Probabilistic Hosting Capacity and Risk Analysis for Distribution Networks

By

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in

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Abstract

Hereby I present a PhD thesis by publications. Altogether, the thesis includes: a) two journal papers, b) three IEEE conference papers. The journals include IEEE Transactions on Industrial Informatics while the second has been submitted. The conference list includes World Renewable Energy Congress (WREC), Asian conference on energy, power and transportation electrification (ACEPT) and IEEE Conference on Probabilistic Methods Applied in Power Systems (PMAPS). The PMAPS conference is the only event that exclusively discusses probability and statistic methods applied to power system analysis.

The thesis presents several novel methods. The first novelty is the development of a new probabilistic model for estimating the solar radiation incident to residential roofs which is compatible with the Australian meteorological conditions. The second is the development of new probabilistic approach called "probabilistic hosting capacity" to estimate the hosting capacity of distribution networks. The third one is the utilization of sparse grid numerical approximation techniques in handling the uncertainty computations. The last contribution is the new assessment method for quantifying the risk of connecting a large number of correlated distributed generators (DGs) into the distribution networks. In glance, these contributions are highlighted in the following paragraphs.

The development of the probabilistic method to estimate the solar irradiation is aimed to represent the uncertainty of produced power from residential solar panels. By utilizing the relation between clearness index and diffuse fraction, a probability density function (PDF) of produced power is derived from the total radiance quantity incident of a tilted area to the horizontal plane. Given the characteristics of the day time and the place, the uncertainty associated with power production by solar panels can be probabilistically estimated from the total solar irradiation of a tilted area. Two mathematical models are proposed: the first utilizes the HDKR (Hay, Davies, Klucher, Reindl) mathematical representation for total irradiance, while the second one involves the use of Hay-Davies mathematical representation. Without losing the scope of the work, only the first model is compared with real data obtain from a site in Adelaide. The second model is used for conducting the power flow calculations due to the low computational time is required to deliver results.

The interest in the development of probabilistic hosting capacity comes as DGs in the distribution networks rely mainly on the renewable energy. Probabilistic hosting capacity is aimed to deliver a probabilistic estimate of the maximum amount of DGs that can be connected into the existing distribution network without jeopardizing the utility's system operation and/or customers' connected appliances. The approach is built up after defining the main uncertainties, resulted from the stochastic behaviours of the small-scale of wind turbines and solar panels as well as domestic loads. The impacts of these uncertainties on the operation of a distribution network are assessed by establishing a set of operational performance indices and the use of the probability of occurrence notion. Three types of hazardous impacts are defined (tolerable, critical and serious). The approach is time-dependent and includes network bi-directionality feature which

complies with the fundamentals of automation approaches for active distribution networks.

The third contribution is the use of sparse grid numerical techniques (SGTs) as an efficient tool to handle the uncertainty computation which is multi-dimensional problem. It replaces the use of classical numerical techniques based on tensor product grids which suffers from the curse of dimensionality. Additionally, the SGT in comparison with Monte Carlo Technique (MCT) is able to achieve improved efficiency in computation with acceptable accuracy.

The last contribution is the development of a new risk analysis approach to quantify the effect of increasing levels of DG penetration on distribution networks. The proposed novel analysis utilises the following techniques and concepts: the Nataf transformation to represent spatial correlation of the DGs connected in the same distribution network; the consideration of likelihood (relative frequency of event occurrence) as well as severity (accumulative depth of event occurrence) of the performance indices in assessing the operation of distribution networks with the increase of DG connections. The Nataf transformation was used to ensure the rank correlation modelling among the non-Gaussian uncertainty representations in which the inter-dependences are modelled. The risk components, likelihood and severity, are visualized along with the increase of correlated DG connections. The purpose of this analysis is to provide an estimate of degree of risk in assessing the operational performance of a distribution network as whole, instead of the traditional methods that assess the network by parts, such as assessing individually a line or bus.

The effectiveness of developed methods in this thesis is demonstrated by performing tests on two actual distribution networks: small and large. The small network consists of 11 buses with one substation transformer; while the existing large distribution network, situated in South Australia, consists of 59 (11/0.4 kV) feeder-transformers serving commercial, residential and industrial loads. The large network is segmented into different zones according to their likelihood of having DGs. The results are visualized, analysed and discussed for each proposed methods or approaches. All system modelling and algorithms are performed using MATLAB software and implemented on the distribution networks modelled in the industry accepted software OpenDSS, introduced by Electrical Power Research Institute (EPRI).

Declaration

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in my name, in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint-award of this degree.

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20-08-2018

Singed Date

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Conventions

The following conventions have been adopted in this Thesis:

1. The typeset is compiled with Microsoft Word 2016.
2. IEEE style is used for referencing and citation.
3. Australian English spelling is adopted, as defined by the Macquarie English Dictionary, A. Delbridge (Ed.), Macquarie Library, North Ryde, NSW, Australia, 2001.
4. Mathematics presented in the thesis are performed using Matlab Version R2017a; URL: http://www.mathworks.com. While the modelling of power distribution networks is achieved using the Open Distribution System Simulator, OpenDSS Version 8.1.4; URL: https://electricdss.sourceforge.io/.

Publications

Journal Papers

- **H. Al-Saadi**, R. Zivanovic and S. Al-Sarawi, "Probabilistic hosting capacity for active distribution networks," *IEEE Transaction on Industrial Informatics,* vol. 13, no. 5, pp. 2519-32, Oct. 2017. **13 pages**
- **H. Al-Saadi**, R. Zivanovic and S. Al-Sarawi, "Risk Analysis of Distribution Networks with Large Number of Correlated PV Connections," has been submitted. **34 pages**

International Refereed Conference papers

- **H. Al-Saadi**, R. Zivanovic and S. Al-Sarawi, "Uncertainty model for total solar irradiance estimation on Australian rooftops," presented in World Renewable Energy Congress-17, Dec. 2016, Manama, Bahrain; published in E3S Web of Conferences Nov. 2017, vol. 23, pp. 01004. **12 pages**

- **H. Al-Saadi**, R. Zivanovic and S. Al-Sarawi, “Probabilistic analysis of maximum allowable PV connections across bidirectional feeders within a distribution network,” presented in Asian conference on energy, power and transportation electrification (ACEPT), Oct. 2017, Singapore, published in IEEE Xplore pp. 1-6. **6 pages**

- **H. Al-Saadi**, R. Zivanovic, Hatim G. Abood and S. Al-Sarawi, “Hourly-Assessment of Grid Hosting Capacity for Active Distribution Network,” presented the

International Conference on Probabilistic Methods Applied to Power Systems (PMAPS), IEEE, Boise, Idaho, USA, 2018, published in IEEE Xplore. **7 pages.**

Chapter 1

Contextual Statement

1.1 Introduction

Nowadays, the number of domestic-owned distributed generators (DGs) connected to distribution networks is increasing rapidly. For example, the accumulated global capacity of residential PVs has increased to 227 GW in 2015 after it was 4 GW in 2003 [1]. Economic factors and global concerns about the environment have widely contributed to this momentum [2, 3, 4] which also place the distribution system in a major evolution state, from being passive into active DNs. It is likely that smart meters along with other advanced technologies will vastly take a place in controlling the performance of the DGs connections and alleviate their negative impacts. However, given current situation of distribution system operators, the pace of the DGs increase is evolving at a faster rate than anticipated, and this diminishes automatic solutions that are currently being implemented. In this thesis, the risks associated with a large number of DGs integration have been investigated where the maximum network capacity for hosting DGs, so called hosting capacity (HC), has been determined based on statistical information of the involved uncertainties.

The evolution of the distribution grids is further discussed in Section 1.2. Then the different approaches to the integration of the renewable energy sources are discussed in Section 1.3. This will then be followed by power planning research direction that has been developed in this thesis in Section 1.4. In Section 1.5 the thesis objectives are listed, and the contributions are summarised in Section 1.6. The thesis structure is presented in Section 1.7 including highlights of published research articles relate to this thesis.

1.2 The Evolving of the Distribution Grids

Electricity distribution grids are passing through a significant and challenging transformations, mainly due to the presence of large number of DGs connected to the grid. There are several benefits of DG connections: from gener.ation point of view it can locally compensate for rapid load growth, contribute to great increase of renewable energy and reduced fossil fuel use. By avoiding system reinforcement, it is possible to achieve major economic benefits, and more. However, tremendous changes have been happening in operation of power generation and distribution networks. For example, unlike the common conventional electricity networks with generation units of 100 MW to 1 GW at large distance from the consumption sites, the current networks have small-to-medium DGs installed locally, close to consumers (see Figure 1.1 adapted from [5]). These new generators are changing the power flows from unidirectional to bidirectional in distribution network [6]. The increasing connections of small to medium size distributed generators, which are primarily based on renewable energy sources such as photovoltaics (PVs) and wind power turbines (WTs), contribute to these changes.

Official figures show that just over third of households in some states have already installed PVs such as in Queensland and South Australia, and more than 1.6 million PVs have been installed throughout Australia [7]. As a result, the structure of the distribution system is moving from being passive (consuming energy) into being active (producing/consuming energy). Such network is named active distribution network [8, 9]. In the past few years, the liberalisation processes regarding the electricity supply such as tax breaks, tax incentives, feed-in tariffs, favourable subsidized energy policies and

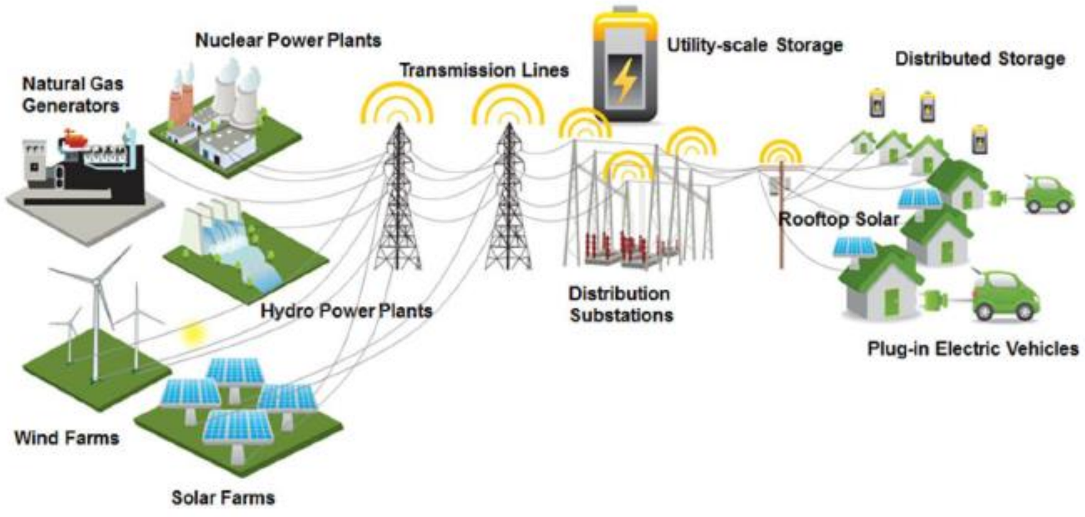

Figure 1.1 Current structure of electrical system adapted from [5]

guarantees have put the electrical system in a transition. As side effects, the problematic issues have emerged such as difficulty in voltage control, the reduction in the effectiveness of electrical protections, reliability, stability and quality of the power supply and the management of the reactive power, network congestion as well as yet unrecognized pitfalls [10]. The distribution grids have become much more complex to plan, operate and maintain. Therefore, the current research directions are moving towards the replacement of the traditional power system methods to cope with this evolution. The developments of new concepts, technology and techniques are at high demand by the research and industry communities to ensure reliable, secure and sustainable power system.

1.3 Integration of Distributed Energy Resources

The issues related to DGs have been investigated since late 1990s by the review reports presented by the working groups of the International Council on Large Electric Systems (CIGRE) and the International Conference and Exhibition on Electricity Distribution (CIRED). It is concluded as a universally accepted definition for DG is that DGs are not centrally planned or dispatched by power utility, usually connected to distribution networks of voltages 230/410 V or up to 11 kV, less than 50 MW in maximum capacity [8]. Ackerman et al defined DGs as "*Distributed generation is an electric power source connected directly to the distribution network or on the customer side of the meter*" [11].

Table 1.1 Definition of DGs

Ref.	Classification	Definition
[11, 14]	According to the location	Power generation sources installed close to the demand's side.
[15, 16, 17]	According to the location	Power generation sources placed strategically in the distribution networks.
[18]	According to the capacity	Large group of power generators, less than 1MW, distributed within the distribution networks.
[19]	According to the location and capacity	Generations located at or close to the loads that are not served by the main central power control and with a capacity of less than 1 kW to more than 1 MW.
[20]	According to the location and capacity	Generating unites less than 30 MW located near or at load center.
[21]	According to the location and capacity	Small units located near consumption centres.

Other definitions can be found in Table 1.1. They help in the utilization of renewable energy such as solar, wind, hydro, geothermal, biomass and tidal energy etc [11, 12, 13].

In this thesis, we define the 30 kW for domestic small-size DGs as: not centrally planned or dispatched by power utility, always connected to residential or commercial distribution networks of voltages 230/410 V or up to 11 kV with a capacity of 30 kW or less.

The general policies regarding the integration of DGs are continuing as a matter of updates amongst different countries and utilities. Within the context of the thesis, we define DG as a power source (30 kW maximum power delivery) mostly consisting of rooftop PVs and domestic WTs connected at the distribution networks that may or may not inject power into the utility at the point of common coupling (PCC). If distribution network operators (DNOs) own and control DGs then automation strategies for ensuring network security may be relevant. However, distribution network planners must be prepared for unobservable grid-connected DGs. Such grid is predominantly uncontrollable, neither measurable in terms of total generation capacity for frequency balance despite its contribution to system capacity. It is mentioned that the lack of standards in Australia and administrative and legal barriers require reassessment for successful integration [8]. For example, in Australia, the policy for promoting PVs was initiated without DNO’s input [22]. Afterwards, inverter requirements are imposed in the new version of AS 4777 [23] that requires the power factor (PF) to be between 0.95 leading and 0.95 lagging if the produced current does not exceed 20 A per phase. If it does the PF must be between 0.9 leading and 0.9 lagging [23]. These requirements are selfmanaged by the inverters and still the utility has no control over their performance. Each state, in the United States, has their own policy in which DNOs are opting to apply their service on the shared territories. For example, according to PV-integration policies in Arizona and California [5], some voltage volatile areas are clustered in order to use action control approaches such as volt-var control, which could benefit protection schemes and generation/load balance control. The mitigating strategies might be in place where the issues with the affected areas arise. In contrast, a general policy is active in European Union (EU) that requires PV inverters to be equipped with reactive power control to mitigate voltage volatility that might occur in the distribution networks [24]. Maintaining a power security and reliability with an efficient integration of renewable energy has created opportunities and challenges for power system community.

To assist in creating authentic and homogenous policies that also promote maximizing the share of renewable energy use, the mathematical quantification of the stochastic performance of distribution networks under high number of DG connections may require a special attention from research community. So far, the biggest share of DGs in Australia came with no planning, and even without proper data monitoring to justify the planning almost everywhere in Australia. Adding to that the lack of controllability in most of LV networks, the necessity of adopting a streamlined quantification approach for future electrical system becomes urgent. However, the restrictive decisions based on worst case planning approaches may not allow a satisfactory result, due to the stochastic nature of renewable energy resources as well as the growing volatility in electricity consumption.

1.4 Power Planning Research Direction of the Thesis

The large-scale of renewable energy sources integrated into distribution system requires new operation planning studies. Traditionally, deterministic criteria are used to perform security and reliability assessments and have satisfied the power industry for decades. However, the stochastic intermittence of the produced power from these sources increases the level of system uncertainties. Therefore, the research direction of this thesis is to present mathematical models and simulations using probabilistic methods to address the most likely scenarios of distribution networks when high number of DGs are connected. Particularly, the hosting capacity (HC) determination and risk analysis (RA) of distribution networks are carried out for deep and thorough investigation. The present work can serve DNOs, network designers, renewable energy specialists, energy consumers, cost-benefit analysts, governing bodies, policy and decision makers at planning and operational levels.

1.5 Thesis Objectives

The presented work in this thesis investigates the DG integration in power distribution networks. Two main frameworks have been analysed namely: the hosting capacity and risk analysis within the context of distribution networks. The impacts of large DG connections on the distribution network have been investigated from a planning point of view having an hourly basis. The main objective of the thesis, in the hosting capacity study, is outlined as follows: To develop a methodology that can quantify the impacts of increasing DG connections while considering associated uncertainties to determine the network hosting capacity. The proposed methodology should have the following features:

1. The ability to estimate the uncertainty of the solar irradiation while taking into the consideration the local meteorological conditions.
2. The ability to estimate network hosting capacity in a timely manner, ideally by considering the uncertainties arisen from the connected DGs and loads.
3. Ability to utilize efficient computational technique, such as sparse grid, for handling the uncertainty computations in a multi-dimensional problem in efficient way.

The main objective of the thesis, in the risk analysis study part, is outlined as follows: To develop a new risk analysis that can provide a qualitative degree of the risk assessment for the entire distribution network when the DG connections are increased. The proposed method should have the following features:

1. The formulation of inter-dependences existing among the uncertainties of DGs and loads.
2. The operational performance of the entire distribution network has to be examined while taking into the consideration the two risk concepts: likelihood (probability of an event to occur) and severity (consequence of an event when it occurs).

1.6 Thesis Structure

This is a PhD thesis by publication. Altogether, the thesis includes: a) two journal papers, and b) three international conference papers. The first article was published in the IEEE Transactions on Industrial Informatics, the second journal has been submitted. The conference publications include World Renewable Energy Congress (WREC) 17 which was held in Manama, Kingdom of Bahrain, 3-8 December 2016. The WREC is one of the most effective non-profit organizations in the support of utilising and implementing renewable energy sources that are both environmentally safe and economically sustainable. The conference has a significant contribution to the research community such as the conference's official journal *Renewable Energy*. The second conference is the Asian conference on Energy, Power and Transportation Electrification (ACEPT) which was held in Singapore, 24–26 October 2017. The ACEPT is a part of Asia Clear Energy Summit which is aimed to be the hub of clean energy in Asia. The conference brings the advancements in clean energy technology, policy and finance supported by leading government agencies, research institutes and industry to collaborate on critical issues in harnessing clean energy for future. IEEE Conference on Probabilistic Methods Applied to Power Systems (PMAPS) which was held in Boise, Idaho, United States, 24–28, June 2018. The PMAPS conference is the only event where engineers and scientists worldwide come to share and discuss their experience, ideas, and research on applying probability theory and statistic methods to power system analysis. The theme of PMAPS 2018 is "*Probabilistic Methods: Practical Approaches for Managing Risk and Uncertainty in the*

Electric Power Industry" that contributes significantly to the risk and uncertainty related studies, which fits with the purpose of this thesis.

