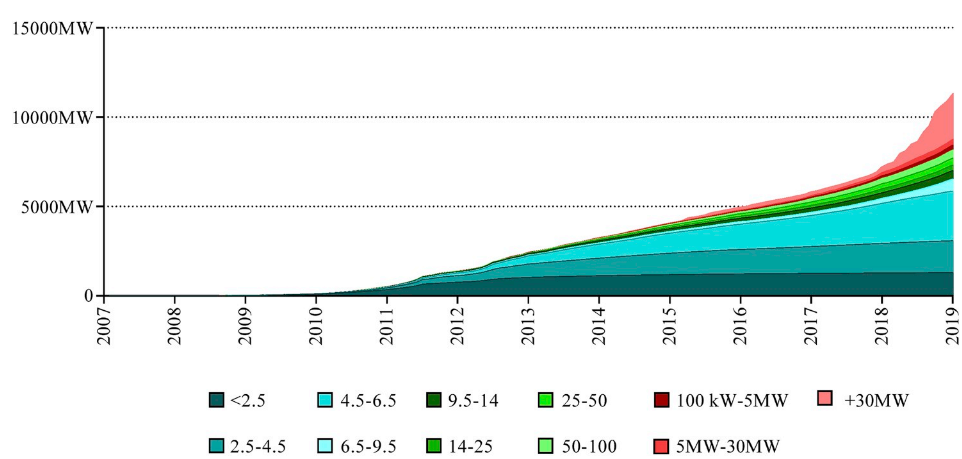

Fig. 2. Solar PV growth by capacity and scale (utility, commercial and residential) of installation in Australia, 2007–2019 [8].

Table 1
Uncertain parameters of solar PV.

Category	parameters	Sample Uncertainty modelling of parameters	Remarks
Solar	Solar Irradiance	PDF: Normal [19], Beta [20,21] Uniform [22], Time series: AR model [23] ARMA [24]	Solar irradiance could be considered uncertain due to climate variation (clouds), seasonal variability, inaccurate measurement
	Sky Clearness Index	PDF: calculated mean and deviation from diffuse factor (cumulants method) [25,26] Spatial Correlation Copula [27]	The randomness due to passing clouds characterized based on sky cleanness index
PV system	Location of PV system	PDF: Uniform [28,29]	The location of PV system in the feeder is considered uncertain, normally a uniform distribution is considered for sampling space
	Size of PV systems	PDF: Uniform [29], Normal [28]	The capacity of PV systems could be considered as an uncertain parameter, for rooftop PVs this could range from 2.5 kW to 30 kW
	Rooftop Area	PDF: Built from statistical data from estimation or measurements methods like GIS methods [30]	The available rooftop area in urban networks could be considered as an uncertain parameter
	Penetration Level	PDF: Normal distribution for various level	The penetration level in a distribution network could be considered as an uncertain parameter
	Output power	PDF: Built from solar irradiance or historical data [26] Time series: ARMA [31]	The active (and/or) reactive power of PV is modeled as an independent or correlated uncertain variable
	PV system reliability	PDF: Binomial Distribution [31]	The Probability of a PV system to be offline due to maintaenance
Uncertainty from Other sources	Load, Topology of feeder, Energy prices, Inflation rate, Electric vehicle penetration		The correlation of uncertain parameters could be considered

treats the system as a black box to which, the random samples of the inputs are fed, and the outputs are recorded. It also has a high level of accuracy since it covers all domains of uncertain parameters. It is normally considered as a benchmark for other probabilistic techniques. However, the computational cost of this method is high since a huge number of experiments should be executed. In order to reduce the computational cost of MC, sample reduction techniques could be employed (Also known as Quasi Monte Carlo method). MC has been used in many topics related to a power system including DER's impact assessment, reliability, and safety assessment, Probabilistic Load Flow (PLF), optimization problems, etc. [33–35]. Three types of MC simulation techniques, based on methods of random number generation could be mentioned: Non-Sequential, Sequential and Pseudo-Sequential.

2.2.1.1. Non-sequential Monte Carlo. This method is based on the assumption that a system state could be established based on the combination of states of each component of that system. The component's state is determined by sampling through the probability of the component being in that state. In other words, the sample values of the random input variables are selected in each iteration, and the outputs are calculated. This iterative process will continue until a stop criterion is met. Normally the stop criteria are defined on the convergence of the mean or variance of statistical data of the output variables. This method does not consider the chronological dependency of the uncertain parameters, which reduces the complexity of the method [35].

2.2.1.2. Sequential Monte Carlo. This method considers the chronological data sampling by considering a time sequence which in turn adds to the computational cost of the simulation. The uncertain values would be sampled through temporal sampling strategy from time series of input variables. Although it is a convenient method to compute the posterior distribution for many applications, the substantial computational effort needed, makes it infeasible for some applications [33].

2.2.1.3. Pseudo-sequential Monte Carlo simulation. Pseudo-sequential Monte Carlo is a hybrid approach. It has been first used in Ref. [36] to calculate the power system interruption costs. The approach is based on a non-sequential sampling of system states and chronological simulation of subsequences with a certain attribute. This method is significantly faster than the sequential approach due to the lower computational efforts needed [34].

2.2.2. *Analytical methods*

These techniques perform an arithmetic operation on the PDF of input variables to identify the PDFof the desired output variable. Analytical models are computationally more efficient. However, they are based on certain mathematical assumptions like linearization of the system. Based on this approach, the PDF of the output is obtained from the PDF of the inputs by use of an analytical technique like convolution or based on approximation of the output PDF. Thus the analytical models could be divided into two categories: linearization based methods and approximation-based methods.

2.2.2.1. Linearization based methods. The main linearization method is convolution which directly estimates the PDF of uncertain output parameters by performing convolution on a linear combination of PDFs of input variables. This technique is computationally inefficient for large systems due to convolution operation. In order to avoid convolution operation, Cumulants-based method has been used. This method uses the Moments and Cumulants to determine the PDF of a linear combination of input random variables [37,38]. Another technique is Gram-Charlier A series which allows the PDFs of variables to be expressed as a series derivatives [39]. Another method is Taylor series which approximates a given function including uncertain variables using a finite number of terms of its Taylor series and evaluate the estimation error. If the PDF of input variables is unknown, the first order second moment method could be employed which is based on first order Taylor series approximation [40]. Another method worse mentioning is the corner fisher expansion which is based on approximating the quantile of the CDF function of input variables in terms of quantile of normal distribution [26].

2.2.2.2. Approximation-based methods. These methods try to approximate the PDF of the output which is an easier task compared to approximating a nonlinear transformation. However, these methods do not return the PDF of output, and the PDF should be approximated from moments of output variables. The most well-known approximation method is the point of estimation which is based on deriving the mean and standard deviation of output, using a small number of weighted samples from the probability distribution of input variables. Like MC simulation, this method is based on obtaining a deterministic result from nonlinear transfer functions [41]. However, it requires much lower number of calculations. Another approximation method is the Unscented Transformation (UT) which is capable of providing solution with correlated input variables. It is based on feeding weighed sample points from input variables to the nonlinear function, from which, the mean and covariance of output are calculated [42].

Table 2
Voltage unbalance indices in various standards.