The thesis body is formed by eight Chapters:

Chapter 1: contains an introductory part showing the significance of the work for the power system analysis; also highlights the research directions, objectives and structure of the thesis.

Chapter 2: presents a critical analysis of the recent literature on the practicality of the bidirectional power flow in the active distribution networks where the power in the distribution lines can flow in reversed direction, i.e. from the point of common coupling (PCC) to the utility. The chapter also presents a literature review on the issues arising from high DG penetration specially in the LV networks with an emphasis on the power flow analysis with the reliance on the major data such as bus voltages and lines' loadings. The performed hosting capacity concepts are also discussed and briefly summarised. In addition, this chapter contains the details for the definition of risk within the context of distribution system planning and operation.

Chapter 3: presents the research results published under the title "Uncertainty Model for Total Solar Irradiance Estimation on Australian Rooftops". The uncertainty model of ground-reaching radiation has been formulated in this chapter. Using clearness index[1] characteristics represented in the form of probability density function (PDF), the uncertainty of the total radiation incident on a tilted surface is driven in anisotropic sky

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[1] Clearness index is a measure of the atmosphere transparency acting in accordance with the daytime and seasonal variations; and mathematically it is the ratio of beam irradiance to global irradiance.

condition. The model of total irradiation estimation incorporates the circumsolar diffuse, horizon brightening and anisotropy factor resulting an isotropic HDKR model [25]. The logistic function for estimating the diffuse radiation from clearness index is used to comply with the Australian meteorological conditions. The goodness-of-fit techniques, root mean square error, mean bias error, Kolmogorov-Smirnov test and the correlation coefficient (R^2) are employed to assess the quality of the model with the utilization of the actual data collected in the city of Adelaide, state of South Australia.

Chapter 4: presents the research results published under the title “Probabilistic Analysis of Maximum Allowable PV Connections across Bidirectional Feeders within a Distribution Network”. The concept of bidirectional feeders is proposed in this chapter to expand the connections of PVs in the hosting distribution network. The purpose of this chapter is to analyse the feasibility of bidirectional feeders considering the uncertainties of grid-connected PVs. Understanding the bidirectional feeders helps in achieving a smooth transition of distribution networks from being passive into active. The increase of PV connections is performed in a stepwise fashion against the amount of load connected in the same PCC. By the utilization of Quasi-Monte Carlo (QMC), the probabilistic performance is established in a co-simulation integrated environment between OpenDSS, the advanced distribution network modeller, and Matlab through a common object model (COM) port. In the assessment of the network, the reverse power index is formulated to show at which degree the bidirectionality becomes an issue.

Chapter 5: presents the research results published under the title “Probabilistic Hosting Capacity for Active Distribution Networks”. Furthermore, a new novel approach is presented for determining HC of distribution networks. The approach is extended version of the HC idea, as discussed in [11]. The proposed extended technique is time-dependent and involves the use of probabilistic assessment. The HC approach is discussed with the mathematical representation in a probabilistic fashion. The PV, WT and load uncertainty models are formulated mathematically. The PV uncertainty representation based on the Hay-Davies model [25] for the estimation of the total solar irradiation, in addition to one presented in chapter 3, is also introduced in this chapter. The model is included in this thesis due to its simplicity and practicality. In the HC approach, the three different regions, related to gradual increase of DG connections, are identified. The regions are used in classification of the degree of threat to distribution system. Power quality and network overloading are set to be the operational performance indices. Another new contribution in this chapter is the proposal of using sparse grid numerical technique as an efficient alternative to the MCT in terms of computation time. Lastly, an application example using the large distribution network situated in South Australia is included.

Chapter 6: presents the research results in publication style under the title "New Risk Analysis Approach for Bidirectional Distribution Feeders under High PV Penetration considering Spatial Correlations using Nataf Transformation". In this chapter, a new temporal risk analysis approach for distribution networks is presented. The purpose of the chapter is to quantify the degree of risk for distribution network as whole instead of more conventional methods that assess the network by parts, such as assessing individual operations of lines or buses. The risk components, likelihood and severity, are considered when formulating three novel operational risk indices, bus overvoltage violation R^{VV}, lines ampacity violation R^{AV} and the reversal power flow violation at the grid supply point (GSP) R^{RV}. Therefore, in practice, there are six operational indices (R_{lik}^{VV}, R_{lik}^{AV}, R_{lik}^{RV}, R_{sev}^{VV}, R_{sev}^{AV} and R_{sev}^{RV}) established to assess the performance of distribution networks during high DG penetration. The inter dependences between the sources of uncertainties have been formulated using Nataf transformation [26] to tackle the nonlinearity of the correlations. This is because of PV uncertainty model is strictly non-Gaussian and by using the Nataf transformation we study a rank correlation rather than direct correlation, avoiding the mismatch between different L^2 spaces. The rank correlations are hypothesised according to the pre-given spatial correlations of probability distributions presented in [27]. The risk assessment has been visualized in three-dimensional view with the coordinates: likelihood and severity of the risk and increase of PV connections in percentage relation with connected load.

Chapter 7: presents the research results published under the title "Hourly-Assessment of Grid Hosting Capacity for Active Distribution Network". Particularly, the concept of probabilistic hosting capacity presented in chapter 5 has been utilized to conduct a new analysis of high DG connections in distribution networks with the utilization of the risk analysis presented in chapter 6. The hourly correlation of PV outputs is explained based on the degree of dependence between a pair of random variables using the Nataf transformation. The increase of PV connections with correlated PDFs in distribution system has been a time-space problem in which spatiotemporal evaluations are performed. The procedures for risk assessment starting from specifying the characteristics of connected sources of generations with correlated uncertainties up to the determination of HC have been provided with details. The purpose of this chapter is to provide a methodology that determines the HC of the distribution feeders under assessment taking into account the non-perfect positive correlations between connected sources of uncertainties.

Chapter 8: presents a summary of the presented contributions in this thesis and proposals for future work.

1.7 How the Publications are related to the Thesis

The publications included in this thesis are strictly related to the thesis objectives. In the following paragraphs, a brief summary of contribution/formulation/outcome of each publication and how it is related to the thesis are provided. Chapters three, four, five, six and seven are the original novel parts of the thesis, see the Table 1.2. The paper titled "Uncertainty Model for Total Solar Irradiance Estimation on Australian Rooftops" provides a new model to estimate the uncertainty of the total solar radiation incident on a tilted area and is compatible with Australian meteorological conditions. The main reason is that the readily available uncertainty models for PV power production have not considered the logistic function between the clearness index and the diffuse fraction in estimating the total irradiation. The logistic function is proven to be best-fit for the conditions of Australian meteorology (see reference [8] in chapter 3). The mathematical formulation of this model is written in a Matlab code. The uncertain behaviour of a PV at each hour for a day in a year is factorized by a time-based PDF. The performance of the

Table 1.2 the distriubiton of pablications into chapters

Paper Number	Chapter Number	Paper Title	Status
1	Chapter 3	Uncertainty Model for Total Solar Irradiance Estimation on Australian Rooftops	Published
2	Chapter 4	Probabilistic Analysis of Maximum Allowable PV Connections across Bidirectional Feeders within a Distribution Network	Published
3	Chapter 5	Probabilistic Hosting Capacity for Active Distribution Networks	Published
4	Chapter 6	New Risk Analysis Approach for Bidirectional Distribution Feeders under High PV Penetration considering Spatial Correlations using Nataf Transformation	Submitted
5	Chapter 7	Hourly-Assessment of Grid Hosting Capacity for Active Distribution Network	Published

model is examined against the real data taken for Adelaide with a satisfactory result. This paper answers the first thesis objective in terms of HC determination.

The paper titled “Probabilistic Analysis of Maximum Allowable PV Connections across Bidirectional Feeders within a Distribution Network” provides an insightful analysis of the bidirectionality in power flow analysis of distribution networks. The main reason is to test the technical behaviour of the distribution feeders when the reversed power flow is occurring at certain daylight hours. The bidirectional feeders promise a solution to the power congestion in the exchange among the sub-feeders and feeders, i.e. residential to/from commercial areas [28-29]. The results obtained support the need to adopt active distribution network concept and technology as early as possible due to the high probability of reversed power occurring once a PV is connected. The probabilistic expectation of bidirectionality occurrence is very high which promotes our attempt in the adoption of ADN in the next chapter.

The paper titled “Probabilistic Hosting Capacity for Active Distribution Networks” provides a thorough definition of the proposed approach for determining network HC, utilizing the analysis of bidirectional feeders for ADNs in the previous chapter. The approach establishes the functional relation between the operational performance indices and the increase of DG connections and mathematical formulation for identifying the HC limits. The paper is considered the most important part of the thesis and this approach is used in other related work hereinafter. Also, a PV uncertainty model based on the Hay-Davies mathematical expression is formulated and used because of its simplicity. The uncertainty models for loads and WT are, in addition, formulated in this paper and used later in other papers. Beside the main purpose of the paper which is proposing probabilistic HC, the SGT is utilized for handling the computations and has proved its superiority in terms of delivering an efficient computational time and accuracy. This paper answers the second and third thesis objectives in terms of HC determination.

The paper titled “New Risk Analysis Approach for Bidirectional Distribution Feeders under High PV Penetration considering Spatial Correlations using Nataf Transformation” provides the notion of applying risk analysis on distribution networks. The uncertainty propagation of the technical impacts when increasing DG connections is performed taking into the consideration the effects of spatial correlations among the random quantities i.e. PV outputs or electricity consumptions. The main contribution from this paper to the thesis is the presented stochastic model that facilitates the mathematical complexity for conducting correlated random variables and risk assessments, making it trackable through a schematic diagram with three collective layers. In addition, the risk components, likelihood and severity have been utilized via a new algorithm to quantify the degree of the risk, defined by six risk indices. The outcomes of this study provides answer to the first thesis objective in terms of risk analysis.

The paper tilted “Hourly-Assessment of Grid Hosting Capacity for Active Distribution Network” presents the application of probabilistic HC introduced in the third paper combined with the risk analysis presented in the fourth paper. The relative frequency of number of violations and the relative frequency of the accumulative depth, defined in Chapter 6, of violations have been utilized to assess the network’s performance. The hourly probabilistic HC considering the spatial correlations is then determined with the use of six operational performance indices formulated in the fourth paper. The effect of the contractual loads has been investigated with the results showing very low effects on the system operation. The descriptive statistics techniques, such as the percentile functions, are employed in the analysis of the impacts. This can support the specialists to quantify the impacts according to the localized utility standards, i.e. using other than statistical expectations. This paper answers the second thesis objective in terms of risk analysis.

1.8 Thesis Format

The thesis is written as a collection of publications and research contributions by these papers are complementary to the aforementioned thesis objectives. All these publications are written within the PhD candidature duration and purposely linked and pre-planed according to thesis by publication format, the University’s *Specifications for*

Thesis [30]. Each publication is accompanied with a statement of authorship showing the publication status, publication details, principal author, co-authors and the contribution of each author with their signatures. The online version of the thesis is provided as a PDF and readable with the use of Adobe Reader 9. The hardcopy printed version of this thesis includes all the publications mentioned in this chapter while the online version includes only the addresses of these publications. The proof reading and editing of this research thesis is covered by the academic supervisors according to the C, D and E Standards of the Australian Standards for Editing Practice (ASEP).

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Chapter 2

Literature Review

2.1 Introduction

With the vast increase of DG connections in residential areas, the concept of active distribution network (ADN) was introduced, making the distribution network operates in a bidirectional way allowing more injected power from DGs to be used. As a result, the power distribution networks are facing several challenges. Of these, the uncertainty of the power injections from DGs has led to uncertain performance of networks due to the fact that most of these DG connections are neither controllable nor observable yet. In this thesis, solutions to the problems are set upon a number of supporting issues. To enable a better understanding of the research context, a literature review is presented for the following relevant directions:

1. Active distribution network
2. Hosting capacity
3. Risk analysis

2.2 Active Distribution Networks

2.2.1. Importance of ADN

Active distribution network comes as an alternative technique to allow efficient exploitation of the inadvertent power produced by DGs. The small-scale power producers and consumers that are commonly called "prosumers"[1] are largely distributed within distribution networks nowadays. Since they are mostly invisible to the network operators,

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[1] Consumers equipped with DG e.g. rooftop-PV or WT are referred to prosumers (producer - consumer).

their power integration into the grid would become technical and commercial issues. The level of uncertainty in the operational violations increases and brings additional problems such as tracking the possible locations of voltage rises within a network or where a voltage drop could occur [1]. Some proposed or already implemented solutions may require heavy financial means compared to other solutions. For example, the proposals for introducing ancillary services to support the network normal operation such as online voltage/reactive/harmonic compensator or other that require installation, management and maintenance such as regulator, storage, online tap changer (OLTC). In addition, providing extra infrastructure such as network reconfiguration facilities (online static and dynamic switches) or network reinforcement (cables and transformers) requires major investments [2]. Although more techno-economic and cost-benefit studies are presented in [3, 4], more studies are needed as the concept of ADN is considered as a viable alternative to cope with the high DG penetration [5]. Even with the involvement of ordinary information and communication technology (ICT) such as hourly readings and operational actions, an important active role would be settled by these dispersed prosumers comparing with what happening with the locally massive power production, especially around noon time. For the following discussion it is more helpful to be clear about what is meant by ADN?

2.2.2. Definition

Active distribution network is developed to systemize the shared renewable energy sources that are connected in the distribution networks. Although there is no acceptable global definition. According to CIGRE (International Council on Large Electric Systems) Working Group (WG) C6.11 [6, 7, 8], ADNs can be defined as distribution networks that have systems in place to control a combination of generation sources, consumptions and even energy storages. A vast array of different names may link anyhow to the same concept of ADNs such as smart grids, virtual power plants, cells, etc, which sometimes are used interchangeably. Examples are: the non-islanded microgrid in [9] or the virtual power plant in [10] and [11]. The term "active distribution network" comes in the fourth position after smart grid, microgrid, and virtual power plant concerning its popularity in the published research. In Figure 2.1, the frequency of the research publications in the field of power system with these terms is plotted as a word cloud. The size of the word or phrase is proportional to the frequency of these terms appeared in the published research. The main fundamental of ADN is to maximise DG penetration by managing DG outputs and other management means through centralised coordination or distributed control [12]. The main characteristic of ADN is the bi-directionality of the power flow allowing the exchange of the energy between the neighbouring networks. Even with the recommendations towards more investigations for multi-directional power flows [13], several researchers have already based their proposed solutions under this characteristic. For example, studies are to: optimising energy storage usage [6] [14], indicating reversed power flowing when estimating PV feed-in power through a satellite-derived irradiance data [15], evaluation of the life expectancy of utility transformers [16], and consideration the multi-directional power flows in the system. The trend is heading towards intelligent and automated central control such as in [17]. The centralized system is responsible for coordinating and optimizing the operation of ADN via automatically organized controllers [18, 19, 20]. However, there is still a need for new tools that promote probabilistic planning with a time horizon before ADN to become a reality. In order to answer the roaming question: “Why most of ADN has failed to be adopted by many utilities” these tools are worth further study.

The significance of including probabilistic means in the thesis has been propagated upon a number of published research in regard to ADN planning. As summarized in the Tabel 1 in Chapter 6. Furthermore, the reports emerged such as [21, 22, 23, 24, 6] from WGs of CIGRE highlight the importance of short-term strategies, risk assessments and predictive models in ADNs. Beside these WGs, other research also tends to follow the same suggestions and recommendations. For example, the review of next distribution networks

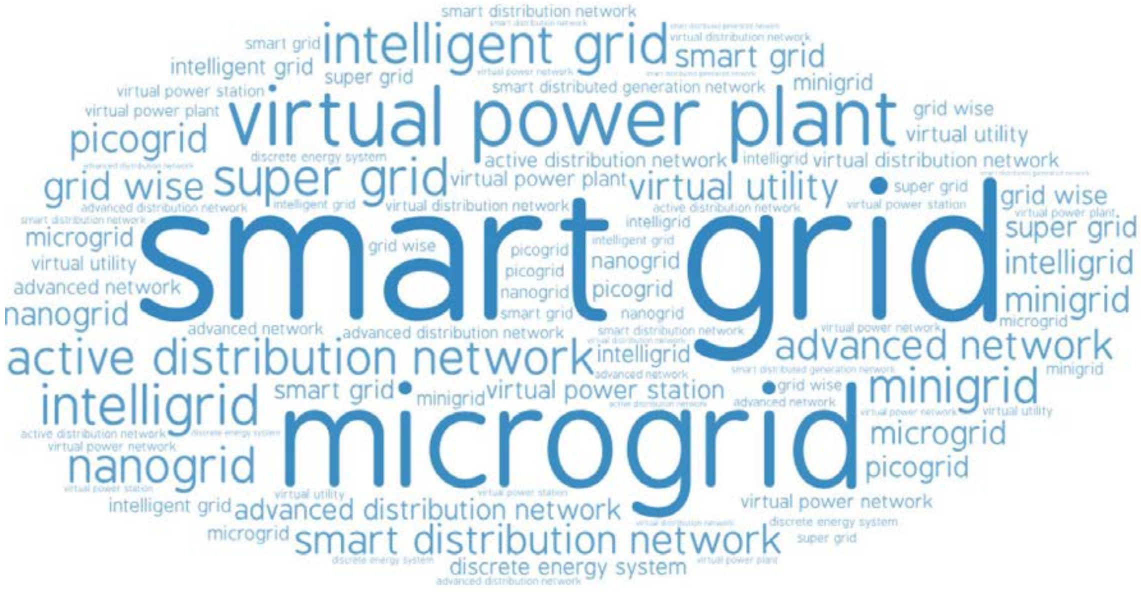

Figure 2.1 Word cloud of names that could refer to the concept of ADN. The size of a word or a phrase is proportional to the number of times appeared in Google scholar web-search.

planning in [5] strongly supports probabilistic approaches and considers that the use of the deterministic methods in the current paradigm of distribution networks can lead to unreliable services and system quality degradation. In [25], another review suggests using probability theories to understand the associated risks and perform stochastic automated optimizations. On the top of these, vulnerability and risk analysis for the current infrastructures have been critically investigated in [26] where the emphasis goes to extend the classical and historical modelling to understand the system behaviour. Furthermore, following the study [27] on how to characterize the risk, the use of probabilistic means is inevitable since the concept of ADN can be considered as a complex system with recognized and unrecognized uncertainties. Finally, to make the concept of ADN viable to power utilities, more studies for short term solutions, risk analysis and predictive evaluations are needed by which the proposed approaches in this thesis are regarded complementary to the corrective actions of the automation control strategies.

2.2.3. Look Ahead Policy

Look ahead policy (LAP) is also another important factor recommended for the new planning of ADN. Moreover, LAP tools are becoming essential elements for idealizing the next grid designs [28, 29], as they allow for load forecasting, demand management, end-to-end control capabilities, market enabling, service and power quality assessment, cost and asset optimization, security, performance, and grid self-healing and restoration [30]. Look ahead policy has been widely employed for trading in the electricity market for arbitrage opportunities such as in [31]. Recently, adaptation and resilience related research that addresses the significance of this policy in power system planning is presented in [29]. The adaption refers to the actions taken by operators or automatic control operators to decrease system vulnerability. In other words, it refers to the approaches to moderate possible harm, risk of harm or exploit opportunities by estimating actual or expected events. While resilience is the system's ability to overcome extraordinary (high impact probability) events or rapid recover after disruptive events and update its operation to prevent future similar events [32, 33]. The objective of LAP is to optimize the network operation and/or to prevent a risky event. The short-term resilience measures can help drive preventive and corrective actions such as power reservation planning or generation dispatching. In other words, a post disturbance overloading of lines can be alleviated via minimizing the feed-in generation and then line power flows in pre-planned measures. In this regard, an accurate forecast within a time frame is the key success for the effectiveness of LAP. That is where some intensive work has been conducted to improve the level of accuracy in forecasting, such as for PVs or electricity consumptions [34]. Whether it was an intra-hour, intra-day or day-ahead, LAP would replace the fit-and-forget models designed for the current networks. Actually, a general consensus is forming towards that the "fit and forget" models are no longer suitable for planning and design of the modern distribution networks [35]. Solutions are proposed for automatously managing the network operation from few seconds to minutes forecasting for PV and storage controls in [36], while one-hour policy is usually suggested for the purpose of asset management [37]. Examples of one-hour policy are: for risk assessment [38], load forecasting [39], dynamic thermal rating [40], PV's probability density function

(PDF) [41] and state of charge in storage sizing [42]. In this way, the ADN concept development is going ahead.

These studies have motivated us to direct the models and approaches presented in this thesis for one-hour policy to estimate the network performance. In general, the processes in the planning of distribution networks can be summarized as follows [25]:

1st process: Data gathering,

2nd process: Forecasting and performance assessment,

3rd process: Problem identification and project formulation,

4th process: Alternative solutions identification,

5th process: System evaluation, prioritization and approval.

The routine practices of these processes are highlighted as follows: the examination to identify and quantify the planning process of the project in regards with utility's capabilities and requirements is based on the knowledge of forecasting exercises through a set of system assessments. In other words, the necessity of the planning is examined by meeting the utility's criteria such as system reliability, system security, customer satisfaction etc. If the utility's criteria are met, then identifying of the problem can be established. So, network designers and planners can incorporate the outcomes of the examination to formulate the problem with a planning for alternative solutions such as power quality enhancement, capacity expansion etc. After formulating the problem objectives, the development of the planning measures such as modelling, simulation tools, optimization is preformed to evaluate various planning solutions. In this regard, Chapters 4, 5, 6 and 7 follow the aforementioned rhythm or practice in conducting research for power distribution planning and operation.

2.3 Hosting Capacity

2.3.1. General Concept

The high DG penetration into a distribution network impacts normal operational condition. While a little penetration can have positive impacts like voltage improvement or transformer relief, on the other hand high penetration can have adverse impacts on voltage regulators, direction of the power flow, LV feeder congestion, frequency, transient current etc [43]. For example, the intermittent output power injected into the network can make voltage profile to be either over or under the specified limits. In another example, reactive power compensator (i.e. Automatic Q Control - AQC) will be significantly affected if a high DG penetration exists, especially when the majority of connected generators result in active power produced DGs such as PV. When the DG penetration is high, the amount of active power withdrawn from a substation will be low while the reactive component stays the same. This will trigger the AQC to react with PF correction. Also, the capacitor banks and tap-changing transformers will play a big role in controlling over/under voltage conditions of a feeder. In addition, DGs connected may overlap with the principle work operation of On-Line feeder voltage regulator. As On-Line VR (OLVR) reacts in accordance with measurement equipment installed at the end of the feeder to keep the voltage within its standard limits, DG connected at the end of the feeder can deceive the OLVR allowing the measurements to send positive voltage levels.

This can lead into voltage dip at the mid of the feeder where OLVR is designed to correct and raise the voltage [44]. The problems mentioned above give rise to a new term in the power system taxonomy called “Hosting Capacity” (HC). While the meaning may refer to the maximum ability limit of a power network in hosting DGs without jeopardizing the utilities’ and customers’ appliances, the impacts of DGs on a distribution network can only be assessed through developing a set of indices, according to [45] [46], which also introduces a clear concept of the hosting. In general, the definition of HC is the maximum capacity of DGs that can be connected to a distribution without disrupting the normal operational conditions. The HC is network oriented and based on DGs’ types and number with other details explained in Table 2.1 for existing methods for assessing high DG impacts and HC (the table is elaborated more in the following subsection). In the table, the studies are classified, concerning system hosting capacity assessment, into steady state planning [47] or dynamic planning [48, 49, 50, 51, 52] so that the timely behaviour of the system is considered. Thus, the HC has been evaluated with different criteria, method and grid type. The grid type, herein, means that the total amount of generation from DGs can suppress the local demands in which the network starts exporting power back to the bulk grid through grid supply point.

2.3.2. Definition and Related Studies

Recently, there has been a growing interest in the topic of HC when having a mix of renewable and non-renewable generating technologies. It has been found that definition of HC is consistent in the reviewed publications. Examples of these definitions are:

> “*the hosting capacity of the LV grid for dispersed generation is restricted by the maximum permissible voltage rise within the grid and the maximum short-term loading of the transformer and the cables, due to the diurnal cycle of the PV*” [53]
>
> “*The maximum amount of new production or consumption that can be connected without endangering the reliability or quality for other customers*” and “*the acceptable degree of DER penetration under given circumstances*” [45]
>
> “*the upper limit of DG before network congestion occurs*” [54]
>
> “*the largest PV generation that can be accommodated without violating the feeder’s operational limits*” [55]

In [56] the literature of HC is categorized into two. The first category is dedicated to the methods and techniques for HC determination, while the second is for HC maximization. It should be emphasised that it is part of the thesis’s interest to develop methods and techniques related to the HC determination only, no consideration is paid for HC maximization. Up to the time of writing this thesis, HC determination methods have not been classified yet into groups in the reviewed literature, except the presented classification of steady state and dynamic approaches, mentioned in the previous subsection. Several methods for determining HC are reviewed here with a special attention being paid for the approaches looking at the problem from totally different views.

The market statistical distributions of common sizes of residential and commercial PVs are used by EPRI to conduct scenario-based analysis involving a huge number of load flow calculations [48]. In the EPRI analysis, exceeding the voltage standard limits is set for determining the HC of a network. The study considers stochastic PV deployments from pre-set quantity distribution of PV sizes, according to their likelihood of being purchased from the market. Six million unique scenarios were created and the worst-case scenarios (high power productions at low consumptions) were considered for minimum HC limit. The study was then further advanced by streamlining the possible capacity of extra PVs with exceeding voltage limits [57]. Distributing randomly PVs into a set of locations (to create one scenario) in the distribution was addressed in [58] with voltage exceedance limit being displayed as PDF. Hosting capacity is calculated according to the scenario that delivers a minimum value of PV power injection [59]. The procedures of the method mentioned in [59] are:

Step 1: deploy PVs randomly to create an i-scenario,

Step 2: increase the amount of rated power generation from these PVs until one voltage violation occurs in the network,

Step 3: assign the value of PV power to be hc_i,

Step 4: repeat step 1 to 3 until $i = n$, where n is the total number of scenarios,

Step 5: find the min$\{hc_i, \ldots, hc_i, \ldots, hc_n\}$.

The concept of coincident hours is introduced for HC determination using two different sets of one-year recorded data for two wind power turbines and one set of recorded data for electricity consumption for a network in Scotland [52].

The procedures of the method (coincident hours) are performed by creating different scenarios (0-100% demand and 0-100% generation with 10% interval). At each single scenario,

Step1 a range of load and DG (e.g. 10-20% load and 70-80% DG connected) that needs to be monitored is specified.

Step2 an hourly LF for one-year is preformed using 2003 recorded profiles of two wind turbine outputs and one load, when the range in step 1 occurs, record the number of hours for load and DG that coincide at this range which is called "coincidence hours", i.e. a joint hourly probability of occurrence.

In other different methods, the characteristics of feeders are examined to determine the HC. Notably some research examined the link between network feeder characteristics (e.g. number of house connections, total path impedance, sum of wired line length etc.) and HC in one-day analysis [49]. The study involved constant PV sizes (3 kW) with HC maximum limit is set when voltage standard limit is violated. Five HC categories are established to classify the distribution network in terms of its ability to host PVs (very weak, weak, average, strong, very strong). The method matches HC values of a grid with its parameters. A summary of the method is given below:

Step 1 start with an i-th grid, where $i = 1$, i is a counter for the grids under test.

Step 2 randomly select a DG, then assign a power value in-between [0, P_{max}] where P_{max}= 1 kW,

Step 3 distribute the selected power value into each network node according to a uniform distribution until all nodes reached

Step 4 check HC criteria, if criteria have been reached, then perform $i = i + 1$ then select a new i-th grid and start from step 2. Otherwise, go to step 5,

Step 5 if $i \neq N$, continue to Step 6, where N is the total number of grids under test. Otherwise, go to step 7.

Step 6 increase P_{max} by a stepwise amount of 0.1 kW and repeat Step 2 till 4,

Step 7 categorize all grids into one of the five categorizes (very weak to very strong) according to their HC values.

The similar classification approach was conducted in [50] as well.

Bollen and Hassan [45] described the fundamentals for the HC concept and introduced the guidelines for determining network HC. It is stated that "*The impact of distributed generation can be quantified only by using a set of performance indicators*". The method is further explained in [46]. The method can be summarized as follows:

Step 1 Establish one or more performance indices.

Step 2 Specify one or more standardized limits for the performance indices in Step 1 in which the operation system will be in different state (such as acceptable deterioration, unacceptable deterioration or critical deterioration) if these limits are exceeded. Such a limit can be as defined by EN50160 [60] or any other standards defined by the local utility.

Step 3 Find the functional relation between the indices and the increases in the number DG connections;

Step 4 Identify network HC according to the limits' exceedance in Step 2;

The method is depicted in Figure 2.2 with the x-axis represents DG penetration increase started from a certain amount of DG power penetration in kW and the y-axis is to show the degree of system deterioration. The region shaded in green is to indicate that the system is under deterioration which can be considered tolerable, from DNO's point of view. The region shaded in red is where the system is considered under intolerable deterioration. The network HC limit is identified once the deterioration index crosses from the tolerable region into the intolerable one. The method was utilized on a MV network involving two wind turbines, then, the network performance was assessed using a local load flow simulation software with two years of recorded data [51]. In addition, time-series analysis was performed with two performance indicators regarding power quality and overloading.

The key components for applying the last method is to establish performance metrics. In the literature, indices were established for assessing the network performance variation according to the point of interest. In fact, there is no particular number of indices that

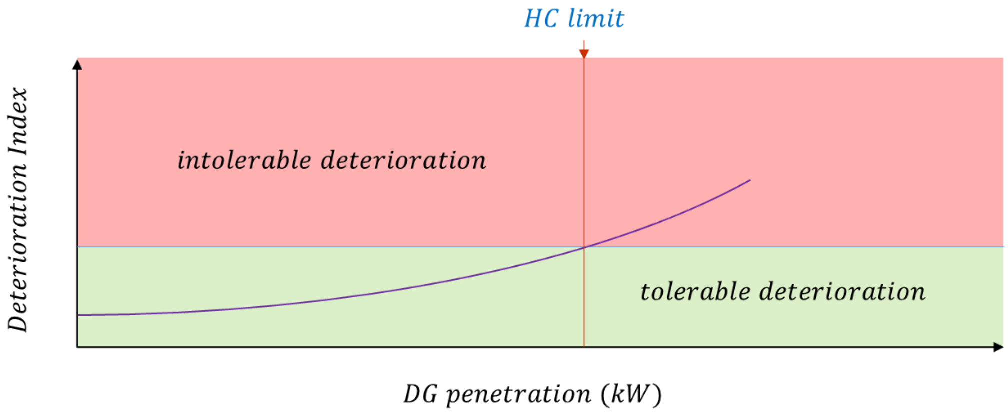

Figure 2.2 HC method introduced by Bollen and Hassan [45].

should be involved nor particular type of indices. The purpose of the indices is to quantify the impacts of DG penetration in which it enables an explicit determination of network HC. The issues related to over/under voltage, network overloading, power losses, power and current quality, harmonics etc, can be used to formulate these indices [61]. Other indices include high-frequency harmonic distortion levels [62], fast voltage variations, low frequency [63] and more [64]. Despite the growing interest in assessing the performance of distribution network based on permissible voltage standards, lines carrying current capacity or network overloading and harmonic distortion, in this thesis, harmonic related indices are out of the thesis scope. The voltage violations and network overloading are still the most common concerns from the utility's point of view [65-68]. Examples of indices are voltage standards related [69, 70] and overcurrent indices [71]. In the following subsection, the common policies and standards are reviewed to support the formulation of operational indices related to voltage and overloading issues. In chapter 5, the development of probabilistic HC is developed upon the last HC approach explained [45]. It is worth noting that while drafting this thesis, HC related topics are reviewed [72, 73], which tend to cover HC methods, HC improvement, HC measures, and identification of research gaps. In addition to highlighting the importance of assessing the impact of DG penetration through performance indices.

2.3.3. Regulatory Policies and Standards

In some countries, the large DG penetration in low voltage distribution networks drives policy makers to legislate changes to existing regulations. For example, EU directive [74] imposes reactive power compensator equipped with PV provider device to counter the voltage volatility and other impacts. German regulations [75], for instance, requires each DG to have a Power Factor (PF) regulator. In contrast, in USA such as in California and Arizona, the impacts resulted from the connected DGs are treated by local utility facilities. In Australia, there is very limited participation from DNO regarding the operational policy of connected DGs [76]. Generally, [77] addresses the risk of increasing PV systems connected to a utility grid as well as some measures taken by 6 countries (Germany, The United States, Japan, Italy, Belgium and Australia). In this thesis, six country-specific case studies of improving the PV integration are covered and presented as follows [77]:

1. German PV and wind power integration uses smart PV inverter functionalities (balance active and reactive power control) to reduce the grid reinforcements. Four scenarios were conducted according to reactive power injection by PV systems.
2. US study, utilities allow 15% PV penetration to limit the impact on voltage regulation, protection coordination, equipment ratings and risk of islanding.
3. Japanese solution is to control the voltage level if it is exceeded the specified limit (1.07 pu) through adjusting reactive power in the nearby network (see fig.9 in [77]). This allows PV penetration[2] to reach 7% (for the definition of PV penetration, see section *2. PV Uncertainty Model and Penetration Increase* in *Chapter 6* in page 104) with using autonomous control methods. Another

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[2] "PV penetration" refers to the actual power injected by a PV into the grid, which is mainly dictated by the uncertainty of solar irradiation.

solution is to use remote control method which is to let other PV to share their reactive power.

4. Italian university study aims to simulate two yearly maximum load scenarios (702 kW and 180 kW) with presence of PV (see Tables VII and XI in [77]). It also suggests that reconfiguration of the grid is required to increase PV penetration.
5. Belgium is leading some studies for the placement of storages to avoid congestion and increase PV penetration. Also, some companies want to address the active participation of large scale PV penetration.
6. Australian grid codes specify the requirements for inverters such as power rating up to 10 kVA for single-phase and 30 kVA for 3-phase. Some power provider such as ActewAGL, limits the maximum capacity of combined PV installations to be less than 30% of the rated capacity of the feeder's transformer.

Particularly, a quick review on the available policies and standards concerning voltage quality and network overloading may help understand the requirement from the utilities and how these requirements differ between utilities. The regulatory standards are driven by the technical standards where the nodal voltages, line and transformer currents play a vital role in low voltage distribution networks. Herein, voltage deviation at the point of common coupling (PCC) shall comply with the specified tolerance of the nominal voltage. For this context, the PCC is where measurements can be accessible for both utility and customer, according to IEEE 519. As stated in the technical standards for the acceptable steady state voltage, there are slight differences between standards as shown in Figure

2.3. The figure also shows the difference in the over/under threshold voltages specifically at the normal operation condition within the most adopted standards and at PCCs. The narrowest normal operation bandwidth is found within ANSI c.84.1 specifically for customer service voltage in range A and followed by the latest released standard (AS 61000.3.1) where over/under voltages are split in two thresholds namely preferred and allowed. In contrast, German standards (VDE-AR-N4105) states the widest bandwidth of normal operation with plus 10% and minus 20% of the nominal voltage. Also, it is obvious that voltage swell and sag are considered differently within the aforementioned standards. For instance, in VDE-AR-N4105 the action, which is either disconnecting the DG from the grid or return the voltage to the normal state, is required within no more than 0.2s. However, in IEC 61727 and IEEE 1547 the required time response is specified to be faster, 0.05s and 0.16s respectively. This is with the emphasis on monopoly utility policy, or in other words, no voltage protection or voltage control are to be equipped with DG. Despite other specific purposes of these standards, the general goal is to maintain and upkeep low-voltage distribution networks with high, efficient and reliable power quality. However, the introduction of new technologies such as advanced network automation [78] (in particular automatic network reconfiguration, Volt-Var control, remote metering, load management, integrated GIS with dynamic management, demand side management and load survey) may require new standards or the current standards need to be revisited or revised within the context of efficient DG integration. Although the thesis has used the voltage standard EN 50160, it does not affect the technical outcome of the proposed approaches in Chapter 4-7 if other voltage standard is adopted."