Standard/Document title	Indices definition	Limits
IEEE Standard 936™_1987 [57] IEEE guide for self-commuted converters	$PVUR\% = \dfrac{Maximum\ of\ \{V_{an}, V_{bn}, V_{cn}\} - Minimum\ of\ \{V_{an}, V_{bn}, V_{cn}\}}{Mean\ of\ \{V_{an}, V_{bn}, V_{cn}\}} \times 100$	Where, V_{an}, V_{bn}, V_{cn} are the phase to neutral voltages The standard is inactive
IEEE Standard 112™-2017 [58] IEEE Standard Test Procedure for Poly-phase Induction Motors and Generators	$PVUR_{IEEE112}\% = \dfrac{Maximum\ deviation\ from\ mean\ of\ \{V_{an}, V_{bn}, V_{cn}\}}{Mean\ of\ \{V_{an}, V_{bn}, V_{cn}\}} \times 100$	Where, V_{an}, V_{bn}, V_{cn} are phase to neutral voltages Limit 0.5%
IEEE Standard 1159™_2009 [52] IEEE Recommended Practice for Monitoring Electric Power Quality	$VU_{TD} = \dfrac{Negative\ Sequence\ Voltage(V_-)}{Positive\ Sequence\ Voltage(V_+)} \times 100$	Where, V_- and V_+ are negative and positive sequence voltages respectively Limit 2%
ANSI C84.1_2011 (NEMA [59]) The American National Standard for Electric Power Systems and Equipment	$LVUR\% = \dfrac{Maximum\ deviation\ from\ mean\ \{V_{ab}, V_{bc}, V_{ca}\}}{Mean\ of\ \{V_{ab}, V_{bc}, V_{ca}\}} \times 100$	Where, V_{ab}, V_{bc}, V_{ca} are phase to phase voltages Limit 3%
IEC/TR6100-3-14(-13-15) [56,60,61]	$VUR\% = \xi_h^U = \dfrac{\lvert \vec{U}_h^2 \rvert}{\lvert \vec{U}_h^1 \rvert} \times 100$	Where, $\vec{U}_h^2$ and $\vec{U}_h^1$ are negative and positive sequences respectively. h is the harmonic order Limit: as objectives in the procedure of [56], e.g. $\xi^U_{1,vs,99Weekly}$ below 2% (99 percentile of weekly measurements for very short 3s intervals)
EN 50160 [53] Voltage Characteristics in Public Distribution Systems	$VUR\% = \dfrac{V_{neg}}{V_{Pos}} \times 100$	Where V_{neg} and V_{Pos} are negative and positive sequence voltage components Limit: $VUR_{95\ Weekly,sh}$ below 2% (95 percentile of the weekly measurement for short intervals 10min)
CIGRE [62]	$VUR\% = \sqrt{\dfrac{1-\sqrt{3-6\beta}}{1+\sqrt{3-6\beta}}} \times 100$ Where $\beta = \dfrac{\lvert V_{AB}\rvert^4 + \lvert V_{BC}\rvert^4 + \lvert V_{CA}\rvert^4}{(\lvert V_{AB}\rvert^2 + \lvert V_{BC}\rvert^2 + \lvert V_{CA}\rvert^2)^2}$	Where V_{AB}, V_{BC}, V_{CA} are the phase to phase voltages

2.3. Other uncertainty modelling techniques

Most of the techniques mentioned above are based on the assumption that the historical data of input variables and their PDFs are available. However, in some cases it is difficult or impossible to obtain the PDF of uncertain variables or the historical data are not available. Scenario based techniques are used when uncertainties are expressed based on possible scenarios and probability of each scenario [43]. Clustering techniques like k-means clustering are used when sufficient historical data exists. Each cluster represents a possible scenario. Possibilistic techniques are another useful approach when historical data are scarce. In these techniques, a linguistic description of uncertain parameters is expressed as fuzzy sets [44]. It is also possible to use hybrid techniques where some uncertain variables are modeled as PDF and others as fuzzy sets.

3. Power quality assessment of rooftop PVs

This section studies the assessment techniques of the impact of rooftop PVs on power quality analysis. The focus is on three power quality issues: voltage unbalance, voltage rise and harmonic distortion. The effort is on reviewing the most recent techniques to model the uncertainty and perform the stochastic assessment.

3.1. Voltage unbalance

The condition of any difference in the magnitude of the voltages and currents of the three phases and deviation in the 120-degree phase difference is known as the voltage/current unbalance [45]. The sources of voltage unbalance are identified as structural (non-transposed overhead transmission lines or asymmetrical distribution of wiring of transformers) or operational (uneven distributed single phase loading, a fault in one or two lines of a three-phase system) [46,47]. Overheating of the transformer and end-users devices and acceleration in thermal aging are the adverse impacts of voltage unbalance [48]. It also affects the normal operation of induction motors by lowering the efficiency and increasing the vibration [49,50].

3.1.1. Voltage unbalance indices and standards

Voltage unbalance indices are defined to quantify and evaluate the level and severity of voltage unbalance in a three-phase system [51]. Based on the application and the complexity of the system under study, different communities use different parameters and relations to define the indices. Table 2 depicts the different definitions and relations used by different communities to establish an index to measure the level of voltage unbalance. The most commonly used definition known as Voltage Unbalance True Definition (VU_{TD}), used in IEEE Standard 1159 [52] and EN Standard 50160 [53], which defines the voltage unbalance as the ratio of negative sequence component voltage to the positive sequence component of the voltage. The acceptable limit of voltage unbalance rate is indicated based on the ratio obtained from these relations. IEEE recommended practice for monitoring Electric power quality (IEEE Standard 1159 [52]) indicates that the allowable limit for VU_{TD} is 2%. According to the American National Standard Institute (ANSI) [54], electrical supply systems should be designed to limit voltage unbalance ratio (LVUR) below 3%. UK Engineering recommendation P29 [55] limits the VU_{TD} to 1.3% at the load point. In many standards, the measurement procedure of voltage unbalance is not based on the momentary values of the indices. For example, the IEC 61000-3 standard [56] recommends the measurement to be done in very short (3s) or short (10min) intervals. Then, the acceptable limits will be defined based on the percentage of measurements that exceeded the acceptable limit in a weekly or daily measurement campaign with the defined time-averaging fitting of measurements. For example, in IEC/TR Standard 61000-3-14 [56], the 99% weekly measurement for very short interval (3s) and 95% weekly measurement for short interval (10 min) are defined. In the following section, the Voltage Unbalance Rate (VUR) is used as a generic term for all the indices.

3.1.2. Voltage unbalance assessment methods

The integration of rooftop PVs into low voltage feeders could potentially improve or deteriorate the VUR. The connected phase and the location of rooftop PVs are the determining factors on how PV generation will impact the voltage unbalance. The feeder characteristics such as voltage level, load profile, the topology of the feeder and distribution network component (lines, regulators, transformers, etc.) would affect how a feeder responds to PV integration. The assessment of the impact of rooftop PVs on VUR involves a suitable model of locational and weather-dependent uncertainty and a judicious stochastic assessment method. Another challenge of the assessment of voltage unbalance is calculating nodal voltages' amplitude and phase along the feeder known as load flow calculation. Most low voltage residential feeders are radial networks with high R/X ratio [63]. Due to these characteristics, conventional methods applied to the calculation of three-phase load flow such as Newton-Raphson are not suitable for radial distribution feeders due to poor convergence.