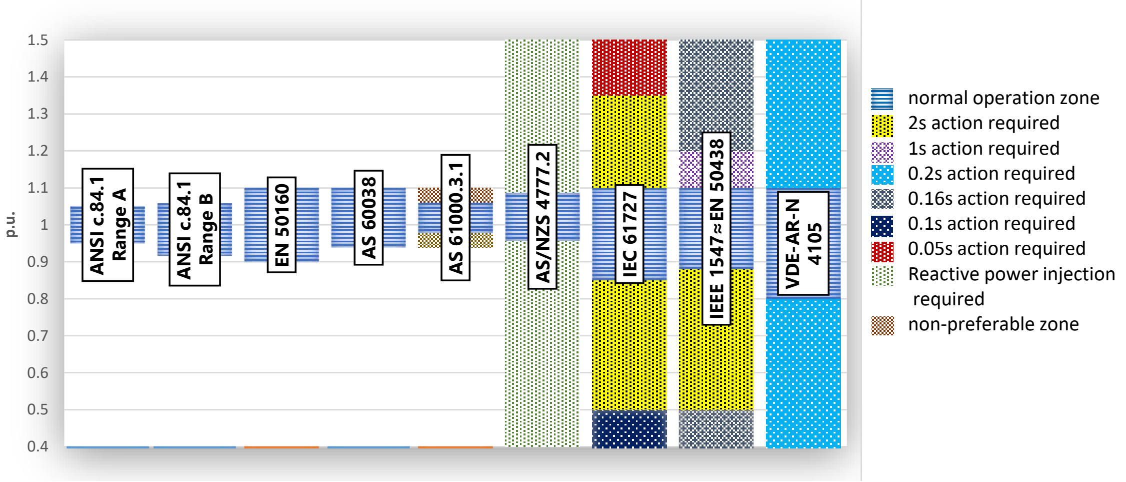

Figure 2.3 Service, utilization and DG voltage standards (all are available at www.freestd.us)

The power penetration from the DG connections may overload the utility equipment and appliances. The review of lines and cables standards could be endless as different network structures would result in different standards and based on the utility preferences; however, the technical line ampacity recommendation is widely used such as IEC 60364-5-52 Standard, 2008 [79]. Ampacity is the maximum current that a conductor can carry for a specified period of time which is affected by frequency, average current density and temperature [80]. In practice, cables' capacities are set with two different ratings, normal and emergency [81]. Despite the inconsistence of normal and emergency ratings [53], it is commonly assumed that the normal rating is about 50% to 75% of the emergency ratings. Or sometimes, the normal ampacity ratings are considered in percent quantities such as 150% of nominal values in [53]. The dynamic ratings are to be considered rather than constant values which could be utilized for different applications as for voltage control in [82]. The normal transformer rating in a steady state operation varies between 100% [83] to 150% [53] depending on factors like ambient temperature, age, oil-cooling type …etc., further details are given in [6]. Particularly, this differs from the nameplate rating perhaps by 10%. In addition, it is common to consider an emergency rating between 140%-170% to the normal ones. Contrary to the lines and cables, this rating is not always an hourly rating quantity in which it could be dependent on the loss-of-life criterion; for example, losing 1% life-per-day while under emergency loading [83]. For this reason, other researchers have adapted a dynamic real-time rating system for grid lines and transformers [19]. To conclude, the thermal overloading rating depends heavily on the local utility and their adopted standards. The regulatory standards for transformer's emergency power rating is used in this thesis to set for the occurrence and the depth of the overloading violation.

Recently, employing bus voltage and line ampacity constrains have been highlighted through a comprehensive work [84], which also emphasized these two constrains as an issue that needs situational awareness. More practically, hosting-capacity related studies have been also developed based on overvoltage and overloading aspects [85]. So, in short term analysis, corrective and preventive actions can be included for automation approaches such as the LAP in ADN [86]. From the current research point of view, these [29]. The standards assisted the formation of the operational performance indices, as will be explained further in the contents of Chapters 4-7.

2.4 Risk Analysis

2.4.1. Definition

The safety of distribution network can be evaluated based on risk analysis methodologies that takes into account the increase in DG penetration. Generally, risk is often considered for the expected damage or loss [87-89]. Some typical definitions of risk are:

"*Risk is a measure of the probability and severity of adverse effects*" [90]

"*Risk is the combination of probability of an event and its consequences*" [91]

"*Risk is equal to the triplet* (E_i, P_i, C_i)*, where* E_i *is the* i*-th event,* P_i *is the probability of that event and* C_i *is the consequence of the* i*-th event,* $i = 1,2, \dots, n$" where n is that the number of expected or possible events [92, 93]

The common of these definitions is that they consist of events, consequences and probabilities. In details, an event is the problem that can occur, for example, petrol leakage from a car while driving. The consequence is what is going to happen, for example, fire or explosion that could occur in the car. The probability is the measure of how certain that problem could occur. In other words, the uncertainties of events can be expressed via probabilities. Even right now the risk is defined in a similar manner according to the recent update of the Australian Risk Management standard AS/NZS ISO 31000:2018 [94] as stated "*Risk is usually expressed in terms of risk sources, potential events, their consequences and their likelihood*", which is the latest update of the previous one AS/NZS ISO 31000:2009.

2.4.2. Probability in Risk Analysis

Risk analysis and probability theory are related. According to [95, 96], a probability is interpreted through two notions. The first is that a probability functions as a relative frequency. The relative frequency is the relative number of times that an event occurs and is hypothetically concluded where the system situation is repeated infinitely. This type of probability is commonly represented by random variables in a form of PDFs. In addition, it is usually referred to as aleatory, objective or stochastic [97]. The second notion refers the probability that is described by Bayesian theory. Bayesian probability is influenced by the assessor's belief and knowledge of how the uncertainty is going to look like in the future scenarios. This is often referred as epistemic, subjective and knowledge-oriented [97] and usually modelled as fuzzy numbers in a form of possibility distributions [98]. Despite both notions are used within the risk contexts, risk analysis related research heavily relies on the first interpretation of probability due to the empirical models of observed variability and supported sufficient statistics in practice. In fact, many works are still in the stage of defining the risk and the role of probabilities such as [99, 100]. Nevertheless, risk analysis builds on the general approach introduced by Kaplan and Garrick [92] more than three decades ago. Their approach becomes the skeleton of "quantitative risk assessment" (QRA) in which applicable risk analysis techniques are established based on accordingly [101-104] and [27]. Quantitative risk assessment is a method based on the system models, responses and sensitivities, which is utilized to find causal relations and measure quantitatively the involved risks [105]. The method can be advantageous for safety and security related concerns; for example, forming decisions on an acceptable risk, provided the input into risk evaluation and treatment are available. Also, it can be advantageous for economists, maintenance analysts, decision makers …etc. and at various degrees of details.

2.4.3. Risk Analysis in Power System

The involvement of risk analysis tools in power system has gained a wider attention recently. The trend is expected to continue rising in the purpose of seizing the uncertain operational behaviours and scaling the associated risks. Scaling the risks through appropriate risk assessments may assist in reducing the system vulnerability to acceptable levels [106]. Risk is considered as an optimization objective [107]. However, according to QRA, risky events should be evaluated not only in terms of their likelihood to occur but also in terms the severity of their consequences [89, 106, 108, 109]. This risk is characterized by two components: likelihood and severity, as it appears in the aforementioned definition in [92, 93] and the following reviewed literature. Examples are: the use of zonal risk assessment in regards with the investigation of security risk measure for contingency purposes [110] [107]. Other example, the possible failure is estimated using log-log risk chart after the normalization of the occurrence and consequence of a violent event [108]. In [111] [112], the resilience of small distribution network is examined against the extreme natural events with the employment of several reliability based indices such as loss of load probability index, expectation of load not being served, damage recovery index and line outages index. Risk index for detect a line overloading within the network is introduced in [113] with consideration of spatial correlation existed among consumptions and generation schemes. The risk analysis is used to analyse the cascading failures considering the topology and connectedness in a network [109]. Hazards under epistemic uncertainties are quantified using the systematic six levels of Paté-Cornell scale [114]. In terms of establishment of operational risk indices, Bayesian network is presented in [115] to quantify the risk in the dynamic form in which the short-term analysis is performed to evaluate the system steady state operation under high PV penetration. Different operational risk indices are established in [116-118] for line overload, voltage collapse or out of standardized range, transient instability which are intended for transmission lines. Thus, it is crucial to consider both components in conducting risk assessments.

For the sake of avoiding under/overestimation of risk, it is worth noting that when more factors are considered in evaluating risk, such task might become a complex task to achieve. Some studies [119] start to address the complexity of system in terms of

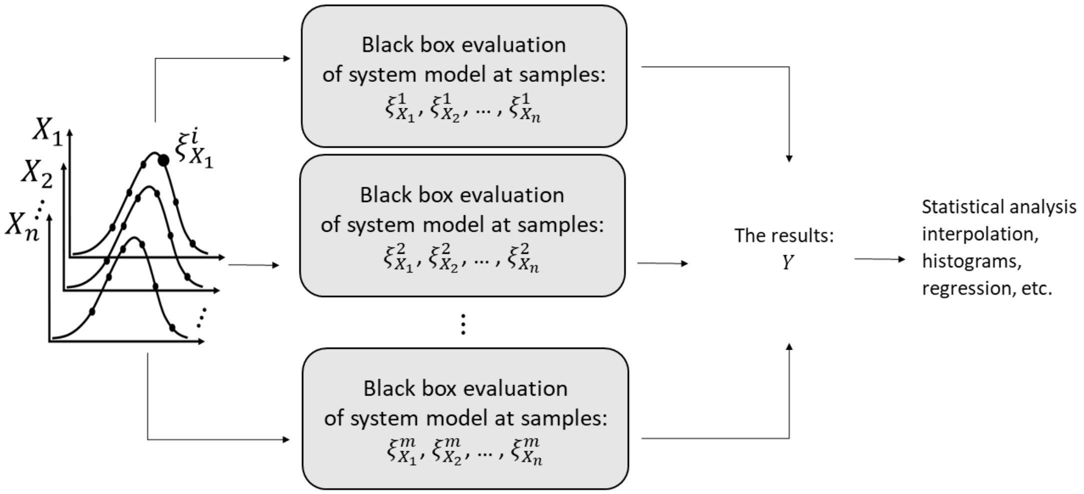

Figure 2.4 Simplifying the complexity of system risk assessment through the use of a non-intrusive method.

dependent and independent parameters. This is where non-intrusive methods appear to be applicable for uncertainty propagations so that risk evaluations can be driven. The non-intrusive approaches exploit the numerical solutions rather than analytical ones taking the advantage of the advancement in computing power in the last decade. It is common for other disciplines to use the non-intrusive approaches such as the study of finite element problems [120], but it till recently tends to be used for power system analysis such as the application for probabilistic power flow calculations [121, 122]. The non-intrusive approaches do not require the governing internal equations in which the deterministic evaluations are considered within a black-box (see Figure 2.4). In the figure, the m-number of realizations $\xi_{X_1}^{m}, \xi_{X_2}^{m}, \dots, \xi_{X_n}^{m}$ of the n-number of uncertainties $X_1, X_2, \dots, X_n$ are considered in the black box where the results represented by Y can be statistically analysed, interpreted and discussed. The non-intrusive approaches can make use of statistics for deterministic models such as sampling, quadrature and linear and non-linear regressions. By utilizing these approaches, the system complexity such as interdependences amongst system uncertainties are considered. Thus, the non-intrusive approaches simplify multi parameter and multi-dimensional problems which can be very helpful for risk analysis purposes.

Following what have been reviewed hereinbefore, in Chapter 6, a risk analysis based on the two components (likelihood and severity) has been conducted by establishing novel operational risk indices. The system is evaluated using the non-intensive approach which is explained further as a stochastic model in Chapter 6.

2.5 Conclusion

This chapter offers a modest attempt to provide literature on the published work related to the objectives of this research. The chapter is divided into five sections including an introductory and concluding sections. Section 2.2 briefly deals with the ADN technologies. Section 2.3 reviews the high DG penetration related work, HC concepts and regulatory standards and polices. Section 2.4 presents the definition of risk analysis and risk analysis related work in power system studies.

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Chapter 3

Uncertainty Model for Total Solar Irradiance Estimation on Australian Rooftops

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Principal Author

Name of Principal Author (Candidate)	Hassan Al-Saadi		
Contribution to the Paper	Developed ideas, performed simulations and calculations, analysed data, wrote manuscript and acted as corresponding author.		
Overall percentage (%)	85%		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	2-08-2018

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Rastko Zivanovic		
Contribution to the Paper	Supervised development of the work, reviewed and assessed the manuscript.		
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The further explanation regarding the literature review and the correlation coefficient R^2:

1. The paper did not provide a detailed literature review. This is due to the high number of review publications. The reader is referred to the web for reviewing the literature where some are included as follows:
   - Gueymard, C.A., "Direct and indirect uncertainties in the prediction of tilted irradiance for solar engineering applications." *Solar Energy*, Vol. 83, No. 3, pp. 432-444, 2009."
   - Evseev, E.G. and Kudish, A.I., "The assessment of different models to predict the global solar radiation on a surface tilted to the south". *Solar Energy*, Vol. 83, No. 3, pp. 377-388, 2009.
   - Loutzenhiser, P.G., Manz, H., Felsmann, C., Strachan, P.A., Frank, T. and Maxwell, G.M., "Empirical validation of models to compute solar irradiance on inclined surfaces for building energy simulation." *Solar Energy*, Vol. 81, No. 2, pp. 254-267, 2007.

2. Further explanation is provided for the values of goodness-of-fit technique named "the correlation coefficient R^2". Some clarification might help the reader in regard with the negative values of the correlation coefficient R^2. For the values when R^2 is less than 0, the correlation coefficient R^2 implies that the model predictions are worse than you could predict by just using the mean of provided sample case outputs.

Chapter 4

Probabilistic Analysis of Maximum Allowable PV Connections across Bidirectional Feeders within a Distribution Network

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Overall percentage (%)	85%		
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Further explanation regarding the PV increased connection

It is mentioned in this paper that A can be used to perform PV increased connections in a stepwise fashion and then examine the impacts at each step. For more details on how the PV increased connection is performed, the reader is referred to Section *C. DG Connection Increase* in the publication presented in Chapter 5.

Chapter 5

Probabilistic Hosting Capacity for Active Distribution Networks

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Contribution to the Paper	Developed ideas, performed simulations and calculations, analysed data, wrote manuscript and acted as corresponding author.		
Overall percentage (%)	85%		
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Signature		Date	2-08-2018

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Further explanation regarding the PV increase connection

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Chapter 6

New Risk Analysis Approach for Bidirectional Distribution Feeders under High PV Penetration considering Spatial Correlations using Nataf Transformation

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Contribution to the Paper	Developed ideas, performed simulations and calculations, analysed data, wrote manuscript and acted as corresponding author.		
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New Risk Analysis Approach for Bidirectional Distribution Feeders under High PV Penetration considering Spatial Correlations using Nataf Transformation

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Abstract

The distribution networks are in a transition stage from being “passive” (consuming energy and typically with unidirectional power flows) into “active”: (consuming/producing energy with bidirectional power flows). This transition has exposed the networks into stochastically behaving risks such as violating the prescribed limits of power quality or overloading the network elements. This paper presents a new risk analysis approach to quantify the risks of violating operational constraints of distribution networks that are connected with a large number of small-capacity Photovoltaics (PVs). The Probability Density Function (PDF) of the localized clearness index[§] is utilized to formulate the uncertainty model (stochastic performance) for individual PVs. The effect of spatial correlations existing among PVs on risk quantification has been addressed using the Nataf transformation. The proposed stochastic model is presented through a schematic diagram where the following features of the model are incorporated: stochastic realizations, inverse cumulative density functions, inverse transform sampling, Cholesky decomposition, uncertainty propagation outputs and risk quantification techniques. In risk quantification techniques, three risk metrics are proposed, and informative risk visualizations are developed as well. The approach is implemented in two distribution networks: a small-size test network with nine buses and a large distribution network with multiple zones and feeders situated in South Australia. The approach is location-specific and time-varying. The resulting risk estimates and metrics are intended to assist distribution network operators, technical analysts and policy makers in managing and regulating the increase in PVs capacity being installed in distribution systems.

Keywords: High PV penetration, PV modelling, spatial correlation, risk assessment, Nataf transformation, uncertainty propagation.

[†] Corresponding author.

[§] Clearness index is the ratio of the irradiance on a horizontal plane It [kW/m2] to the extraterrestrial total solar irradiance Io [kW/m2].

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1. Introduction

1.1 Problem Description

The number of Photovoltaics (PVs) on residential rooftops in Australia is rising and this has triggered a number of questions. The official figures show that just over third of households in some states have already installed PVs such as in Queensland and South Australia and more than 1.6 million PVs have been installed throughout Australia [1]. The trend is occurring due to a number of factors, including the ongoing decline in the average PV installation prices, the increasing cost of grid supplied energy and continuing government policy developments in electricity market liberalization and feed-in tariffs. The state of South Australia (SA) has a relatively high penetration of PVs and so it is used as a specific example in the following discussion. It is noted that the situation is quite similar within other jurisdictions within Australia. The Distribution Network Operators (DNOs) in SA generally require that small single-phase PVs have an inverter rated capacity of no more than 10 kW and that export from the PVs to be limited to maximally 5 kW [2]. A home-owner with a three-phase connection can install a PVs with a capacity of no more than 30 kW and is permitted to export power up to this limit [2]. There are, generally, no restrictions preventing a home owner installing a PV within the above capacity providing the installation meets specified technical requirements. Importantly, the DNO does not, generally, restrict PVs capacity or withhold approval to connect on the basis of the potential for Hosting Capacity (HC) violation. Hosting Capacity is defined as "*the acceptable degree of DER*[*] *penetration under given circumstances*" [3]. During the last five years, in SA particularly, the percentage of dwellings with installed PV systems has increased by about 81.6% from 17.4% [4] in 2013 to 31.6% [5] in 2018. The installation of new PVs in other Australian states is continuing. This growth does raise three important questions. (i) Despite the current capacity restrictions, will the hosting capacity of the distribution network be violated as more PVs are installed? (ii) Could current PVs capacity constraints be relaxed such that the network can be satisfactorily operated; and (iii) Given the stochastic nature of the output from PVs, is it possible to relax PVs capacity limits and instead constrain PVs output on the relatively few occasions when the network HC would otherwise be violated?

As a result of the high and increasing penetration of PVs, there is an increasing likelihood that PV generation on some distribution feeders will exceed their connected loads at certain hours during the day in which the surplus energy will be exported back into the main grid. This impacts the quality of power supply and overloads the under-operation network elements. Therefore, the concept of Active Distribution Networks (ADNs) has been introduced as an alternative solution to comply with the increase. The ADN allows the bidirectional power flows so that the distribution feeders consume and produce energy without jeopardizing any connected electric appliances. According to the Working Group (WG) C6.11 of International Council on Large Electric Systems, known as CIGRE[†] [6], ADNs are distribution networks that have systems in place to control a combination of Distributed Generations (DGs) defined as generators, loads, and storages. In fact, the network future scenarios regarding the possible impact of PVs has been studied by the specialists [7, 8], in order to create awareness of possible problems among policy and decision makers including DNOs. The specialists argue that there is need to transform the current distribution networks into being active in order to efficiently utilize the high PV penetration.

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[*] Distributed Energy Resources which is used in this paper as distributed generation (DG).

[†] CIGRE stands for the phrase in French language: Conseil International des Grands Réseaux Électriques.