Shahnia et al. [29], have used stochastic approaches on a typical 3-phase 4-wire residential urban distribution network shown in Fig. 3. The conductors and loads are considered as impedances (ignoring mutual impedances of the lines) and rooftop PVs as power sources (shown in Fig. 4). In the stochastic assessment, a non-sequential Monte Carlo (MC) simulation is developed to assess the impact of location, size and penetration level of PVs on VUR. MC simulation is predominantly used in most of the researches. Fig. 5 shows the flowchart of the MC simulation used in Ref. [64]. The result could be shown in the form of scatter plots or probabilistic representation (PDF and/or CDF). Fig. 6 shows the scatter plot of trials as performed in Ref. [28]. In Ref. [64], a pseudo-sequential MC simulation is employed to perform a sensitivity analysis of random variables related to PV outputs and loads on the voltage unbalance ratio. The location of the nodes with single-phase PV and the connected phase are the random variables with uniform PDF for MC simulation. The time-dependent random values for PV output and loads are represented in form of marginal distribution (PDF and CDF) for every 10 min intervals for each month. The PV random output is built from random variables of hourly diffuse fractions and daily clearness index as proposed in Ref. [26]. Then, the probabilistic load flow is performed using a $2n+1$ scheme Point of Estimation (PEM) approximation method. By observing the result of the probabilistic assessment method, it has been concluded that the connection of large size PV (15 kW) will not exceed the limit for low level penetration (5%). For lower size (5 kW) the permissible penetration level could be up to 15% (As

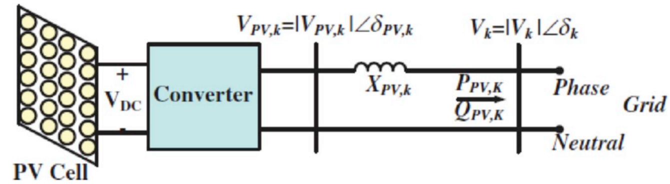

Fig. 4. Single line diagram of a PV connection to the grid [29].

shown in Fig. 7).

Silva et al. [31] presented a stochastic model considering the load fluctuation and uncertainty associated with temperature variation and PV reliability model. The temporal dependency of solar radiation and temperature as well as load curves are modeled as time series using the Auto-Regressive Moving Average (ARMA) and Fourier models. PVs' reliability is introduced in the form of a binomial distribution function, considering the failure rate and the repair time of a string of PV Panels Klonari et al. [65], proposed an emulation framework based on pseudo-sequential MC simulation and real statistical data from smart metering (SM) measurements. The random input variables to MC simulation are PV injection and energy consumption defined as CDFs produced from 15-min time averaged recorded data The application of the proposed framework to a 19-node real LV feeder is demonstrated, and the result of simulation shows that it is highly unlikely that PV injection causes exceeding of VUR limits. It is also concluded that the effects of unbalance loading on VUR are higher than PV power injection. Schwanz et al. [66] use a stochastic method to investigate the impact of single phase PVs on the negative sequence voltage. A non-sequential Monte Carlo simulation is performed by generating random location and phases for single phase PVs. The VUR at every bus is calculated as a negative sequence voltage at each point which is calculated based on unbalanced emission from all the buses and the background negative sequence voltage. When multiple sources exist, the negative sequence voltage is calculated from the superposition of contribution of each unit added to the background negative sequence voltage. From the result of the simulation, it is clear that the introduction of PVs will exceed the 1% limit of VUR but exceeding 2% is highly unlikely in many scenarios.

In Ref. [67], a pseudo-sequential MC simulation is performed considering the random nature of temporal and spatial characteristics of both load demand and PV generation profile. In Ref. [68], a comprehensive assessment of the hosting capacity of rooftop PVs in 50,000 real LV feeders in Brazil is performed. The location of rooftop PVs is the

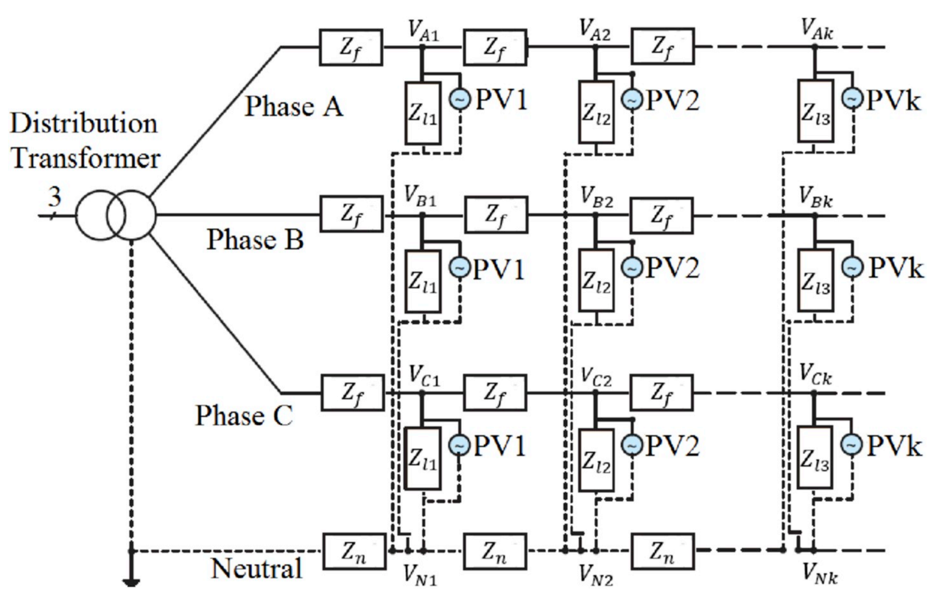

Fig. 3. Single line diagram of the studied LV distribution network [29].

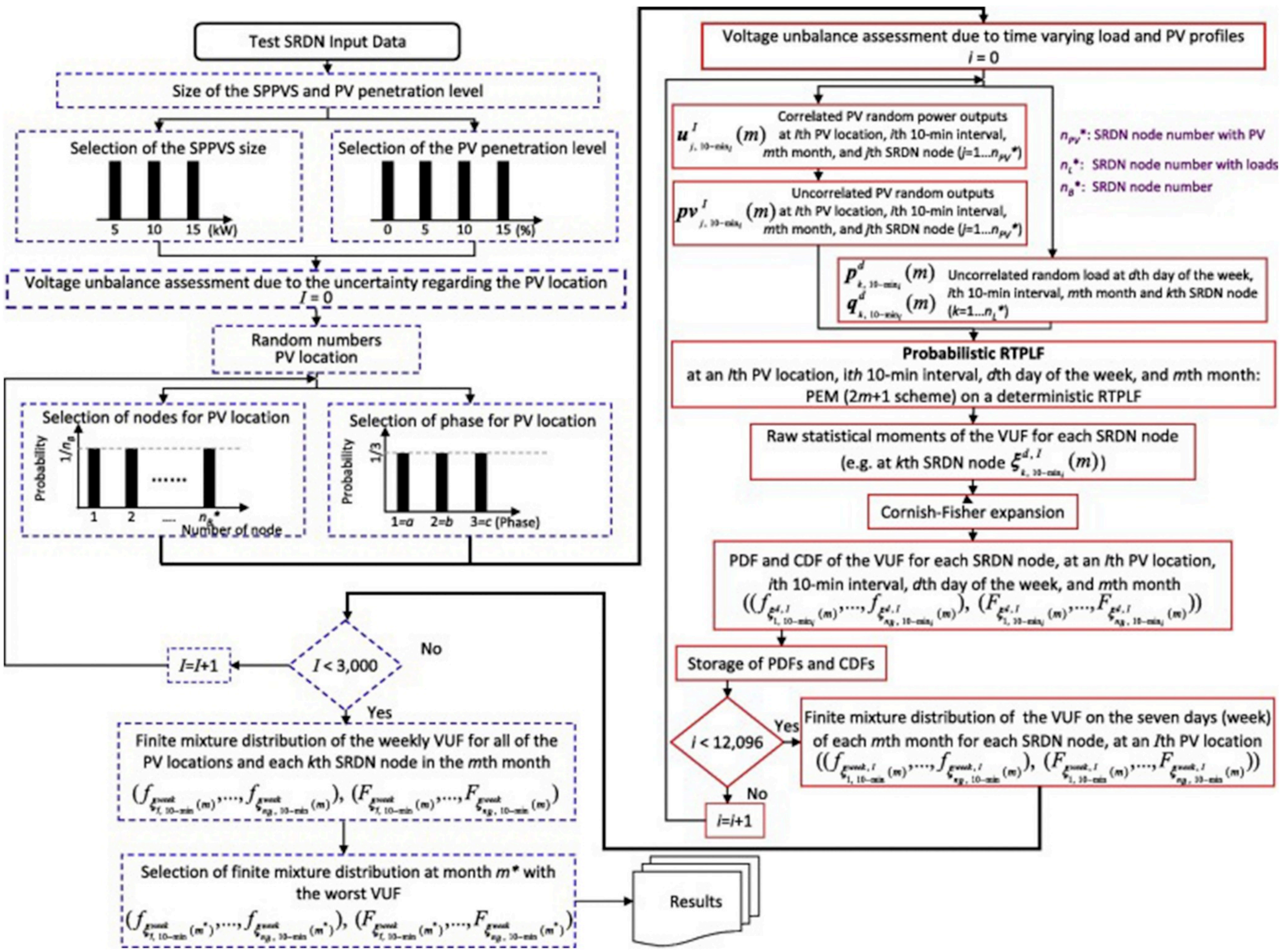

Fig. 5. A sample of the Monte Carlo simulation chart [64].