1.2 Recent Research Directions

To transform from passive to active distribution networks, we may require facilities such as: SCADA, smart meters (wireless and power line communication…etc.), advanced protection systems (Dynamic phasors by phasor measurement unit PMU and dynamic line rating …etc.), static synchronous compensators (e.g. STATCOM), solid state controllers, remotely controllable On-Line-Tap-Changer (OLTC), wider application of Geographical Information System (GIS), isolation and restoration devices, new regulations (e.g. standards, understanding administrative and legal barriers, market mechanism etc.), and energy storage systems. In addition, automation and control approaches are suggested for the future distribution networks including: multi-agent control and optimizations, real-time data processing, advanced communication networks, demand dispatch and bidding features, dynamic state estimation, cyber security, etc. [9,10]. However, before implementation of such new equipment and features which can occur at scale, there remains a pressing need for simulation and risk assessment tools that properly and practically account for the stochastic nature of generation and load within distribution networks. In fact, up to date, a tiny portion of already installed PVs in residential areas are measurable and controllable because of high additional costs per installation [11]. Majority of PV installations are still not observable. In this regard, locations and maximum nominal power of the connected PVs are the only information known by DNOs [12]. In discussions held by WGs of CIGRE, the triggering question has been raised [13]: "Why the concept of ADN has failed to be adopted by most of DNOs?", despite a plenty of appealing studies being proposed. In Table 1, outcomes and recommendations of relevant WGs [6,14,15,16,17] have been summarized. Needless to say, consensus has not been made but all participants seem to converge towards the necessity of using short-term strategies, risk assessments

Table 1 The reviewed CIRGE meetings with suggested research directions.

CIRGE	Year	General theme	Outcomes/recommendations
C4.601	2010 [15]	Planning risk and probabilistic tools	• Arguing the need to consider uncertainty analyses, risk assessments, • Highlighting the lack of practical probabilistic solutions
C6.11	2011 [6]	Planning and operation of ADNs	• Short-term operational solution rather than long term solutions. • Highlighted the limiting aspects of hosting capacity. • Defining ADN. • Addressing the barriers to facilitate the transition. • Focusing on dynamic approaches rather than fit-and-forget ones.
C6.19	2014 [14]	Existing and required methods for ADNs	• The advanced approaches for ADNs have failed to be adopted by 90% of the respondent utilities. • The alternative planning tools lack the ability to depict future scenarios. • Pointing the necessary research directions such as reliability models, short, medium and long-term solutions, demand-side integration, and storages. • More studies needed on bidirectional networks for new regulatory moves.
C4.29	2016 [17]	Addressing power issues due to solar power integration	• Detailing harmonics, paraharmonics, fast voltage variations (faster than 10-min time scale), slow voltage variations (slower than 10 min), overvoltage, flicker, and voltage unbalance.
C4.24	2017 [16]	The power quality and protections	• New quantitative indices needed for voltage variability in end-user equipment. • Urging a need for new assessment tools during connected and/or islanded operation with an emphasis on the number and severity of violations of network constraints. • Suggest further studies to understand potential adverse impacts of smart applications, recommending to use predictive simulations.

(as in this paper, assessing the risk of violating network operational constraints, specifically (i) bus voltage constraints; and (ii) network component current limits) and predictive simulations.

Narrowing down to the requirement for risk analysis, the complexity of the problem seems not being adequately treated in the available literature published so far. Appropriate risk-assessment of the power system may help in managing certain risks within acceptable limits for planning, design and/or operational purposes, although quantifying the risk is a challenging task [18]. The perceived unsolvable and difficult problems in the recent past can now be tackled numerically, thanks to the significant developments in computing power. One such example is a security risk measure that was investigated in [19] for contingency analysis using so called "Zonal risk assessment". Similar work has been described in [20]. Out of limit probability and severity indices are counted for probable degree of violation and the consequence [21]. By normalizing the scales of the consequence and the occurrence of an event, a log-log risk chart is utilized for the potential failure estimation [22]. Reliability based indices (e.g. loss of load probability index, expectation of load not being served, damage recovery index and line outages index) were developed to quantify the resilience of microgrid under extreme events (Hurricanes, blizzards and earthquakes) [23], and a similar index has been developed in [24]. Relevant work presented in the reference [25] addressed the cascading failures from the viewpoint of topology and connectedness in a network. A probabilistic forecast for short-term PV output was performed using dynamic Bayesian network for the quantification of the operational risk in a distribution network with high PV penetration [26]. The Paté-Cornell scale is used for risk quantification under epistemic uncertainties [27]. Risk index to indicate the degree of specific transmission line overloading is established considering the spatial correlation between load-generation patterns [28]. Some of methods developed for transmission network to calculate technical operational risk assessments for line overload, voltage collapse, voltage out-of-limit, and transient instability introduced by Electrical Power Research Institute (EPRI) [29,30,31] might be possible to adopt for ADNs. The common mathematical analysis tool in the literature surveyed above is the application of likelihood and severity of an event. These are always considered as the determinants of the target risks. The recent work [32] addressed part of the complexity when formulating the analysis of system risk where some of the factors affecting the outcome are dependent on each other and where other factors are independent of the others.

In distribution systems with large numbers of PVs, hosting capacity is introduced to characterize the uncertain effects of PVs on the operation of the system within operational constraints. An important attempt from EPRI through a stochastic analysis to determine HC limits of traditional distribution networks resulted in considering the worst-case scenarios, using overvoltage violations [33]. However, the Look-Ahead Policy (LAP), short-term assessment, is more preferred than EPRI's long-term determinations, as suggested earlier here for ADNs in Table 1. An important concept related to HC was introduced to quantify the distribution network in the presence of distributed generators as it is stated "*The impact of distributed generation can be quantified only by using a set of performance indicators*" [3]. Following the last concept, two probabilistic indices are introduced in [34] for hourly determinations of network HC. The focus of the last work is the time-computational enhancement with the utilization of a sparse grid technique rather than Monte Carlo method. In the mentioned two studies [33,34], the uncertainties of the PVs power injections into different points of common coupling (PCC) are either uncorrelated as in the first research [33], or perfectly correlated as in the second study [34]. Neither of these correlations are accurate. Rather, in practice, the correlation between the power output of two PVs is found to be relative to the distance between them [35]. This latter method of correlating the power output of PVs is employed in this work. To the best of our knowledge, the effect of correlation on risk quantification has not been studied yet within the context of distribution networks. The objective of the current research is to develop a probabilistic understanding of the locational and temporal congestion patterns within a distribution network due to high power penetration from connected PVs.

1.3 Paper Contribution

In this work, the main purpose is to provide a roadmap for stochastic risk assessment using a schematic diagram. The propagations of the uncertain behaviors of PVs on distribution networks are easily tracked and depicted when conducting the proposed method for risk assessments. The followings are the new contributions in this paper:

1. Utilizing uncertainty knowledge (temporal and spatial stochastic variations) of solar irradiation to develop a model and to fit parameters of the model using Australian meteorological conditions. The advantage is to realistically formulate the problem (the simulations of correlated PVs within a distribution network) and thus avoid unnecessary theoretical assumptions.
2. Adding to the system a stepwise increase to represent the number of PV connections to be a percentage of the time-average of loads connected to the corresponding PCC. The PVs capacity and the level of solar irradiation are introduced in a nonlinear relation of the network power flow.
3. Formulating spatial correlation characteristics of the involved uncertainties using rank correlation transformation in which the nonlinearity of inter-dependences, due to non-Gaussian models, can be represented. The Nataf's transformation [36] is proposed here to formulate the nonlinear correlations (more details are provided within section 3.3).
4. Establishing three novel risk indices for risk assessment where the consideration is given to the risk components: likelihood and severity. Furthermore, graphs to effectively visualize the impact of increasing PV connections on the risk components are developed.
5. Introducing a new temporal risk assessment approach for distribution feeders in which bidirectional power flow is possible. The focus of the new assessment is to provide a degree of risk for the distribution network as whole instead of more conventional methods that assess the network by parts, such as assessing individual lines or buses.

1.4 Paper Organization

The organization of the paper is as follows: after this introductory section, uncertainty model of individual PVs connected to the same PCC is formulated. In the same section, the power flow constrains for the distribution network is equipped with the model representing increase of PV installations. In the next section, the complexity of the problem is explained in the schematic diagram with three computation layers. In each layer, tractable and observable procedures of the random variables, their correlations as well as risk assessment techniques are formulated and computed for the entire stochastic system. In section 4, the term "risk" is defined and, then, risk assessment indices are established; in addition, discussions regarding likelihood and severity are presented. Illustrative examples are given in section IV. In this section, two distribution networks are used to demonstrate the effectiveness of the proposed approach, supported by the informative risk visualizations. The concluding outcomes of the paper are given in the last section.

2. PV Uncertainty Model and Penetration Increase

The increase in residential PV connections is performed through a stepwise fashion. It allows us to assess the network for individual steps. Each step is denoted mathematically by lower-case (used as super or sub-script in the expressions that follow). It should be noted that the term "PV connection" refers to the PV size in which a PV is designed to maximally deliver power according to the manufacturers specifications. Meanwhile, "PV penetration" refers to the actual power injected by a PV into the grid, which is mainly dictated by the uncertainty of solar irradiation. Assuming the standardized maximum delivering power of a PV panel is in a linear functional relation with its size (surface area) a^s, the increase in power can be taken into account by adjusting the surface area of the PV. With the assumption that the grid-connected PVs are equipped with a one axis tracking system, a linear function between PV's size and output power can be formulated as follow [37]:

$$P^{s,t}(k_t) = a^s \cdot eff \cdot I^{\beta}\ (k_t), \tag{1}$$

where $P^{s,t}$ represents active power produced at uniform timeframe denoted by t-time; eff signifies the PV array's efficiency. $I^{\beta}\ (k_t)$ represents the total solar irradiance received on a PV array surface area with an inclination angle β to a horizontal plane at t-time. The k_t is a clearness index of the sky, represents mathematically as a *global radiance*, kW·m^{-2}, reaching the ground (which is uncertain) over the *extraterrestrial radiance*, kW·m^{-2}, that reaches the earth's atmosphere, and serves as a measure of the atmospheric transparency (water vapor, dust, smoke etc.); acting in accordance with the daytime and seasonal variations. The nonlinear function $I^{\beta}\ (k_t)$ is given by [34]:

$$I^{\beta}\ (k_t) = \begin{cases} D \cdot k_t + D' \frac{k_t}{1+e^{-B(B'-k_t)}} & D > 0 \quad D' \geq 0 \\ D \cdot k_t - D' \frac{k_t}{1+e^{-B(B'-k_t)}} & D > 0 \quad D' < 0, \\ 0 & D \leq 0 \end{cases} \tag{2}$$

where D and D' are combinations of many parameters including (β, R_b, r_d, L_{loc}, L_{at}, L_{lat}, L_{st}, ρ, γ, ω, ω_{slr}, n, $\overline{H}_o$), details can be sought in [34]. Their definitions are: β, tilt angle; R_b, ratio of beam radiation on tilted surface to that on horizontal surface; r_d, ratio of hourly to daily diffuse radiation; L_{loc}, longitude; L_{at}, latitude; L_{lat}, altitude; L_{st}, standard meridian; ρ, ground reflectance; γ, solar inclination; ω, angular displacement; ω_{slr}, solar angular time; n, assessment day; $\overline{H}_o$, extraterrestrial solar radiation; $k_{t\,\max}$, maximum bound of k_t; $k_{t\,\min}$, minimum bound of k_t; k_d, diffuse fraction which is a function of k_t detailed in [38]; B and B' are the logistic function's parameters that shapes the relational curve between the diffuse fraction and k_t. For further details of these definitions, the reader is referred to the important reference in this field [39]. Speaking probability theory, during the last half century and throughout extensive studies, it has been found that clearness index follows several probability density functions (PDFs) such as unimodal PDFs (Boltzmann [40], double beta [41] and Single Gamma [42]) or bimodal shapes (bi-exponential [43], double normal [44], triple normal [45] and Weibull-logistic distribution [46]). In this study, Single Gamma PDF is used to characterize the uncertainty of the hourly k_t.

Figure 1 shows the probability densities of the output power of one PV, $a_s = 1$ m^2, estimated at different times in a day for a specified location. The involved quantities in this figure are taken for Adelaide, SA (35°S) with $k_{t\,\min} = 0$ and $k_{t\,\max} = 1.2$, $\rho = 0.3$, $eff = 0.7$, β=15° as well as the monthly average irradiation needed for computation of H_o is 8.8 MJ. m^{-2}, and all other quantities can be computed using the series of models presented in [39].

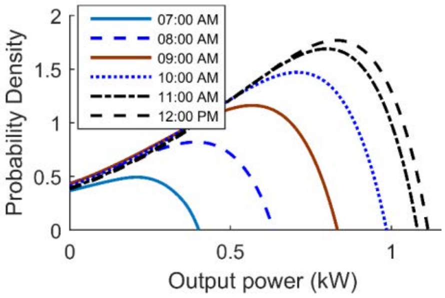

Figure 1 PV generations (kW) versus probability densities using different PDFs for different daytimes.

When several PVs are connected into a PCC, the sum of the individual output lossless powers is the injected power:

$$P_i^{s,t} = \sum_{k=1}^{N} P_{i,k}^{s,t}, \tag{3}$$

where $P_i^{s,t}$ is the total active power injected from a combination of N-PVs into i-th bus within s-step increase at t-time. According to (1), increasing individual PV's surface area will prospectively increase the uncertain power generated from the individual PV. For example, a^s of a PV is increased piecewise by s-step such that $a_1 = a_{intial}$ and $a_2 = a_1 + s$ and $a_3 = a_2 + s$ and so on; where a_{intial} is the initial area of each PV. Within each s-step, the reactive power of DGs, resulted from the interfacing passive components of the integrated converter, is also considered and can be expressed using the following formula:

$$Q_i^{s,t} = P_i^{s,t} \frac{\sqrt{1-(\cos\theta)^2}}{\cos\theta}, \tag{4}$$

where the Q_i^s and θ are values specified for reactive power and constant power factor (PF), respectively, at i-th bus within s-step.

From a power flow perspective, the grid-connected PVs are treated here as active-reactive power injectors [47]. The power balance at i-th bus can be expressed as follows:

$$\begin{aligned} P_i^t &= -P_i^{L,t} + P_i^{s,t}, \\ &= |V_i| \textstyle\sum_{\forall j} |V_j| (\mathcal{G}_{ij} \cos\theta_{ij} + \mathfrak{B}_{ij} \sin\theta_{ij}) \end{aligned} \tag{5}$$

$$\begin{aligned} Q_i^t &= -Q_i^{L,t} + Q_i^{s,t}, \\ &= |V_i| \textstyle\sum_{\forall j} |V_j| \big(\mathcal{G}_{ij} \sin\theta_{ij} - \mathfrak{B}_{ij} \cos\theta_{ij}\big) \end{aligned} \tag{6}$$

where P_i^t and Q_i^t represent the active and reactive traffic power at i-th bus during t-time. Considering the bidirectional power flow in ADNs, the power is injected in either directions: towards the load ($P_i^{L,t} + Q_i^{L,t}$) or injected from a PV ($P_i^{s,t} + Q_i^{s,t}$) into the utility grid; V_i and V_j the voltage phasor at i-th and j-th bus respectively; $\mathcal{G}_{ij}$ and $\mathfrak{B}_{ij}$ are the conductance and susceptance of the ij-th line's admittance; θ_{ij} is the angle difference between the voltages at i-th and j-th bus.

The PV connection increases are expressed in terms of a percent value of the maximum delivery active power (size) of PVs connected at each i-th bus, denoted by P_i^{size}, with respect to the time averaged loads, $P_i^{L,\text{avg.}}$, connected to the same i-th bus as follows:

$$PV\ connection\ increase\ \% = \frac{P_i^{\text{size}}}{P_i^{L,\text{avg.}}} \cdot 100. \tag{7}$$

Please note that P_i^{size} is a certain quantity, while $P_i^{s,t}$ is uncertain and has a probabilistic definition that is a function of the weather conditions. For example, a cloudless day means the clearness index has to be at the upper maximum bound of $k_t = k_{t\,\max}$. In other words, its uncertainty obeys the state of clearness index.

3. Stochastic Performance with Spatial Correlation

To model the uncertain variables of the system, stochastic simulations are most commonly used. Stochastic simulations are a set of numerical processes able to generate realizations of a discrete random variable (RV) (for example, stochastic variations of solar irradiance or electric demand across different times in a day and in a season) or continuous random variables (solar irradiance or electric demand) [48]. The stochastic model exploits numerical methods in which the analytical expression is not obtainable due to the complexity of the system. In addition, the stochastic model takes the advantage of the conceptual deterministic models to form the final projection model (e.g. a surrogate model [49]). Probabilistically, once appropriate probability distributions are founded for drawing the sources of uncertainties, the performance of the targeted distribution network can be assessed through a defined stochastic model preserving the t-time and s-step.

To make the problem more tractable, we provide an illustrative diagram shown in Figure 2 encompassing three computation layers. The procedures of the method should be read from the left to the right. Layer 1 concerns the system evaluations with the marginal PDFs of PVs and loads, power sum at PCC (3) including (4) and then load flow equations (5) and (6). In Layer 2, the dependence among the RVs and the quantitative risk measures are computed, where in this section, only the dependence is discussed. In Layer 3, Nataf transformation for the establishment of rank correlations as well as the risk analysis and risk visualization are introduced where only Nataf transformation is explained in this section. The quantitative risk indices and their developments are explained in the next section, giving more space for further explanations. Moreover, the diagram is presented to be a roadmap for further adequacy assessments and feasibility studies. For instance, the stochastic simulations also facilitate the use of a non-intrusive approach [50] for further evaluations such as involving a stochastic optimization [51].

In the finite dimensional random space L^2, the system can be described by random input vector $X = \{X_1, X_2, \ldots, X_n\}$ that are orthogonal in $\mathbb{R}^n$ where arbitrary output vector(s) Y is mapped into the co-domain $\mathbb{R}$ through a functional relation g as follows:

$$Y = g(X), \quad g: \mathbb{R}^n \to \mathbb{R}, \tag{8}$$

where g includes the collection of system-mathematical relations (the marginal PDFs of PVs and loads and load flow equations, power sum at PCC as well as the values of the quantitative risk metrics and their developments). Herein, the X represents the information for the system uncertainties while Y is output and g describes uncertainty propagation. In the diagram, a combination of different formulae is added as moving from one layer into a larger layer. The contents of each layer are explained as follows.