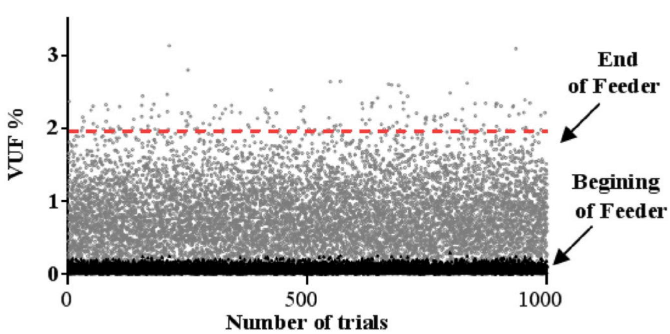

Fig. 6. A sample scatter chart, the result of Monte Carlo simulation [28].

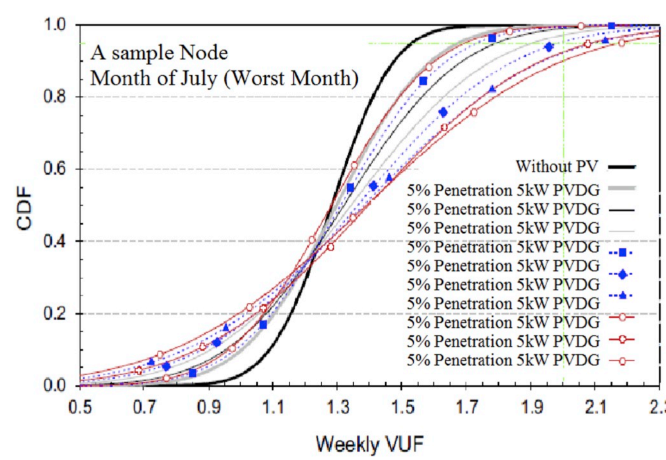

Fig. 7. Weekly VUF based on a 10-min mean for a sample node of low voltage grid in the worst month (July) with different PV penetration levels and rooftop PVs sizes [64].

random variable of a non-sequential MC simulation. The capacity of PV is increased in simulations until one of the limits of PQ indices is breached. The result of simulation suggests that most of LV feeders will operate according to the standard limits if PV penetration is curtailed to 20% of associated transformer capacity. However, only 9.6% of the networks under study have their hosting capacity limited due to the occurrence of unacceptable VUR. Table 3 summarizes the specification and the conclusion of each study.

3.2. Voltage rise

One of the most likely observed impacts of integration of rooftop PVs in the distribution network is voltage regulation disturbances specifically voltage rise issues. The distribution networks are traditionally designed based on the downstream flow of power from the transmission network to the distribution network, delivering power to passive consumers. The focus of voltage variation control was mainly on the voltage drop alongside the feeder. The integration of rooftop PVs as a source of

Table 3
Comparison of voltage unbalance assessment studies.

Ref Year	Uncertain Parameters (modelling techniques)	Network Topology	Power Flow Method	Output metrics \result	Merits	Demerits
[29] 2011	Location and size of rooftop PVs Non-Sequential (Mont-Carlo on a uniform distribution space)	Typical LV feeder 400 m 3 phase 4 wires, 60 nodes	Recursive Nodal Analysis	A failure index of 30.19 at the end of the feeder	Simple algorithm low computational cost. Easy to extrapolate to other network topology	Ignores the chronological variation of PV output, ignores the variability of loads
[28] 2017	Location of PVs (Non-sequential Monte-Carlo on a uniform distribution space) Size of PVs (Non-sequential Monte-Carlo on a normal distribution space)	Real MV/LV feeder with 480 nodes	Newton-Raphson (DIgSILENT Power factory)	A failure index of 30.19 at the end of the feeder	Simple algorithm, detailed model of MV/LV network, non-uniform sampling of PVs output	Ignoring the chronological variation of PVs output and loads
[64] 2015	Location of PVs (Monte-Carlo on a uniform distribution) Phase connection of PVs (Monte-Carlo on uniform distribution) PV output power (10 min intervals marginal distribution for each month built from random variable hourly diffuse fraction and daily clearness index) Load (10 min interval active and reactive for each node modeled as Gaussian random variable from statistical data of smart meters)	Rural secondary radial distribution network with 31 nodes and 211 KVA	Deterministic: Forward/backward sweep Stochastic: Point of estimation on deterministic power flow	Large sizes of rooftop PVs (15 kW) is permissible for low penetration (up to 5%)	Considering the randomness due to load variation, Considering chronological variation of PV power and load, Considering the correlation of PVs output power	Complicated algorithm, Dependent on existing historical data, high computational cost
[31] 2016	Temperature, solar irradiance and load (time series model obtained from autoregressive moving average and flourier model and sampled by pseudo Monte Carlo simulation) PV reliability (Binomial distribution)	Real Distribution feeder in Brazil with 1560 nodes and	Forward/backward sweep	IEC 61000-4-30	Comprehensive modelling of all uncertainties, Lower computational cost due to Pseudo-sequential sampling	Low accuracy of time series models
[65] 2016	Nodal power flow (pdf from statistical data of smart meters) Voltage of feeder transformer (pdf from statistical data of smart meters)	Typical LV feeder 19 nodes radial	Unbalance three phase power flow using sequence and phase component and forward backward method	EN 50160 VUR metric No violation of 5% limit observed, single phase load affect unbalance in much more sever manner	A generic model that could be used for various network topology	The uncertainty models are based on historical data from smart meters
[66] 2017	Location and size of rooftop PVs Non-Sequential (Mont-Carlo on a uniform distribution space)	Three networks, 6 customers, and 28 customers in Sweden 40 customers in Germany	Voltage unbalance emission using transfer impedance	Negative sequence propagation \Exceeding 2% is unlikely	Simple algorithm with low computational cost, no need to perform a cumbersome load flow	Ignoring many uncertain parameters and chronological dependency
[67] 2018	Load, PV output and occurrence of SLG (Pseudo Monte-Carlo sampling on Triangle distribution)	IEEE EU low voltage test feeder with 55 customers	Phasor mode power flow OpenDSS (Newton)	EN 50160 VUR metric Rooftop PVS reduce the voltage unbalance	Considering very high penetration levels, simple simulation with low computational cost	Low accuracy of uncertainty modelling of variability of load and PVs
[68] 2018	PV location (Monte –Carlo sampling 0n uniform distribution)	50000 real LV feeders in Brazil	OpenDSS (Newton)	EN 50160 VUR metric 9.6% of all feeders will experience breach of limit above 20% penetration level	A huge number of LV feeders has been studied	Dependent on statistical data of load profile, limited uncertainty modelling
[69] 2018	Deterministic	A 630 kVA urban network with 107 customers and 12 buses	Real time simulation Using RTDS network simulator	The average injected power before exceeding the limits is 10–13 kW for the balanced case and 3.5–4.5 kW for unbalanced	Real time simulation with real parameters	Ignores uncertainty, the result could not be extrapolated to other networks

power generation at consumer site will change this passive role into an active role, known as prosumers. Injecting current from these active prosumers changes the old mechanism of downstream power flow and consequently alters the voltage profile of the distribution feeders. The worst case scenario is when the generation level is higher than the demand of the feeder and the excess power is injected back into the upstream grid. This reverse power flow (RPF) may cause a voltage rise (VR) beyond acceptable limits throughout the feeder.

Fig. 8 shows a simple network of a typical pair of nodes with loads and grid-tied Rooftop PVs. According to Fig. 8, the formula for the voltage drop across the conductor is:

$$\Delta\overrightarrow{U} = \overrightarrow{U}_m - \overrightarrow{U}_n = I(r+jx) = \Delta\overrightarrow{U}_{Re} + \Delta\overrightarrow{U}_{Im} \tag{1}$$

We can fairly assume that the phase difference between the two neighboring nodes is very small, and the imaginary part of the voltage drop is negligible. Considering the relation between active and reactive power we obtain:

$$|\Delta\overrightarrow{U}| \approx |\Delta\overrightarrow{U}_{Re}| = \frac{r.P_r + x.Q_r}{|\overrightarrow{U}_n|} \tag{2}$$

The derivative of Eq. (2) w.r.t power transfer could be written as:

$$\frac{\partial|\Delta\overrightarrow{U}|}{\partial P_r}dP_r + \frac{\partial|\Delta\overrightarrow{U}|}{\partial Q_r}dQ_r = \frac{r}{|\overrightarrow{U}_n|}dP_r + \frac{x}{|\overrightarrow{U}_n|}dQ_r \tag{3}$$

From Eq. (3), it could be seen that the voltage difference will increase if the active power is increased. In other words, if the active power from PV generation is larger than active power demand in node m, the voltage at this node would be larger than node n.

3.2.1. Voltage regulation indices and standards

The standards covering voltage level in power systems are shown in Table 4. The RMS value of the voltage is the most commonly used index for voltage variation. Grid codes in different countries have their specific voltage limits as well. Some examples are 6 ±% in Australia, ±7% in Spain, ±7.5% in Hungary, and ±6% in Korea [70].

3.2.2. Voltage regulation assessment methods

The assessment of the impact of the integration of rooftop PVs on the voltage profile of the feeder is through field/experimental measurement or analytical techniques. Table 5 summarizes the recent publications in the field. The main goal is to indicate the penetration level beyond which, unacceptable voltage rise might occur if no mitigation measures are planned. As reported in Ref. [72], a field measurement campaign was conducted where the data from three real urban estate development sites were used to analyze the impact of three different penetration levels (30%,80%, and 110%) on the quality of the supplied voltage. The only observed power quality disturbance reported was voltage rise at the end of the LV feeders.

Load flow calculation is an important part of analytical methods. Also, the neutral wire in multi-grounded 4-wires systems should be modeled properly due to the impedances of neutral grounding points. In Ref. [73], Alam et al. have proposed a 3-phase load flow approach, suitable for 3- wire (MV side) and 4-wire (LV side) configuration by developing a model for the transformer at the interface of MV and LV networks.

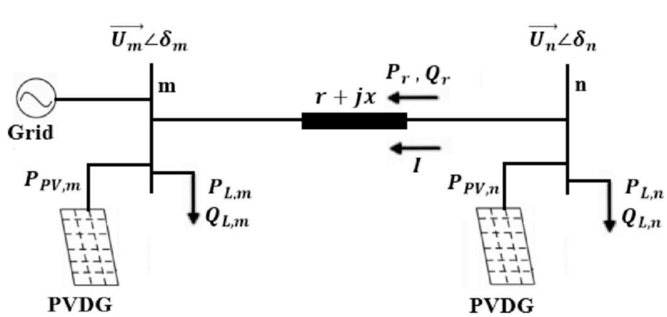

Fig. 8. A simple grid of grid-tied PV systems.

Table 4
Voltage level limits in various standards (for the full range of higher voltages refer to standards).

Standards	Limit	Remarks
EN 50160 [53] Voltage characteristics of electricity supplied by public distribution systems.	Low Voltage: ±10% (0.9pu to 1.1pu) for 95% of week, mean 10 min RMS values	* Defined for voltage magnitude variation, not to be confused with rapid voltage changes or voltage dip * LV means the RMS value not exceeding 1000 V * Limits as percentages of nominal voltage (1pu)
ANSI Standard. C84.1 [54] Electric power systems and equipment—voltage ratings (60 Hz)	Range A: ±5% (0.95pu to 1.05pu) Range B: 91.7% for minimum voltage (0.91pu) 105.8% for maximum voltage	* Range A is optimal voltage range, * Range B is acceptable but not optimal * The nominal voltage range is between 120 and 600 V
IEC 60038 [71] Voltage Standard	Low Voltage: ±10% for the nominal voltage of 230/400 V	* For 50 Hz system

The assessment method should address different operational scenarios of the distribution network as well. In Ref. [74], a relation is derived between voltage variation and DG capacity considering the worst case scenarios which are defined based on a mismatch of load and generation. The severity of these scenarios regarding stress on the power system is associated with geographical and seasonal parameters.

Many researchers have aimed to propose probabilistic methods for assessment of voltage rise due to PV integration. In Ref. [75], the stochastic characteristics of loads are modeled in the form of a Beta PDF from which the PDFs of nodal voltage drop are extracted using the Herman Beta (HB) transform which is a probabilistic analytical method as explained in Ref. [76]. The probabilistic method is used in an MC simulation with the location and the size of DGs as input random variables. The use of HB transform significantly reduces the number of iterations of MC simulation. To avoid the computational cost of MC simulation, the authors in Ref. [77] propose a sampling method based on Latin Hypercube Sampling (LHS) on a PLF to quantify the overvoltage problem. In order to address the correlation of the input random variable (PV generation and Load demand), Cholesky Decomposition is applied to the sampling process. Jhala et al. [78] have developed a new analytical voltage sensitivity analysis which calculates the upper bound of the voltage changes at an observed node due to the changes in complex power at an active node. The changes of the active and reactive power of active nodes are stochastically modeled as Gaussian random variables. Then a covariance matrix is constructed to correlate the changes in the power of the active nodes.

3.3. Harmonic distortion

PV inverters are regarded as the harmonic producing devices (HPD) and their contribution to the power quality, regarding the harmonic distortion, should be properly assessed to minimize the negative impact of voltage harmonic and current distortion on the losses and the energy transfer efficiency [87]. Due to the aging effect of distorted current on the supply lines and transformers, their loading level should be lower in the presence of distorted current based on the Harmonic Derating Factor

Table 5
Comparison of voltage regulation studies.