3.1 Layer 1

In layer 1, the RVs $\{X_1, X_2, \ldots, X_n\}$ are treated as mutually independent and each RV is independently and identically distributed. In modelling dependences, it is common to consider that all connected PVs have symmetrical output patterns of the injected power, modelled by only one RV such as the case in the residential distribution networks [52]. Usually an assumption is used such that, from the network nodes' point of view, the knowledge of the uncertainty of one PV output is much similar to the knowledge of the neighboring PV. Therefore, one could assume that the RVs of PVs are perfectly positively correlated [52, 53]. The same may apply for RVs of loads wherein, for one feeder, load profiles may share the same characteristics, following the behaviors of residential dwellers such in [54]. In risk analysis, however, this could lead into a severe under/over-estimation of the variability of power flows in the system, and ultimately under/overestimation of the risk related to an event being assessed [55]. For positive dependences in particular, modelling the problem with a perfect correlation may lead to overestimating the risks [56]. Regarding this, RVs are considered, at this layer, independent wherein the transformation of the independent RVs into being dependent is introduced in the larger layers. Another worthy of note is that no dependences are considered between RVs of PVs and RVs of loads. The truth is that these variables should be dependent on each other. For example, during the night, the solar radiance is zero and the demand is at its minimum levels. During the day, the solar radiance increases wherein the consuming behavior for electricity is active. However, such dependence is barely existing in a short-term (hour or less) evaluation.

The objective of this layer concerns the outcomes of deterministic power flow calculations such as the nodal voltages and branch powers. Herein, statistical tools like moments or quantiles with a finite sample size and confidence interval are used. A sample size of m is taken in which a single r-realization is indexed by $\xi^r_{X_1}, \xi^r_{X_2}, \dots, \xi^r_{X_n}$. In a single predefined process box shown in the diagram i.e. a single stochastic process (r), power sums at PCC in (3) including (4) are to be performed in an interactive manner and i-th bus voltage and ij-th feeder power are to be observed, preserving r-realization. Note that, the number of RVs for PVs is considered to be equal to the number of RVs for loads which is $\frac{n}{2}$, where n is the total number of RVs. It has been assumed here that each residential house or sub-feeder has an equal right of connecting PVs as the same as their neighbors. The fact is that the future policy of distribution networks is also uncertain, i.e. provision of a house to have a PV or not is still unknown, the same consideration is discussed in [57, P.692].

3.2 Layer 2

At this layer, two stages are added: establishing dependences and defining risk metrics. To establish dependent RVs, the construction of correlated distributions of RVs is essential. The correlation structure that dictates the behavior of RVs is called a spatial correlation; and it has been a focus of several publications such as the spatial correlation of clearness index [58], or the spatial correlation of PVs' outputs [35,59]. The main scope of these publications is to provide an output power correlation as functions of the distance. These studies demonstrate that this correlation

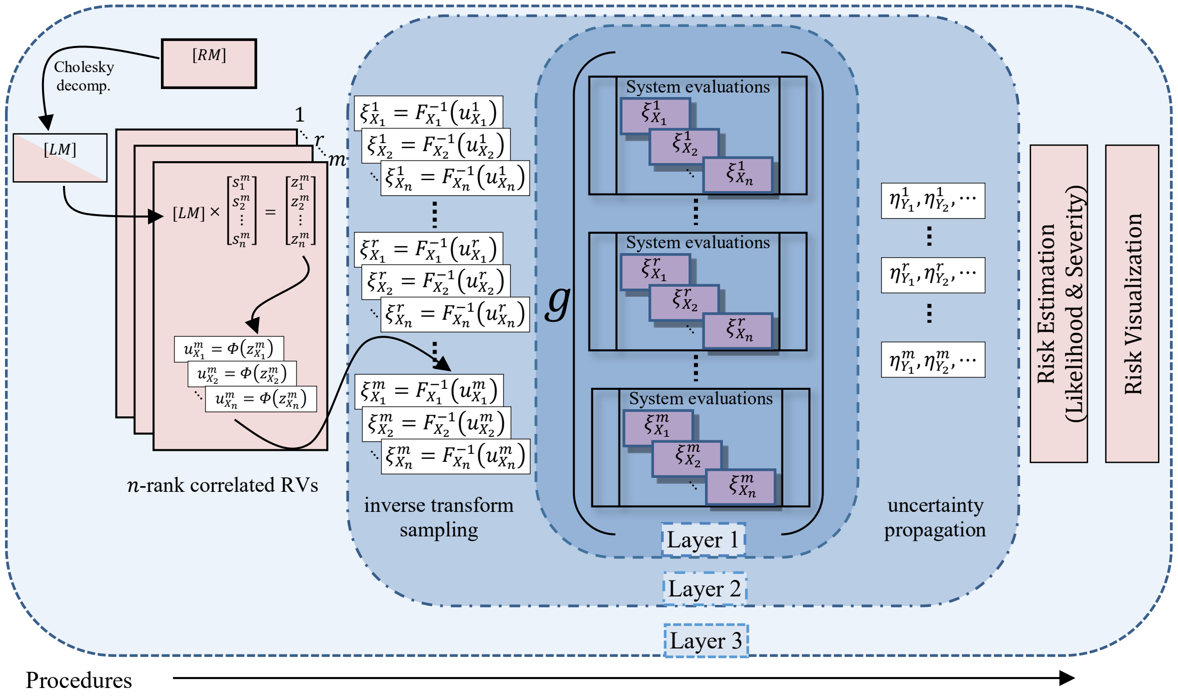

Figure 2 Illustrative diagram encompassing three collective layers for the hourly uncertainty evaluations at each piecewise increase of PV connections.

decays as the distance widens. Intuitively, by assuming one PV to be a location central reference, the outputs of other PVs situated at different PCCs can be conditionally determined with the use of the inverse Rosenblatt transformation [60]. So that theoretically, the dependent RVs can be obtained by applying the inverse Rosenblatt transformation on the independent uniform RVs $\{U_{X_1}, U_{X_2}, \dots, U_{X_n}\}$, assigned arbitrarily for each RVs $\{X_1, X_2, \dots, X_n\}$, see Appendix A for extra details. To utilize this transformation, the conditional distributions of the involved RVs have to be available beforehand in order to find the inverse conditional cumulative density functions (CDFs). Obtaining the conditional CDFs is still not an easy task and even impossible for some engineering applications. Therefore, the transformation is applicable and straightforward for our problem upon providing explicit mathematical formulae of the conditional CDFs.

Otherwise, an alternative path is to formulate the target dependences through the independent uniform RVs $\{U_{X_1}, U_{X_2}, \dots, U_{X_n}\}$ in which it only requires inverse CDFs of the RVs. For this reason and by referring to the schematic diagram provided, the inverse CDFs of RVs are the only ones shown within this layer. The Inverse CDFs, $F_{X_1}^{-1}, F_{X_2}^{-1}, \dots, F_{X_n}^{-1}$ are numerically approximated using inverse transform sampling [61] for all targeted marginal PDFs, e.g. for both PVs and loads. Performing inverse transform sampling will result in r-realization $\xi_{X_1}^r, \xi_{X_2}^r, \dots, \xi_{X_n}^r$ that is explained in Layer 1.

3.3 Layer 3

Layer 3 is introduced to show the alternative path for modelling dependences collectively with the use of inverse CDFs given in the Layer 2. This layer, also, includes a risk analysis toolkit (The quantitative risk metrics and their developments). The method used is the Nataf transformation [36] which does not require conditional distributions, instead it requires the knowledge of dependences to be given upfront in a form of a correlation matrix. The motive for using Nataf transformation is that the correlation matrix is obtainable these days, in a sense of the spatial correlation discussed earlier.

Theoretically, the correlation is represented based on the principles of Sklar's theorem [62]. The theorem states that there is a mathematical representation, later called "copula" C [63], which joins (couples) the distributions of random variables, such as X_1, X_2 into their joint distribution if the following formula holds:

$$F_{X_1 X_2}(x_1, x_2) = C\left(F_{X_1}(x_1), F_{X_2}(x_2)\right), \tag{8}$$

where $F_{X_1 X_2}$ is a joint CDF of X_1 and X_2. If RVs are continuous, C is unique. Copulas are represented by different functional families, and choosing the right one is an ongoing investigation [64]. Examples of copula's types are pair copula [65], Diagonal band copula [66], Archimedean copula [67], and more in [68]. The Nataf transformation exploits the concept of normal copulas.

The Nataf transformation is also known as NORTA (NORmal To Anything) [69]. The method generates dependent RVs $\{X_1, X_2, \dots, X_n\}$ from independent Gaussian deviates $\{S_1, S_2, \dots, S_n\}$[‡] via using two transformations. Whereas the first transformation involves the use of Cholesky decomposition that is further explained in Appendix B, the second transformation preserves monotonic nonlinear relationships in generating dependent sequences using the concept of the rank correlation. This can tackle the problem of correlating non-Gaussian RVs as the probability distribution of PV's output is biased, strictly non-Gaussian (*cf.* Figure 1), which is unlike the load-uncertainty that is commonly modelled using the Gaussian distribution such as in [35]. The second transformation is very important in uncertainty quantification as the modelled linear dependences in the normal space, after using the Cholesky

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[‡] Not to be confused by the subscript s that is used here to denote the stepwise increase.

decomposition, are not necessarily representative if the case involves the non-Gaussian space. Obtaining the rank-correlated RVs can be summarized as follows:

1. Sample uniform vector U_X from dependent Gaussian vector using Gaussian CDF Φ:
$$U_X = \Phi(Z_X), \tag{9}$$
2. Transform the correlated rank distributions into the correlated marginal distributions via the inverse marginal CDF, which is already introduced in Layer 2:
$$X = F^{-1}(U_X). \tag{10}$$

Directives are worthy of note that, since the Nataf transformation employs the pairwise generation, each r-sample of $\{s_1^r, s_2^r, \dots, s_n^r\}$[§] is considered to be having the same values $s_1^r = s_2^r = \cdots = s_n^r$. So that, one RV is considered as a focal point of the spatial distance. Also, note that no correlation is considered between PVs and Loads because, in the short-term assessment (one-hour), the distributions of PVs and loads are barely correlated. An addition to these notes, a comparison between the coefficients of the correlation matrix in the two different spaces is not considered because the outcomes in [35] resulted from real data without indicating the fitted model. A brief glance of [35] is that PVs' outputs have a high positive correlation (between 70-90%), in case, if they are situated within a circular area of 5 km diameter. For this respect, the RVs of PVs have been modelled here with high positive dependences only. Note that this paper just uses the conclusions of pretested results of [35], as diving into the details might divert the reader from the scope of this paper.

4. Network Risk Analysis

4.1 Risk Definition

For the sake of providing a clear framework for risk assessment, the entails of risk assessment have to be clarified and defined. In this regard, identifying and describing possible hazards, their causes and consequences with the uncertainty of their occurrence are particularly the targets. In terms of a probabilistic analysis, the relative frequency of occurrence (occurrence probability) for different scenarios as well as their consequences can be used in the description of the hazard identification, causes and consequences [70]. Generally, the term “risk” has been defined by ISO/IEC [71] to be "*the combination of probability of an event and its consequence*" where the term "*risk analysis*” is defined as "*systematic use of information to identify and to estimate the risk*". Afterward, ISO replaced the risk's definition into "*Effect of uncertainty on objectives*" [72], which AS/NZS ISO 31000:2009 [73] did so as well. In addition, risk has been described, by Kaplan and Garrick [74], using triplet questions: what are the possible events, what are the consequences of these events and what are the associated probabilities of an event. Later, this triplet definition is to become the hallmark of the quantitative risk assessment (QRA), especially in engineering applications [75].

Based on the subject of interest, two main components that characterize the ultimate risk are the likelihood and the severity of an event, which is reviewed in the introductory section. It can be presented in the form of risk matrix as well. In this paper, the expectations of these components that result in a probabilistic estimate of the related risk is adopted.

[§] Not to be confused by the superscript s that is used here to denote the stepwise increase indexed as s-step.

4.2 Risk Metrics

4.2.1 *Overvoltage and Overloading*

Based on the technical standards adopted by the utility, the steady-state operational constrains can be employed to evaluate the overall performance of the distribution network with the increase of PV connections. Within this context, the violations of these constrains determine the degree of deterioration. Off course, it would be ideal to include all the operational constrains; however, some are more of cost-benefit analyses in which they do not serve to metric a network's performance such as line losses, transformer aging…etc [76]. Recently, employing bus voltage and line ampacity constrains has been highlighted through a comprehensive work [7], which also emphasized these two constrains as an issue that needs situational awareness. More practically, hosting-capacity related studies have been also developed based on overvoltage and overloading aspects [34]. This is as, in short term analysis, corrective and preventive actions can be included for automation approaches such as the look-ahead policy in ADN [77].

In the current work, bus overvoltage and line ampacity violations, denoted by VV and AV respectively, have been formulated to establish the first and the second risk metrics. In each metric, the number of violation(s), denoted by $\mathcal{N}$, in the entire network as well as the depth of the violation(s), denoted by $\mathcal{D}$. By performing a single stochastic process, for example, $\mathcal{N}$ and $\mathcal{D}$ of VV are computed and stored in $Y_{\mathcal{N}}^{\text{VV}}$ and $Y_{\mathcal{D}}^{\text{VV}}$, respectively, as illustrated in the simplified algorithm shown in Figure 3.

For example, at each stepwise increase of PV connections, the $\mathcal{N}$ of VV represents violation number (integer) of all buses in the network. While the $\mathcal{D}$ of VV is considered to be the normalization of the exceeding value subtracted from the maximum permissible value. This algorithm is a part of the conceptual framework explained in Figure 2 (right-side in Layer 2). Avoiding repetitions, the same is exactly applied for any other assessment measures.

Another highly important factor needs to be mentioned that the risk assessment presented in this paper is intended to be serving the distribution networks with a promising potential to be transferred into being active i.e. having bidirectional power flows. Therefore, a third risk metric based on the reversal apparent power flow at the grid supply point (GSP), denoted by GV, has been formulated with the transformer's emergency power rating being set for the occurrence and the depth of the violation. The normal transformer rating in a steady state operation varies between 100% [78] to 150% [79] depending on some factors (ambient temperature, age, oil-cooling type …etc.), details for this regard are given within the respected review [6] and its bibliography. Particularly, this differs from

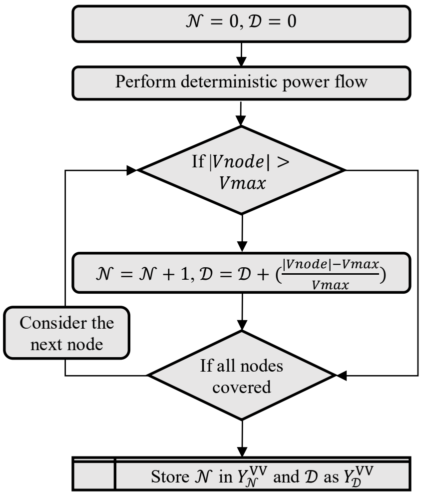

Figure 3 Algorithm to compute the number and depth of nodal overvoltage violations.

the nameplate rating perhaps by 10%. In addition, it is common to consider the emergency rating 140%-170% to the normal rating. Contrary to the lines and cables, this rating is not always an hourly rating quantity in which it could be depending on the loss-of-life criterion; for example, e.g. losing 1% life-per-day while under emergency loading [78]. To conclude, the thermal overloading rating depends heavily on the local utility and their adopted standards.

4.2.2 *Likelihood and Severity*

The likelihood (relative frequency of the number) and the severity (relative frequency of the accumulative depth) of these violations matter when it comes to determine risk metrics probabilistically. The k-th raw moment of any component, likelihood or severity, is calculated as follows:

$$\mathrm{E}[Y]^k = \int f(X) Y\big(g(X)\big)^k dX, \tag{9}$$

where $f(X)$ is the joint PDF of the independent vectors X; Y represents the required quantity to be estimated which also includes the $g(X)$ previously explained in the schematic diagram (*cf.* Figure 2). Deepening a bit, the uncertainty propagations of multiple Y are expressed after the consideration of m-stochastic samples in which $(\eta_{Y_1}^1, \eta_{Y_2}^1, \eta_{Y_3}^1)$ represent the output depiction of the first stochastic run of the three metrics (Y_1, Y_2, Y_3) defined in the previous subsection.

The concept of the first moment is used for the computation of these values. So that any risk metric R can be estimated as follows:

$$R_{lik} = \mathbb{E}\big[Y_{\mathcal{N}}\big] = \int f(X) Y_{\mathcal{N}}(g(X)) dX, \tag{10}$$

$$R_{sev} = \mathbb{E}\big[Y_{\mathcal{D}}\big] = \int f(X) Y_{\mathcal{D}}\,(g(X)) dX, \tag{11}$$

where $Y_{\mathcal{N}}$ and $Y_{\mathcal{D}}$ represent the function of violation number and the function of violation depth, respectively; R_{lik} and R_{sev} are risk metric components for which lik and sev stand for likelihood and severity, respectively. Notice that the risk metric R is kept without a superscript representing any risk metric of the three, VV, AV and GV. For example, bus voltage violation $R_{lik,sev}^{\mathrm{VV}}$ is referred to the coordinate of R_{lik}^{VV} and R_{sev}^{VV} at the same PV increase of s-step during t-time. In addition, each Y is treated here as independent and identically distributed for any further analysis due to the use of the Nataf transformation as alluded to before. The last point, particularly, allows us to involve the exploratory data analysis such as quantiles.

4.3 Risk Visualization

The visualization of risk has not been rigorously discussed in the reviewed literature, especially for applied science studies. In majority of publications, the dimension knowledge of the stochastic model is being the key element in characterizing risk, depend on probability-consequence diagrams. For instance, risk curve approaches, bubble representations, uncertainty boxes and strength-of-evidence assessment are common which also prediction intervals being included for some to add an extra strength of the uncertainty propagation [80]. For the sake of brevity, the selection of suitable diagrams may rely on the preferences of risk analysts wherein understandable and informative diagrams are being sought by a wide range of experts and field reporters. In fact, regardless of being impromptu in diagrams choosing, reasons of using a particular graphic display format in power system analyses are still unexplained subjects in textbooks and practices today.

In our problem, either likelihood-and-severity diagram or risk matrix, but not purposely restricted with, can fit for displaying the expectations of the uncertain impacts when increasing multiple PV connections. Aside from the likelihood and severity taking the vertical and horizontal axes, respectively, the stepwise increases in PV connections are possible to be represented as a third dimension with the use of color bar or direct labelling or even different scatter-point size. So it can enable us to streamlining different regions and then define the state of risk from being tolerable into unacceptable or normal/insecure/emergency, according to [81]. With the inclusion of the prediction intervals, in-depth discussions involving the exploratory data analysis such as boxplot can be established for each increase in which technically the quantile function based on linear interpolation is to be used. Going even deeper in terms of analysis, a risk matrix is possible with full details for a sole stepwise increase i.e. for only a single risk metric at one stepwise increase. However, the last point requires the use of extreme value theory and exceedance probabilities, which is beyond the scope of this paper.