Ref Year	Uncertain Parameters (modelling)	Contribution/methodology	Network/model topology	Conclusion and remarks	Merits	Demerits
[79] 2012	Deterministic	Time domain simulation to investigate the impact of PV system on the feeder and using (PSCAD/ EMTDC)	Canadian benchmark test system	No violation is seen if the capacity of individual rooftop PVs is limited to 2.5 kW considering feeder impedance, feeder length, and the transformer short circuit resistance	Detailed simulation of LV network, considering the effect of feeder parameters, time domain simulation	Only considering some deterministic scenarios, ignoring the variability of location of PVs
[80] 2013	Deterministic	Yearly simulation of different penetration level on 16 feeders/ Deterministic, scenario-based using GridLAB-D version 2.2	16 radial feeders from the available taxonomy of distribution feeder models developed at Pacific Northwest National Laboratory (PNNL)	The penetration level decreases when the PVs are located towards the end of the feeder.	Detail study of impact of location of PVs on voltage violation,	Multiple scenarios are randomly studied but the randomness and variability are not appropriately modeled
[81]2016	PV location (Non sequential Monte Carlo on uniform space sampling) g MATLAB	Extracting a power flow model from SCADA and GIS models/ admittance matrix unbalance power flow using MATLAB	Entire LV network with 10588 service transformers	Clustering the LV network to urban, rural and industrial areas, Urban networks have the lowest capacity constrained by voltage rise issues	An entire network is simulated, the network is analyzed and simulated considering deployment if mitigation techniques	Variability of loads are ignored and the loads are distributed uniformly for all connection pint
[31] 2016	Temperature, solar irradiance and load (time series model obtained from autoregressive moving average and flourier model and sampled by pseudo Monte Carlo simulation) PV reliability (Binomial distribution)	Assessment of the impact of rooftop PVs on long voltage variation (Voltage Conformity) and voltage regulator actions	Real MW network in Brazil with 18483 customers. 13.8 kV with one voltage regulator	Rooftop PVs could improve the voltage conformity by 31%.Also. the effect of PVs on power quality is lower than conventional DGs (e.g. Diesel Gen)	Comprehensive modelling of all uncertain parameters	Computationally exhaustive, the accuracy of modeled time series is low
[82] 2016	Deterministic	Assessment of expansion of LV network with medium and high PV penetration/Deterministic quasi-dynamic load flow using Power Factory DIgSILENT	Residential LV network with 112 houses 630 kVA transformer. Load data from smart meters 15 min intervals	At penetration level of up to 43% of consumption, no violation of voltage limit was observed	Time sweep simulation of the entire LV network, simulating the effectiveness of mitigation techniques	Dependent on smart meters calculation, ignoring the variability of PV location and load profile
[83] 2016	PV and load profile (Pseudo sequential Mnote carlo sampling from pool of generated time series)	Assessment of voltage problems due to PVs and other low carbon technologies\power flow OPenD SS	128 real U.K. LV feeders	The result of assessment are represented in the form of the percentages of customers with voltage problems at different penetration levels: the results show PV technology creates problems in 47% of feeders	The impact of penetration on all nodes of network are assessed, introduction of a look up table which could be used as a references to extrapolate the result to other network topology	Huge computational cost, time series are created based on smart meters measurements and are not valid for other areas
[84] 2017	Deterministic	Determination of hosting capacity in both MV and LV network	Complete MV and LV network 34.5 kV with 414 residential and commercial customers	The hosting capacity is constrained during the off-peak period due to a violation of voltage limit	The voltage violation is studied for both MV and LV network,	The variability of load and PV profile is ignored, A single PV connection is assumed in every iteration
[85] 2017	Location and size of laod and PVs (Non sequential Monte_carlo on Uniform distribution)	Determining the hosting capacity	Three real MV network in Finland in three regions, Predominantly Rural, Intermediate, Predominantly Urban	The hosting capacity in a rural area (250% of maximum load) is higher than in urban areas (100%), the unbalanced integration of rooftop PVs significantly lowers the hosting capacity	Considering the type of network (urban-rural)	Ignores the chronological dependency of PV output power and loads

(*continued on next page*)

Table 5 (*continued*)

Ref Year	Uncertain Parameters (modelling)	Contribution/methodology	Network/model topology	Conclusion and remarks	Merits	Demerits
[86] 2018	Deterministic	Study the impact of higher penetration on voltage profile and OLTC operation Scenario-based deterministic/using OpenDSS quasi-static power flow	Distribution feeder equipped with capacitor bank and voltage regulator	Three penetration level (0%,30% and 100% of maximum peak demand load) a significant increase in the tap changer action above 30% level was observed	High resolution quasi static power flow	Based on deterministic data
[20] 2019	Solar Irradaince (Montee-carlo sampling on Beta distribution, Clustering based on k-mean clusteriung method)	Comparision of clustering of historical data and state enumeration method with Monte carlo simualtion, voltage sag calculation usign Admitance summation method (ASM)	Typical LV 4-wire system	Using clustering methods for uncertainty, modelling of irradiance	Clustering methods has much lower computational cost	Hard to apply the technique to other voltage variation measurements

Table 6
Harmonic indices in standards.

Indices	Indices Formulas	Remarks
Individual harmonic distortion	$IHD_X = \frac{X_h}{X_1}$	X_h : rms value of *hth* order harmonic of I [current] or U [voltage] X_h : rms value of *hth* order harmonic of I [current] or U [voltage]
Total harmonic distortion (current and voltage)	$THD_X = \frac{\sqrt{\sum_{h=2}^{\infty}(X_h)^2}}{X_1}\%$	X_1 : fundamental rms value of I [current] or U [voltage] X_h : rms value of *hth* harmonic order of I [current] or U [voltage]
Total demand distortion current	$TDD_I = \frac{\sqrt{\sum_{h=2}^{\infty}(I_h)^2}}{I_l}\%$	I_h : rms value of *hth* order harmonic current I_l : rms value of maximum demand current
Total rated distortion	$TRD_I = \frac{\sqrt{I_{rms}^2 - I_1^2}}{I_{rated}}\%$	I_1 : fundamental rms value of current I_{rated}: rated current capacity I_{rms} : root mean square value of the current inclusive of all frequency components

(HDF) [88].

The indices used in different standards to characterize the harmonic current disturbances are listed in Table 6. Table 7 compares the harmonic distortion indices and limits, recommended in the various standards for the small-scale units (integrated to the LV network with a voltage lower than 1 kV or a current lower than 16 A). Compliance with standards needs a proper assessment technique which includes testing the proper operation of inverters at the point of connection (PoC) and the proper interoperability of inverter with the Electric Power System (EPS) at the point of common coupling (PCC). The former involves testing the inverter in a test laboratory before certifying the inverter, based on the standards such as UL 1741 [89] and IEEE 1547 [90]. The latter is concerned with the harmonic behavior of the inverter while integrated and interacting with the grid and involves a Harmonic Load Flow (HFL) at the critical nodes of the distribution system [91].

3.3.1. Harmonic distortion assessment methods

The research work in the field of investigation of the harmonic behavior of distribution networks with integrated PV panels is divided into two subjects. The first category focuses on modelling the harmonic characteristics of the PV system's inverters and their interaction with the distribution network (site level). The second category tries to analyze the harmonic behavior of the distribution network with a high penetration level of the distributed PV inverters (system level). The former involves an in-depth analysis of the harmonics characteristics and nonlinearity of power electronic devices and their interaction with the grid, considering the unique characteristic of solar radiation like the transient impact of shading and providing a model in time or frequency domain. The latter is concerned with the harmonic hosting capacity of the entire or a part of the distribution network with the integrated rooftop PVs and calculating harmonic propagation using the HLF techniques.

Finding a proper model of PV inverters for harmonic distortion analysis involves studying a PV system's conversion mechanism, the principle of their operation, and their control algorithms. Also, when integrated into the grid, their interaction with the grid harmonic impedances and the background harmonic should be considered. An investigation of the impact of intermittent solar radiation involves validating the model with the measurement data on a laboratory testbed and the field measurements and finally providing the harmonic profile spectrum. The topics to be addressed are indicating the harmonic magnitude and phase angle with the associated output power level and background harmonic voltages. In Ref. [92], harmonic emission of

Table 7
Harmonic disturbances objectives in various standards (For a full list refer to standards).

Standard title	Indices	Limit	Remarks
EN 50160 [53] Voltage characteristics of electricity supplied by public distribution systems.	THD_U	**8%**	* Harmonic order higher than 25 are neglected as their amplitude are usually small, but largely unpredictable due to resonance effects
	IHD_U(not muptiples of 3)	e.g. (h = 5) 6.0%; e.g. (h = 7) 5.0%	
	IHD_U(muptiples of 3)	e.g. (h = 3) 5.0%; e.g. (h = 9) 1.5%	
	IHD_U(even harmonic)	e.g. (h = 2) 2.0%; e.g. (h = 4) 1.0%	
IEEE Standard 519–2014 [98] Harmonic Control in Electric Power Systems	Weekly $THD_{U,95th,10\ min}$	8.0 %	* The THD_U values are based on $V < 1kV$
	Daily $THD_{U,99th,3s}$	12.0 %	* The TDD_I values are based on $I_{sc}/I_L < 20$
	Weekly $TDD_{I,99th,10\ min}$	**7.5%**	* Measurement equipment compatible with IEC 6100-4-7 (30)
	Weekly $TDD_{I,95th,10\ min}$	**5.0%**	
	Daily $TDD_{I,99th,3s}$	**10%**	
	Weekly $IHD_{U,95th,10\ min}$	**5.0%**	
IEEE Standard 1547–2018 [99] Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces	TRD_I	**5%**	* The measurement methodology based on IEEE Standard 519
	IHD_I(up to h = 50)	**e.g.** (h < 11)**4%**	* Measurements are at Reference Point of Applicability (RPA)
IEC 61000-3-2 [100] Electromagnetic compatibility (EMC): Limits - Limits for harmonic current emissions (equipment input current ≤ 16 A per phase)	I_H(amplitude of current)	h = 3 2.3 A	* Class A equipment, for the definition of classes, refer to standard
		h = 5 1.4 A	* For appliances with current lower than 16 A
		h = 7 0.77 A	
		h = 9 0.4 A	

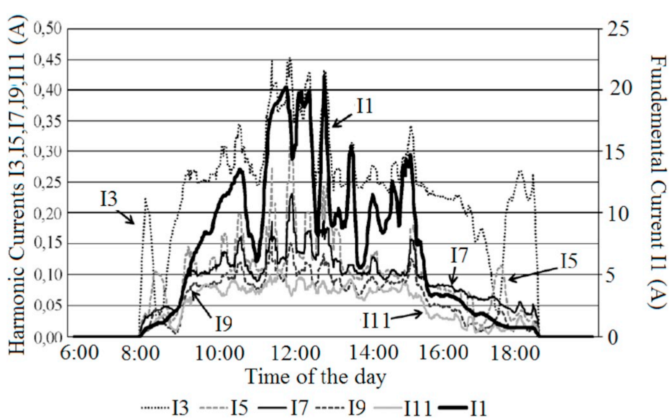

Fig. 9. Fundamental current and harmonic currents based on full day measurement The 3rd harmonic current is high during low solar radiation period [93].

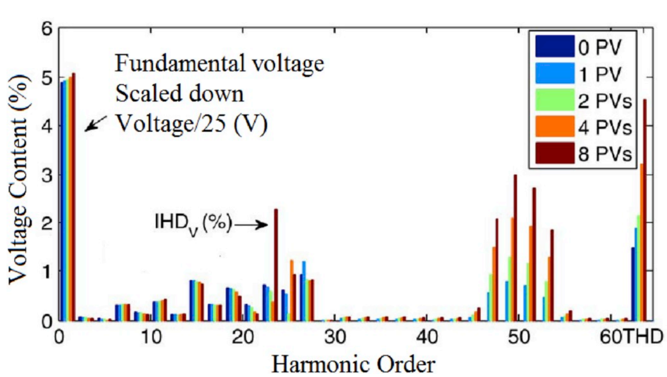

Fig. 10. Harmonic contents at PCC (secondary voltage of transformer) for different number of PVs in the feeder [96].

different size PV inverters in an LV power system has been depicted based on the field measurements. In Ref. [93], a PV panel is modeled as a current source with solar irradiance as the input of the model in the time domain. The model is based on a two-stage conversion system. The first stage is a converter with embedded MPPT algorithm and a switching frequency of 200 kHz. The second stage is a current controlled voltage source H-bridge inverter with low pass filter at the output. The proposed model is simulated in PSIM, and the result of the simulation is compared with field measurement from Ref. [92]. As shown in Fig. 9, it is observed that the Total Harmonic Distortion of Current (THDI) and specifically 3rd harmonic are notably higher during low power generation period, i.e., sunrise or sunset. In Ref. [94],

. Enslin et al. [95] initially present the study of the harmonic interaction between the PV inverter and distribution network, specifically harmonic resonance. The resonance phenomenon can be classified into parallel and series resonance. The parallel resonance due to parallel network capacitance (e.g., household equivalent capacitance) and the supply inductance (e.g., transformer leakage and cables) might be excited by distorted generated current from PV inverter. The series resonance of network capacitance and supply reactance is excited by external injected harmonic distortion. The analysis of the results from experimental measurement shows that some inverters may trip on a distorted supply voltage due to a parallel resonance phenomenon. Hu et al. [96], investigate the resonance phenomenon between PV inverters and grid impedance. Also, the impact of the damping resistor, in series with a capacitor of the filter, and the number of PVs in the feeder on the amplification of the resonance frequency is studied. It is reported that if the linear part of the residential load is big enough, the harmonic resonance is not a big concern. The resonance performance of a typical multi-grounded neutral distribution system in North America is studied through simulation. It is assumed that 10 houses, with two types of linear and nonlinear loads, are connected. Fig. 10 shows the harmonic content of PCC. The impact of PVs on the harmonic component at the resonance frequency (21st order) and switching frequency (60th order) is shown in Fig. 10.

The impact of the ripple of the DC-link on the harmonic characteristic of the output current of the inverter is studied in Ref. [97]. In single phase inverters, due to unbalance between the instantaneous DC input and AC output power, a voltage ripple is seen with a frequency double the line frequency. These ripples are modeled as a closed loop model of

Table 8
Comparison of harmonic distortion studies.