5. Realistic Examples with Discussions

By carefully selecting the parameters of the complex model formulated above, depicting the possible future scenarios via the descriptive probabilistic analysis is reached and illustrated via two realistic examples. Parameters such as the bounds of the clearness index, correlation coefficients, PV connection increases and load variations are the only ones considered in this study. While useful results are promised when using others such as PF, virtual daytime and yearly day of the assessment, steady state standards…etc. Even more detailed parameters such as non-constant PV efficiency, surrounding reflectance, tilt angle for the surface from the horizon worth delicate investigations. Probabilistically, a Quasi Monte Carlo (QMC) method [82] is used to perform the stochastic convolution [83]. The chosen QMC is based on the Sobol sequences with stochastic runs of 1000 for two dimensions. The work is programmed in Matlab and part of it is co-simulated with another software named "OpenDSS" a powerful distribution network modeler, developed by EPRI [84]. The simulations are conducted through COM (common object model) interface and the whole is run on Intel® i7-2600 4-core @ 3.4GHz processor with 8GB RAM. One squared meter of a panel ($1\ \mathrm{m}^2$) is treated to be delivering 1kW along with the common manufacturing standardized conditions. The essential data required for establishing the assessments are given in Table 2. It should be noted that the active power variations, P_i^L, of a load connected at i-bus is assumed to follow Gaussian distribution. This is as an hourly average load, $P_i^{L,\mathrm{avg.}}$, is acquired providing the diurnal load curve. Using inverse transform sampling to generate a random variable, a confidence interval complying with 1σ principle for load variations is employed such that $\{P_i^L : \left|P_i^L - P_i^{L,\mathrm{avg.}}\right| < \sqrt{\left\langle\left\langle P_i^L \right\rangle\right\rangle}\}$. For the sake of generality, we kept a constant PF over all involved PVs and loads with a value of 0.95.

5.1 Small Distribution Network

An actual distribution network with a 11/0.4 kV substation (see Figure 4) is used to implement the aforementioned approach. The technical details are given in [85]. The rated power of the substation transformer is 125 kVA. The distribution of the rank correlation coefficients is arbitrary for both PV and Loads. The loads have been categorized into two independent sets. The loads within the same set are only correlated i.e. no correlation for loads within different sets. The rank correlation matrices for loads connected to (PCCs: 2, 3, 4, 5, 6) and (PCCs: 7,

Table 2 PV Data for the uncertainty model at different daytimes in a day in December.

PV model parameters			PV model specifications	
Time	D	D'	β	15°
12:00	1.327	-0.0465	eff	0.7
11:00	1.288	-0.0409	θ	15°
10:00	1.174	-0.0246	ρ	0.3

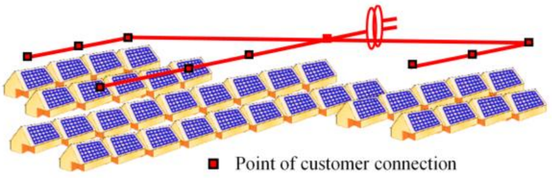

Figure 4 Radial distribution feeders with 36 households. (Adapted from [34])

8, 9, 10) are illustrated through Table 3, whereas the spatial correlation coefficients for domestic PVs are shown in Table 4. Following the discussion in Layer 1, the rank correlation coefficients in Table 3 and Table 4 are created randomly to be between 44% to 94% and sim definite positive symmetric according to RM in (9). The operational voltage at the main substation transformer for both studies is kept constant via OLTC to be 1 pu.

The hourly assessments were run for certain daytimes (10:00AM, 11:00AM, 12:00PM) in which three risk metrics ($R^{\mathrm{VV}}_{lik,sev}$, $R^{\mathrm{AV}}_{lik,sev}$ and $R^{\mathrm{GV}}_{lik,sev}$) were computed against PV increases (20% up to 300% of load) with 20% stepwise of maximum average loads. Following (1), 15 stepwise increases are performed with a_{intial} = 20% and s-step = 20%. The results are shown in Figure 5. Beside the x-axis and the y-axis being *severity* and *likelihood* scaled respectively, the third axis is the PV increase connections represented by the jet-colored scatter points. In order to clearly represent the third dimension, each scatter point represents a percentage of PV increase connections and labeled with a number. The number is the percentage multiplied by 0.01. In addition, the bigger the scatter point means the larger PV size connections performed. Moreover, a more dark (to red color) the scatter point is, the larger PV size connections. The time required to estimate each point is 0.207 second. With the regard of the effect of the correlation in the risk assessments, scatter points for the PVs with perfect rank correlation (near unity) are linked via a black line. While, the rank correlations shown in Table 4 are considered for the other scatter points that are linked via a red line. For both cases, the rank correlation for loads are shown in Table 3.

Table 3 Rank correlation matrices of loads of two categories.

Category 1						**Category 2**				
	2	**3**	**4**	**5**	**6**		**7**	**8**	**9**	**10**
2	1	0.61	0.86	0.83	0.62	**7**	1	0.96	0.85	0.83
3	0.61	1	0.72	0.45	0.46	**8**	0.96	1	0.92	0.89
4	0.86	0.72	1	0.79	0.7	**9**	0.85	0.92	1	0.72
5	0.83	0.45	0.79	1	0.65	**10**	0.83	0.89	0.72	1
6	0.62	0.46	0.7	0.65	1					

Table 4 Rank correlation matrix for the nine PVs

	2	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
2	1	0.92	0.73	0.75	0.68	0.86	0.79	0.85	0.81
3	0.92	1	0.71	0.65	0.63	0.79	0.68	0.73	0.68
4	0.73	0.71	1	0.59	0.54	0.72	0.66	0.75	0.71
5	0.75	0.65	0.59	1	0.44	0.61	0.69	0.68	0.77
6	0.68	0.63	0.54	0.44	1	0.69	0.53	0.66	0.46
7	0.86	0.79	0.72	0.61	0.69	1	0.81	0.78	0.69
8	0.79	0.68	0.66	0.69	0.53	0.81	1	0.71	0.83
9	0.85	0.73	0.75	0.68	0.66	0.78	0.71	1	0.75
10	0.81	0.68	0.71	0.77	0.46	0.69	0.83	0.75	1

Considering the problem with the daytime, it seems that the values of risk metrics start showing up after a certain PV increase. For instance, at 10:00AM, $R^{\mathrm{VV}}_{lik,sev}$ and $R^{\mathrm{GV}}_{lik,sev}$ become noticeable at 200% (written as “2” in the figure) of PV increase while for $R^{\mathrm{AV}}_{lik,sev}$ is at 180%. In addition, these metrics are to become even more noticeable (in earlier stages of PV increases) when the time moves towards the mid of the day, 160% at 11:00AM and 140% at 12:00PM.

In general, considering the perfect correlated PVs (red line), in comparison with the positive non-perfect correlation (red line), overestimates the risk of PV increase impacts. This is the case for all metrics during the three different assessment times. For example, at 10:00AM the value of $R^{\mathrm{VV}}_{lik,sev}$ components (*likelihood* and *severity*) is higher at each PV increase, see the black line in the first subfigure in the top-left of Figure 5. Although the value of the risk metric is higher at each PV increase for perfect correlation than for non-perfect one, the differences are not much significant in PV step increases below 200%. Also, it is due to the smaller scale of both components (*likelihood* and *severity*) that lead a visually large disparity in $R^{\mathrm{GV}}_{lik,sev}$. However, the adoption of the non-perfect positive correlation does show less risk degree comparing to perfect positive correlation. This reflects the fact that most of PVs acting similarly but not exactly the same. Therefore, it is reasonable to only adopt the positive non-perfect correlation (red line) for quantifying the degree of risks.

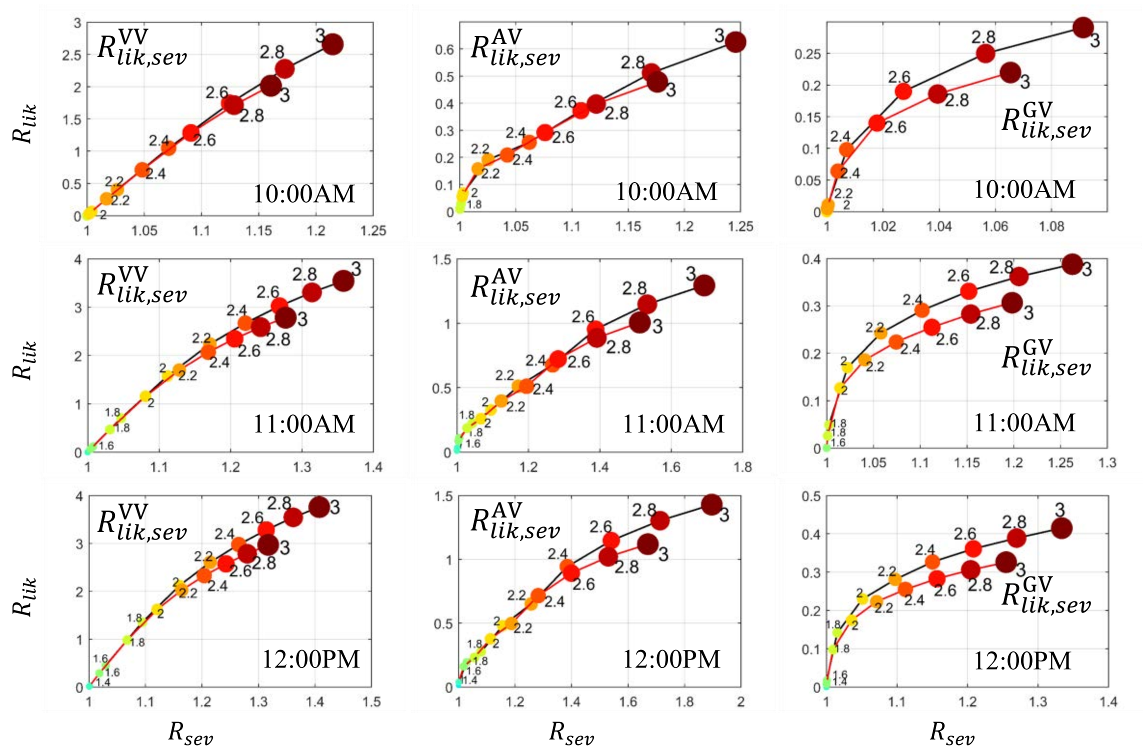

Figure 5 Three risk metrics versus different daytimes in a longest day. The x-axis and y-axis represent the severity, and the likelihood for each subfigure, respectively. The third dimension of PV increase connections is represented by size/color/label of the scatter points. The black line represents the perfect positive correlation whereas the red line represents the non perfect positive correlation modelled using Nataf transformation (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

In terms of considering different day times, risk metric components (*likelihood* and *severity*) are extending when moving towards the mid of the day. The likelihood (y-axis) and severity (x-axis) become obviously bigger (see the scales in Figure 5) when approaching the noon hour. By looking at the column related to $R_{lik,sev}^{\mathrm{VV}}$, the likelihood of the overvoltage occurrences in buses increases as the time passes by towards the midday hour. For instance, at PV step increase of 2, subfigure (10:00AM, $R_{lik,sev}^{\mathrm{VV}}$), the likelihood is almost zero. In Subfigure (11:00AM, $R_{lik,sev}^{\mathrm{VV}}$), the likelihood just exceeds 1. It means that the distribution network is expected to experience "1.1" buses with an overvoltage issue when PV increase is around 2. In Subfigure (12:00PM, $R_{lik,sev}^{\mathrm{VV}}$), this expectation extends to be "1.7" buses when PV increase is around 2 as well. In terms of the severity, the same analysis can be driven as the number "1" means 1 pu of the nominal voltage (400V). So, looking at PV increase of 2 in subfigure (10:00AM, $R_{lik,sev}^{\mathrm{VV}}$), the expectation of the bus voltage(s) across the network is around 1 pu which is acceptable according to utility standards such as EN50160. In subfigure (11:00AM, $R_{lik,sev}^{\mathrm{VV}}$), bus voltage(s) is expected to be around 1.08pu. In subfigure (12:00AM $R_{lik,sev}^{\mathrm{VV}}$), 1.13pu of nominal voltage is expected which is clearly violating the 1.1 voltage limits of EN50160. Off course, it can be read as *if PV connections are around 200% of the hourly average house consumption during 11:30PM to 12:30PM, there is a likelihood of overvoltage issues in 1.7 buses with 1.13 pu severity*. Similarly for $R_{lik,sev}^{\mathrm{AV}}$, *there is a likelihood of 0.4 lines being overloaded with 1.05pu severity*. For R^{GV}, *there is a 18% (written 0.18) likelihood of the substation being overloaded with 1.04pu severity expected*. Needless to say that all risk metrics are the same in principle but slightly different in interpretation.

5.2 South Australian Distribution Network

The relatively large distribution network has been segmented into several zones according to their relevant possibility of having a number of domestic PV connections (see Figure 6). The zonal assessments are carried out separately i.e. no multiple zones being assessed simultaneously. The intention of non-simultaneous assessments of multiple zones is to provide an initial overlook of which feeder is safer and more secure to be under a gradual transition from being passive into active. All the assessments are related to the longest-day related and for only an hour around noon. Details of the entire network are shown in [34], details of the zones are shown in Table 5. The cable types in this table are as 1 for 61/2.50-Flat (3×300 mm^2) AL XLPE, 2 for 30/7/.102 ACSR, 3 for 6/1/2.75 ACSR and 4 for 6/1/3.75 ACSR. The low voltage distribution transformers were chosen to perform the PV increase connections in which the PV increase percentage is to be in relation with an hourly average of power consumptions recorded on these transformers. Only positive non-perfect correlation related assessments were performed for this network.

In terms of entire zone assessments, different zones have slight different reactions as shown in Figure 7. For ease of use, we remove the subscripts lik and sev in this figure such as $R^{\mathrm{VV}}_{lik,sev}$ is to be R^{VV} only, without changing the meaning. The figure is intended to show a trend PV penetration versus the characteristics of each zone. For instance, zone A shows almost similar reactions as in zone C but a significant difference compared with zone B. In Table 5, zone A and C share similar characteristics but totally differ with zone B. However, slight differences are still noticeable between zone A and C, with PV connections increased up to 10 times over the connected loads For example, R^{VV} is around the coordinates of (1.25 3.3), (1.25 for *severity*, 3.3 for *likelihood*), in zone A, while (1.61 3.9) in zone C. In zone B, the risk of overvoltage issues, R^{VV}, is expected not to exceed "1" likelihood (see the horizontal dashed red line in Figure 7) or 1.1 pu severity (see the vertical dashed red line in Figure 7), even when PV connections are increased up to 10 times the loads. It is obvious that the distance from the substation as well as the length of the feeder play a proportional role with the value of R^{VV}. For R^{AV}, all the zones show the similar risk of the network being overloaded. The most influential factors that could contribute to shape this metric are the lines capacity, cable types as well as the average power consumptions. Despite more research needed here, the reason for high values for R^{AV} when increasing PV capacity is that the maximum average contractual loads is chosen to be the maximum average power consumption. In analyzing the R^{GV}, the scalar apparent power of the first upstream line in each zone is assessed against its emergency capacity which is 150% of the normal rating. For zone A, it is clearly shown in Figure 7 that R^{GV} exceeds 150% of normal rating by 10% when PV increase is 5.4 in zone A, R^{GV} exceeds 150% of normal rating by 10% when PV increase is 7.4 in zone B and finally R^{GV} exceeds 150% of normal rating by 10% when PV increase is 4.3 in zone C. However, it is up to DNOs to streamline the threat

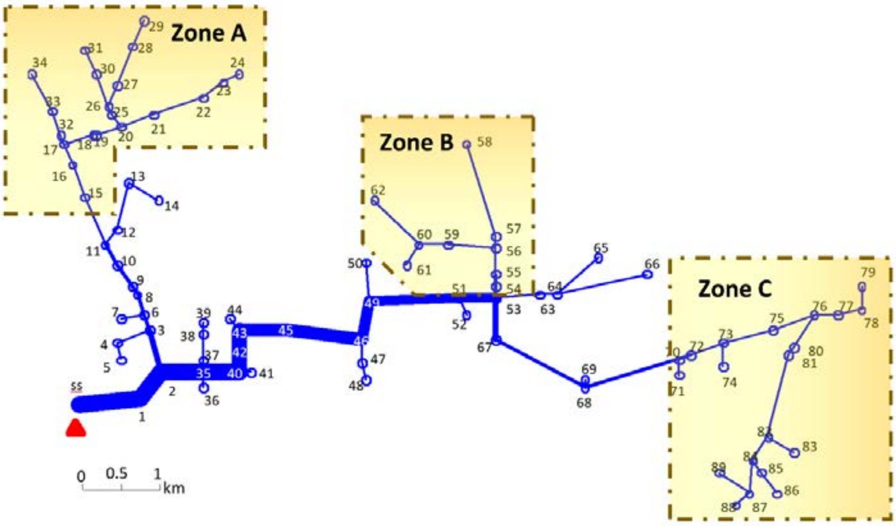

Figure 6 Three distribution feeders under assessment within a large distribution network situated in South Australia.

Table 5 Data of the feeders under assessments

Zone	Number of buses	Number of lines	Number of transformers	Total length (km)	Cable type
A	37	20	15	4.9	1,4
B	15	8	6	3.1	3,1
C	35	19	15	5.2	1,2,4

regions in accordance with their local standards. The risk can be read as for zone B, *there is a likelihood of overvoltage issues in 1 buses with 1.1 pu severity if PV connections are increased up to 7 times over the loads connected*. Therefore, restrictions or streamlining could be at 700% of PV connections/loads, according to (7). So that the operational state of a network can be identified accordingly as normal, insecure or emergency.