Ref Year	Contribution	Model	Remarks
[104] 2006	Maximum harmonic Penetration Level based on THD of Voltage	Typical 350kVA LV network. Harmonic model of PV based on the measurement	Nodal Analysis for calculation of harmonic voltage, Comparison of different conductor type, Considering disturbing load in LV network
[105] 2006	Effect of shading on the harmonic behavior of multi-string transformer-less PV panel.	5 kW PV plant with multi string converter with transformer-less inverter 20 kW sun-shield PV system with 6 arrays and 36 modules in each array with transformer for analysis of shading effect	Field Measurement of current THD for spring and summer cases (different shading duration). The worst case of current THD deterioration when half of the modules are shaded
[106] 2008	Examination of harmonic behavior for different solar radiation	20 kW PV system connected to the LV network with 3 couple of strings with three 5 kW Inverters	Field measurement and PSIM simulation, Not exceeding international standards limits
[107] 2012	Field measurement of typical 10 kW PV systems	The first residential 10 kW residential PV plant in Croatia,	The result of field measurement is used for simulation of LV network in DIgSILENT with three different scenarios of penetration
[108] 2013	Optimization algorithms to determine the optimum DG penetration level considering the harmonic-content in hosting capacity	18 bus 10 MVA MV radial distribution system	Formulation of DHLF and Particle Swarm Optimization Comparison of Centralized and Decentralized penetration of DGs
[109] 2014	Impact of variation of solar irradiance on THD of current and voltage	Simulink Simulation Model	Real data for solar irradiance from UTeM laboratory
[110] 2014	Impact of large penetration level of PV panels on harmonic distortion level	Typical Brazilian LV four-wire network 75 kVA transformer 13 single phase customer	OpenDSS harmonic power flow, Study the impact of a loading level, location of PV and PV power factor on harmonic behavior with integrated PV systems
[111] 2015	Study of the Super-harmonics (high frequency harmonics above 50th order)	850 kW PV system connected to the LV system through eight 3-phase inverters, 1250 kVA transformer at PCC	Field measurement, The analysis of the result confirms the presence of super-harmonics around multiples of 3 kHz.
[112] 2015	Proposing a method for determining the hosting capacity considering the harmonic phase angle (aggregation effect)	A real Brazilian MV distribution network with one hydroelectric generator and three wind power	A mathematical procedure based on the equivalent network at a node in order to find the hosting capacity. Considering the worst case scenario based on the summation of harmonic currents (aggregation effect)
[113] 2016	Investigation of the harmonic contribution of PV and the impact of injected harmonic distortion on transformers (*K*-factor)	IEEE 13 bus and a real PV site at the University of Queensland	Considering nonlinear loads, penetration at a single node compared to multiple nodes. The time-domain model simulated in PSCAD, Harmonic behavior in the unbalanced network
[114] 2016	The impact of firing angles of inverter switches on THD	Time domain model of PV cells, H-bridge inverter and output filter with transformer	The optimal firing angle for lower THD
[115] 2016	Analysis of PV generation on voltage quality using real data	9 kW PV system in Estonia with the tracking system. Connected to PCC through 126 m of cable	The result is presented in the form of scatter plot, smoothing-spline and linear least squares methods
[116] 2016	Impact of passing clouds and the impedance of connecting conductor to the PCC on THD and IHD	Simulink Model of a 250 kW grid-connected PV system	Shadows from passing clouds increase the current THD at PCC The voltage THD is increased when a longer conductor is used
[117] 2016	Investigating the impact of output power (feed-in current amplitude) and operation in non-unity power factor on the harmonic quality of current	The experimental set-up, 1 kW single phase single stage grid-connected inverter.	Comments on factors affecting the harmonic distortion such as dead-time effect, the nonlinearity of power electronic devices, and background harmonic. Study of current harmonic during voltage sag and swell
[118] 2016	Harmonic interaction of multiple PV inverters	A real PV system with three small grid-connected inverters from three different manufacturers.	Field Measurement and analysis based on real data High current THD observed in the low level of injected power
[119] 2016	Evaluation of Current waveform distortion in various output power- of a PV system	The fully automated test bed, with three PV inverters (transformer-less, HF-transformer and LF transformer), PV emulator to adjust the output power	Discusses an example of Phase Balance Current protection relay setting due to high 3rd and 5th harmonic emission in low power operation mode
[120] 2017	Study of power quality of urban distribution network with PV systems	A real urban distribution network with 4 PV systems installed	A LIDAR system is used to evaluate the potential capacity of solar generation in a certain area. Power quality issues in terms of harmonic distortion in a network with low short-circuit power.
[121] 2017	Study the impact of the level of non-linear load and voltage background voltage distortion on Hosting capacity	Benchmark system for passive filter performance analysis, 13.8 kV balanced three phases, 2 bus system with 2.8 km line, with 6 pulse drive as load	Voltage THD and current IHC of 25th order are the main indices to restrict the hosting Capacity
[122] 2018	Applying hosting capacity methodology to harmonic voltage distortion	CERIN site at the Federal University of Itajuba in Brazil	Establish an approach for hosting capacity determination considering the voltage rise due to harmonic distortion
[123] 2018	A stochastic approach to investigate the hosting capacity	Rural area in Sweden with 6 customer buses, with single-phase PV inverters	Stochastic assessment based on Monte-Carlo simulation, No exceeding of limits of the standard was observed
[124] 2018	Effect of high penetration of PV on the harmonic distortion	Real LV network in Germany, the peak demand of 349 kW and 27 single and three phases grid-connected PV system with peak generation of 234.6 kW	Detail model of nonlinear loads, Simulation using MATLAB/Simulink, Study of unbalance harmonic currents
[125] 2018	Analysis of the quality of the supplied voltage of standalone PV inverter	%5.94 kW Panel connected to the 208 V LV network.	Considering the Secure Power Supply (SPS) mode Maximum voltage THD was observed with a purely resistive load

the inverter in the form of a cosine wave sitting on the DC value. Since the model is time-varying, numerical methods have been used to identify the harmonic characteristics of the output. Based on the results, it is observed that the spectrum of output signal consists of 3rd and 5th harmonic originated from the ripples in the DC link.

The phenomenon of interharmonics due to PV inverters is studied in Ref. [101]. It is well known that the MPPT control algorithm is the origin of interharmonics. The variation in DC power, when searching for MPP, may be the source of these interharmonics. Also, in Refs. [102,103], Langella et al. investigate the harmonic and interharmonics performance of PV systems for different operating powers and voltage supply conditions. They also study the impact of the control block, particularly the MPPT control, on the interharmonics performance of the PV system. The result of the investigation shows that interharmonics emission is not significant for frequencies above 100 kHz.

Measurement methods based on statistical data could be used to extract the probabilistic model. As an example, in Ref. [126] statistical data recorded in 1-week campaign measurement is used to define the model of PV harmonic emission and its dependency on the output power. An effort to find a harmonic model for PV systems to be used in probabilistic harmonic load flow is followed in Ref. [127]. In the proposed method, historical time series data obtained from field measurement are used to find statistical characteristics of PV harmonic current using approximation methods such as Corner-Fisher and Legendre series approximations. These approximation methods reconstruct the harmonic current emission PDFs using moments or cumulants of historical data which could be used in probabilistic HLF. The impact of size and location of rooftop PVs on their harmonic contribution in a distribution network is studied in Ref. [128] by Wang et al. In order to deal with the uncertainties of rooftop PVS output power, a Complex Affine Arithmetic Three-Phase Harmonic Power Flow (CATHPF) is proposed which can trace the harmonic contribution of multiple rooftop PVs to distribution network. MC simulation methods have also been used for harmonic emission assessment. In Ref. [129], an MC simulation scheme is developed to model different scenarios of PV installation in a real distribution network.Table 8 lists the most recent publications in the field of PV inverters harmonic analysis and highlights their contribution to this field. A consensus conclusion in most of the publications is that the harmonic emission from PV inverters in lower penetration levels is negligible. However, in low output power mode of operation and in a distribution network with low short-circuit power some violation of limits of standards may be observed.

4. Conclusion

A comprehensive review of the assessment techniques of the impact of the high penetration level of PV systems on the power quality indices is presented. The review covered both deterministic and stochatic assessment methods. Comparing the two methods, it is noted that stochastic approaches offer a more satisfactory representation of the state of the system by modelling the variability of the parameters in the presence of PV systems. In comparing the uncertainty modelling techniques, the author suggests that there is not a single best technique and the choice of proper modelling framework should be thoroughly studied based on characteristics of each case. From the methods studied in this paper, the Monte-Carlo simulation is the most common computational technique which provides a satisfactory uncertainty representation. However the computational cost of this technique makes it implausible and intractable for many applications. The effort of research community is to propose new techniques to model random variables associated with solar PVs and find novel stochastic techniques that are faster and have lower computational costs.

With an increase penetration of PV systems into the distribution network, the probabilistic assessment will become more important. Current challenges in this field are the modelling accuracy and computational burden. These challenges are open and ongoing areas of research. A suggestion for future researches is deploying more advance techniques like possibilsitic method, modelling the correlation of various uncertain parameters.

Regarding the research works reviewed in this paper, it could be concluded that the voltage regulation problems due to excess generation are more likely than other power quality issues and it could occur even in lower penetration levels. Nonetheless, for a very high penetration level, several power quality issues are likely to be observed.

Declaration of competing interest

None.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2019.109643.

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