In terms of the inclusion of prediction intervals, additional exploratory data can provide in-depth analysis as shown in Figure 8 for zone C only (we refer to the subfigures in this figure by top, middle and bottom). The extra data considered here are 2.5%, 25%, 50%, 75%, 97.5%-percentiles of the actual data i.e. three quartiles plus the outlines wherein the confidence interval is 95%. Figure 8 shows the aforementioned percentiles, included in horizontal boxplots for *likelihood* and vertical boxplots for *severity*, as well as the expectations of the three risk metrics for the assessment of zone C only. In this figure, the medians (targets) show notably the tendency of the violation density distributions at each stepwise PV increase. For instance, even though the expectations (jet colored scatter points) that computed with 100% confidence interval show there are values for likelihoods and severities of R^{VV} (see the top subfigure), the density distributions of these risk metric components are biased towards no violation values when considering the medians instead of means (see the severity target symbols on the y-axis and likelihood target symbols on the x-axis). In analyzing R^{AV}, it seems that when PV connections are increased up to 5 times the loads, the median tendency of the density distributions starts to show signs of moving slowly from no violations into sensible values (see the middle subfigure). For analyzing R^{GV}, the medians of likelihood and severity

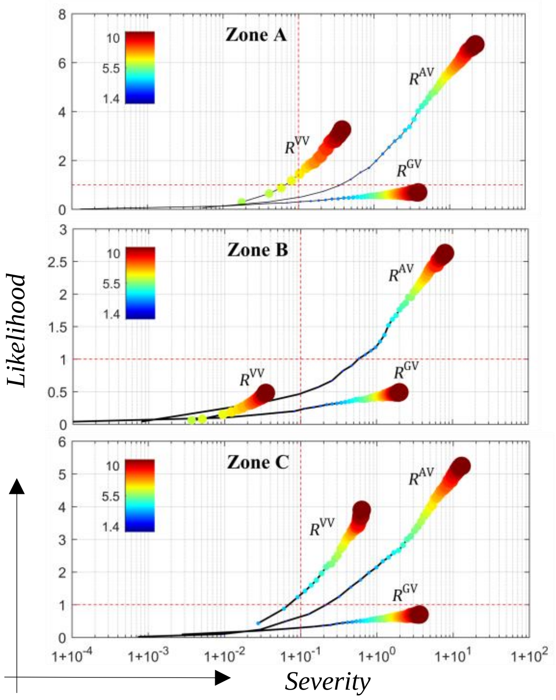

Figure 4 Risk assessments of three zones (A, B, C) as shown in Figure 6. The third deminsin of PV increase connecitons is represented by size/bar-colour of the scatter points.

move at PV increase connections of 2.5 times of loads (see the bottom subfigure in Figure 8). The benefit of this informative degree of risk needs further investigation of what can be done to minimize this risk.

Considering the upper percentiles (75% and 97.5%), the boxplots and outliers for R^{VV}(see the top subfigure in Figure 8) show different trends as it is obvious that likelihoods and severities are to exacerbate when PV connections are increased up to 8.5 times of the loads. For R^{AV} and R^{GV}, 75% and 97.5% percentiles of likelihoods seem to appear at PV increase connections just below 1.4 times of loads. However, the two upper percentiles do not show a rapid exacerbation in terms of severities (see the horizontal boxplots of middle and bottom plots). The significant observation here is the concluded estimates of the number of overloaded lines with their overloading depths. This can facilitate DNO to decide whether to allow PV connections of 10 times the loads which could result (see the tiny red circles in the middle subfigure in Figure 8) 75%-percentile of 8.5 overloaded lines with a 75% percentile of 18 times depth over the lines' rated capacity. Alternatively, PV connections of 4 times could yield about 3.8 lines being overloaded with depths of 3 times, from the viewpoint of 75%-percentiles as well (see the tiny blue circles in the middle subfigure in Figure 8).

The expectations of the impacts with relevant preparedness can be complemental to the existing automation approaches that usually aim to optimally operating ADNs. Time-based assessments in an hourly-ahead strategy are more likely to be an effective solution to seize the risks resulted from the uncertain behaviors of the system with a large number of PV connections. The outcomes of the above study can be considered to be significant in terms of

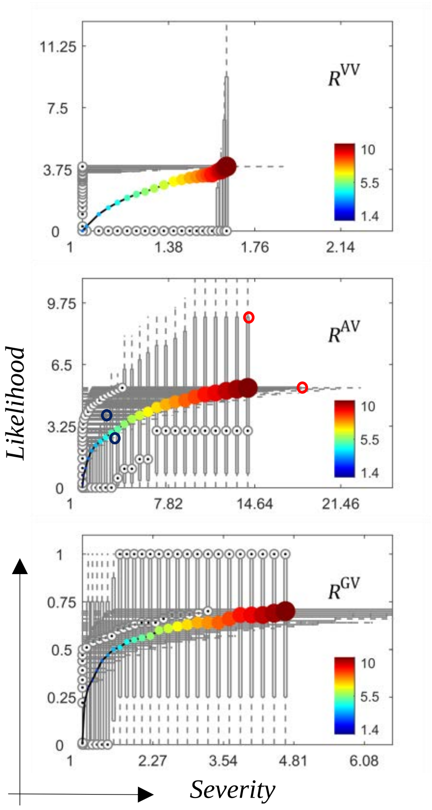

Figure 8 Risk metrics of the distribution n network in zone C with prediction intervals versus the third dimension of PV increase connections represented by size/color of the scatter points. (high quality printing is required for the delicate details display).

the risk display with tractable applied mathematics despite the complicated details. In addition, studies for matching between the network parameters and the network reactions such as [57] and [86] may find the concluded results of different zones informational, especially where this paper results agree with their study results, despite the totally different approaches. The probabilistic logics of impacts can be sought through simulation where extra important details could be easily added in the simulator such as OpenDSS that is used for this paper. Moreover, the assessments of the whole distribution feeders, i.e. no assessments of individual buses or lines, give realistic opportunities to form new regulations and reforms for safety and security purposes.

6. Conclusion

The paper introduces a new risk analysis approach to assess the performance of distribution networks when a large number of small-size PVs are connected. A PV uncertainty model based on localized clearness index is employed to represent the variability in PV output powers. The mathematical complexity of the stochastic system has been simplified through a single schematic diagram with three layers, representing the required simulation processes. The spatial correlation among PVs has been considered by using the Nataf transformation. By applying this transformation, the non-linearity of the correlation in the non-Gaussian space has been addressed.

The definition of risk as well as risk analysis are discussed. Three risk metrics describing the overvoltage and overloading issues have been implemented as well. The probabilistic measures of the two risk components (likelihood and severity) are used to characterize these risk metrics. In short, the relative frequency of the violation number and the accumulative violation depth are chosen to estimate the likelihood and severity, respectively. Additionally, risk visualization in three dimensions have been developed to show the effect of PV connection increases.

A distribution network situated in South Australia is used as a real-life example. This case study can help to understand the transition of any distribution network into being ADN as the OpenDSS, an advanced distribution network modeler introduced by EPRI, has been employed for this demonstration. Two realistic distribution networks have been utilized to show the effectiveness of the approach. Risk analyses of a small network with different daytimes and different correlations among PVs or loads are explained. The study outcomes show that the consideration of using only perfect correlations overestimates the risk metrics computed. Another case study we conducted is based on a network in South Australia divided into three zones with different characteristics. The results have been discussed in the paper. It has been demonstrated that each zonal network segment is unique in reaction to PV connection increases. The results presented include uncertainty intervals based on the percentile functions.

It is evident that the risk sourced from uncertainties is possible to model, predict and analyze. The new approach allows to determine the degree of risk in both terms *likelihood* and *severity* when increasing PV penetration. Thus, the DNOs can regulate and standardize the use of PVs within distribution networks according to this risk analysis approach. Future works are to incorporate other operational performance indicators such as frequency and harmonics, to utilize the approach for risk minimization studies, to integrate the approach into the existing automation methods for loss minimization, storage sizing, HC determination and renewable energy maximization.

Appendix A.

Given $\{u_{X_1}, u_{X_2}, \dots, u_{X_n}\}$ are random values of the uniform RVs, the inverse Rosenblatt transformation is summarised as follows:

$$\left.\begin{aligned} \xi_{X_1} &= F_{X_1}^{-1}\left(u_{X_1}\right), \\ \xi_{X_2} &= F_{X_2|X_1}^{-1}\left(u_{X_2}|\xi_{X_1}\right), \\ &\vdots \\ \xi_{X_n} &= F_{X_{n_1}|X_1,X_2,\dots,X_{n-1}}^{-1}\left(u_{X_{n_1}}|\xi_{X_1},\xi_{X_2},\dots,\xi_{X_{n-1}}\right) \end{aligned}\right\}, \tag{A.1}$$

where $F_{X_1}^{-1}\left(u_{X_1}\right)$ is the inverse CDF of X_1, $F_{X_q|X_1,X_2,\dots,X_{q-1}}^{-1}\left(u_{X_q}|\xi_{X_1},\xi_{X_2},\dots,\xi_{X_{q-1}}\right)$ is the inverse CDF of X_q and conditioned by $X = \{\xi_{X_1},\xi_{X_2},\dots,\xi_{X_{q-1}}\}$ for all $q \in [2,n]$. The inverse Rosenblatt transformation can be employed for any joint distribution and dependence structure.

Appendix B.

he first involves the Cholesky decomposition of the correlation matrix RM can be summerised as follows:

3. Obtain the lower triangular matrix LM of RM using Cholesky decomposition:

$$[RM] = [LM]^T[LM], \tag{12}$$

where

$$[RM] = \begin{bmatrix} 1 & C_{X_1X_2} & \cdots & C_{X_1X_n} \\ C_{X_2X_1} & 1 & \cdots & C_{X_2X_n} \\ \vdots & \vdots & \ddots & \vdots \\ C_{X_nX_1} & C_{X_nX_2} & \cdots & 1 \end{bmatrix}$$

4. Find the dependent-Gaussian vector, Z, form pseudorandom vector, S, by performing the following product:

$$\left[Z_{X_1},Z_{X_2},\dots,Z_{X_n}\right]^T = [LM] \times [S_1,\ S_2,\ \dots\ ,\ S_n]^T. \tag{13}$$

The RM must be positive semi-definite, real-valued as well as symmetric; and the coefficients of the matrix represent the percentage of dependence between a pair of RVs so that a closer value of C to 1 means a nearly to a perfect positive correlation.

List of Abbreviation

PV	PhotoVoltaic
ADNs	Active distribution network
DG	Distributed Generation
SA	South Australia
DNO	Distribution network operator
PMU	Phasor measurement unit
SCADA	Supervisory Control And Data Acquisition
STATCOM	Static synchronous compensators
OLTC	On-Line-Tap-Changer
GIS	Geographical Information System

WGs	Working groups
CIGRE	Conseil International des Grands Réseaux Électriques (International Council on Large Electric Systems)
EPRI	Electrical Power Research Institute
LAP	Look-ahead policy
HC	Hosting capacity
PCC	Points of common coupling
PDF	Probability density functions
PF	Power factor
RV	Random variable
QRA	Quantitative risk assessment
VV	Nodal voltage violation
AV	Line ampacity violation
GV	Reversal power flow at GSP
GSP	Grid supply point
QMC	Quasi Monte Carlo
CDF	cumulative density function
NORTA	NORmal To Anything
QRA	quantitative risk assessment
L^2	finite dimensional random space
$\mathbb{R}$	Real number
$\mathbb{R}^n$	real coordinate space of n dimensions

Indices and Sets

s	Stepwise increase
i	i-th receiving bus index
j	j-th sending bus index
$\mathcal{N}$	the number of violations index
$\mathcal{D}$	depth of the violations index which is the normalization of the exceeding value subtracted from the maximum permissible value.
t	Time index (one hour)

Indicators

VV	bus overvoltage violations
AV	line ampacity violations
GV	reversal power flow at GSP
avg.	Averaged load per a specified time
L	Load
lik	Likelihood of violation
sev	Severity of violation

Parameters

eff	PV array's efficiency (pu)
a_s	PV size (surface area) at s-step (m^2)
a_{intial}	PV size (surface area) at first s-step as a_1 (m^2)
θ	Angle between voltage and current specified for constant PF (°)
θ_{ij}	the angle difference between the voltages at i-th and j-th bus.
$\mathcal{G}$	Conductance which is the real part of admittance of a line (siemens).
$\mathfrak{B}$	Susceptance which is the imaginary part of admittance of a line (siemens).

P_i^{size}	Maximum delivery active power (size) of PVs connected at each i-th bus.
$P_i^{L,\text{avg.}}$	Time averaged load connected at i-th bus.
$Y_{\mathcal{N}}^{VV}$	Operational metric assigned for the number, $\mathcal{N}$, of voltage violations
$Y_{\mathcal{D}}^{VV}$	Operational metric assigned for the depth, $\mathcal{D}$, of voltage violations
D and D'	PV model parameters including (β, R_b, r_d, L_{loc}, L_{at}, L_{lat}, L_{st}, ρ, γ, ω, ω_{slr}, n, $\overline{H}_o$) details in [34].
β	Tilt angle.
R_b	Ratio of beam radiation on tilted surface to that on horizontal surface.
r_d	Ratio of hourly to daily diffuse radiation.
L_{loc}	Longitude.
L_{at}	Latitude.
L_{lat}	Altitude.
L_{st}	Standard meridian.
ρ	Ground reflectance.
γ	Solar inclination.
ω	Angular displacement.
ω_{slr}	Solar angular time.
n	Assessment day.
$\overline{H}_o$	Extraterrestrial solar radiation.
H_o	Monthly average irradiation.
$k_{t\,\max}$	Maximum bound of k_t.
$k_{t\,\min}$	Minimum bound of k_t.
k_d	Diffuse fraction.
B and B'	Logistic function's parameters (details in [34]).
N	Number of PVs connected to the same i-th bus.

Variables

$P^{s,t}$	Active power produced as a function of k_t at t-time during s-step (W).
Q^s	Reactive power (kW) produced by PV during s-step.
$I^{\beta}(k_t)$	Total solar irradiance received on a PV array surface area with an inclination angle β to a horizontal plane at t-time.
$P_i^{L,t}$	Active power consumed at t-time connected at i-th bus.
k_t	Hourly Clearness index.
R_{lik}	First moment of likelihood of risk metric R.
R_{sev}	First moment of severity of risk metric R.
R	First moment of risk metric.

Statistic symbols

Φ	Gaussian CDF
$F_{X_1}^{-1}$	Inverse CDF of X_1.
C	Copula.
$F_{X_1X_2}$	Joint CDF of X_1 and X_2.
RM	Correlation matrix.
LM	Lower triangular matrix.
T	Matrix transpose.
Z	Dependent-Gaussian RV.
σ	Standard deviation
$\xi_{X_n}^{r}$	Single r-realization for the RV represented by X_n.

S, s	Independent Gaussian vector and deviates.
U, u	Pseudorandom sequence.
Z, z	Dependent-Gaussian vector and deviates.
k	Number of the raw statistical moment.
$\eta_{Y_1}^{1}$	First stochastic run of the first output sequence Y_1.
m	Number of stochastic samples.
r	Single stochastic process.
X	Vector of RVs of the system under assessment.
Y	Arbitrary output vector.
n	Random input vectors
r	Realization index.
g	Collection of system-mathematical relations

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Chapter 7

Hourly-Assessment of Grid Hosting Capacity for Active Distribution Network

Statement of Authorship

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Name of Principal Author (Candidate)	Hassan Al-Saadi		
Contribution to the Paper	Developed ideas, performed simulations and calculations, analysed data, wrote manuscript and acted as corresponding author.		
Overall percentage (%)	75%		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
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By signing the Statement of Authorship, each author certifies that:

i. the candidate’s stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate’s stated contribution.

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Chapter 8

Conclusion and Future Work

8.1 Conclusion

The unfolding of electricity markets, the aspiration towards sustainable energy usage and reducing the dependence on fossil fuel are changing the context of the power distribution systems. The distribution networks, especially residential ones, are nowadays loaded with many small scale of DGs such as domestic PVs and WTs. The number of these DGs is in a rapid rise causing some negative impacts on the reliability and quality of power distribution by the utility. This has placed DNOs in a critical position as their role is to maintain high reliable power supply. Therefore, the integration of these DGs would be more beneficial when adjusting the highly restrictive policies of a DNO in order to allow higher levels of renewable generation deployment. Thus, new approaches have been presented in this dissertation to quantify the impact of high DGs connections. In details, the thesis answers the underpinned questions mentioned in Chapter 1. The questions are focused on two main subjects of this thesis: HC and risk analysis within the context of distribution networks. For HC, the questions are related to modelling the uncertainty of the total solar irradiance incident on a tilt surface following Australian meteorology which is covered in Chapter 3 and further developed in Chapter 4 when applying Hay-Davies mathematical representation instead of HDKR model. The question related to determining HC through the utilization of probabilistic means is covered in Chapter 5 while the employment of Quasi Monte Carlo and sparse grid techniques for more efficient computing power is covered in Chapter 4 and Chapter 5, respectively. For risk analysis, the questions are related to formulating the inter-dependences amongst the connected DGs and consumptions covered in Chapter 6. Finally, for examining the operational performance of distribution networks considering the two risk components: likelihood and severity is covered in Chapter 6 and Chapter 7 while performing HC under risk analysis is covered in Chapter 7.

8.2 Main Contributions of the Thesis

The main contributions of the presented research in this thesis are as follows:

1. Two new models (see the mathematical expression numbered 3 in Chapter 3 and the mathematical expression numbered 6 in Chapter 5) to estimate the total radiation incident on a tilted solar panel are developed with the use of best fit correlation for diffuse fraction compatible for Australian grounds. local data in Adelaide. The performance of the proposed model is tested by goodness-of-fit tools against the obtained local data in Adelaide.
2. Sparse grid technique is proposed for uncertainty computations and compared with MCT for efficient time and accuracy.
3. A new approach for determining HC probabilistically is introduced by adopting the likelihood approximation and establishing a set of operational performance indices. The approach does not rely on the worst-case scenario, it delivers the likelihoods of the system to deteriorate, giving several choices for DNOs to discuss and regulate their policies. In addition, the concept of HC is developed in accordance with the requirements of risk analysis criteria.
4. The rank correlation is developed with Nataf transformation in order to consider the nonlinearity of the dependences existing amongst the involved uncertainties.

5. A new risk assessment is developed considering the two risk components: likelihood and severity by the relative frequency of the violation number and the accumulative violation depth, respectively. The assessment enables to quantify the degree of risk under uncertainties when increasing the DG connection in a distribution network.

8.3 Recommendations for Future Work

There are a range of work that can be conducted based on the proposed framework of this thesis. The research directions of the future work are:

1. Even though the presented models for estimating the uncertainty of solar irradiation has been demonstrated to Adelaide city, it would be worthwhile applying these models to more cities as other case studies.
2. In this thesis, six operational performance indices were formulated taking into account the issues related to power quality and overloading only. Also, the effect of the contractual loads has been investigated with the results showing very low effects on the system operation. It is worth considering the frequency deviation, harmonic distortion and phase balance as three additional indices.
3. In this thesis hourly-based uncertainty models for HC estimation were developed with expected values being set for making decisions, it is worth investigating another exploratory data analysis such as mode, median, trimmed mean, interquartile range, midhinge, studentized range, truncated mean, trimean, shewness, kurtosis …etc. along with the requirements of the

utility standards. In addition, the impact of DG connections quantified by the presented risk analysis can be further analysed using different quantiles to comply with local utility standards.

4. The proposed HC estimation and risk analysis can be used with other automation approaches for optimal operation performance or for cost-benefit analysis using mathematical optimization tools.
5. Other type of uncertainties can be considered for the future work such as the epistemic knowledge with possible distributions.
6. By using the proposed method for modelling the spatial correlation, in the large power network, the correlation of power flow with temperature variation due to heatwave is worthy of further investigation.