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Review of power system impacts at high PV penetration Part I: Factors limiting PV penetration

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ABSTRACT

As the number of photovoltaic (PV) installations across the world keeps on increasing, their impacts on power systems are becoming more visible and more severe. In this two-part review, the implications of high PV penetration on the stability and reliability of power systems are comprehensively assessed. This paper, the first of the two, reviews the impacts of PV on the power systems' voltage, frequency, protection, harmonics, rotor angle stability, and flexibility requirement in detail. Factors contributing to those impacts, as well as the level and timeframe at which they occur, are carefully analysed. Subsequently, the limits of PV penetration observed in the literature are reviewed. To allow the readers to verify these impacts and limits, the tools and models typically employed in power system analysis are also elaborated. The second part of the review then completes the investigation by assessing the existing solutions to the PV integration challenges and suggesting the way forward.

1. Introduction

The energy requirement worldwide has risen continuously due to the increase in the population as well as the people's desire to achieve higher quality of life. This is illustrated in Fig. 1 which shows the worldwide energy consumption according to the different primary energy sources. The figure shows that until now most of the energy generation comes from non-renewable sources. However, these sources are limited and are expected to run out in the near future if we continue with this trend. According to British Petroleum (BP, 2019), based on the energy consumption and the known reserves in 2018, natural gas, oil and coal can only last for 51, 50, and 132 years respectively. In addition to their limitation, these fossil fuels are also linked to the emissions of greenhouse gases.

Therefore, efforts to further increase the penetration of renewable sources have been made by different countries. Among these sources, solar energy is the one with the highest potential due to the massive amount of energy that we receive from the sun (Perez and Perez, 2015). This, together with the considerable reduction on their price (PVinsights, 2020), have led to the rapid increase in photovoltaic (PV) systems installation, as shown in Fig. 2. The figure illustrates the exponential increase in the accumulated installed capacity of PV – more than 600 GigaWatt-peak (GWp) by the end of 2019, producing 3% of the worldwide electricity generation according to International Energy Agency Photovoltaic Power Systems Programme (IEA PVPS, 2020). The growth in PV installations has always exceeded the predictions and the trend is likely to continue as the effects of climate change are becoming more visible.

These PV systems can be broadly divided into off grid and on grid. Off-grid systems are those without a connection to a main grid, normally due to the remote or isolated locations (such as islands) or low population density, such that it is not cost-effective to extend the main grid to these locations. These systems can then be installed for the 14% of the world's population which do not have access to electricity (84% of whom live in rural areas) (IEA, 2017).

On-grid systems, as the name indicates, are those connected to the main grid. They represented more than 95% of the total PV installed capacity in 2018 (IEA, 2019a) and can be divided into three main groups based on their installed capacity, namely, residential (capacity of a few kWp), commercial/industrial (tens to hundreds of kWp) and utility scale (MWp and beyond) (Fu et al., 2017). On the one hand, the two former groups can also be considered as 'behind-the-meter PV' installations as their main purpose is to satisfy the local load demand (a household and commerce/industry, respectively), and only the remaining energy produced by the PV system will be injected into the grid. Because of their relatively small size, these PV systems are typically connected at the distribution level. On the other hand, utility-scale systems, also called PV farms, directly inject all the energy into the

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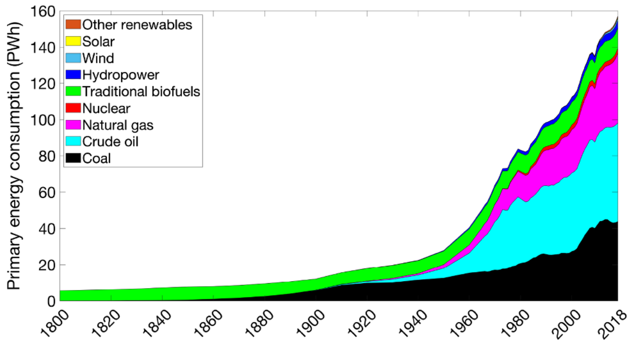

Fig. 1. Historical primary energy consumption worldwide. Data source: BP (2019), Smil (2017).

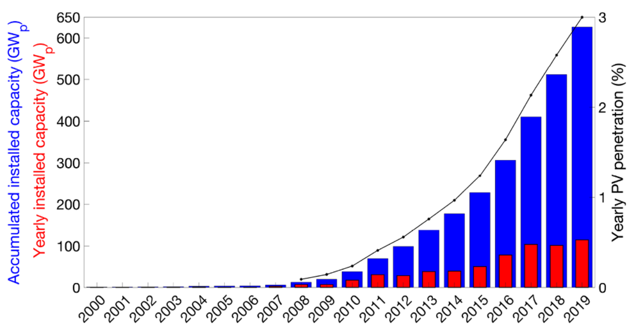

Fig. 2. Historical PV accumulated installed capacity, PV yearly installed capacity, and share of PV electricity production. Data source: IEA PVPS (2016, 2018, 2019, 2020).

main grid (and receive payment for the energy delivered) at the transmission level. By 2019, utility-scale PV represented around 66% of the PV installations by capacity (IEA PVPS, 2020).

PV installations not only have the potential to generate economic benefits, but also advantages in the electrical and environmental aspects. For example, distributed PV systems reduce power losses by generating energy directly at the load, decreasing the electricity to be transmitted from faraway generators. In addition, PV also helps to reduce the CO2 emissions from the fossil-fuel-based generators and fulfil the growing electricity demand.

Nevertheless, as the PV installation capacity increases and starts representing a considerable share of the energy produced, grid quality concerns, such as harmonics, voltage violations, reverse power flow, and miscoordination of grid protection equipment can emerge. Therefore, a detailed study and analysis are necessary to understand these limitations on PV installations and the possible conditions where they occur. Through analysis of the challenges that PV integration brings and their potential solutions, this paper aims to enable even higher PV penetration in power system.

As this paper focuses on the influence of PV systems on the electrical grid, many electrical terms will be used throughout this paper. Therefore, we introduce some of the key terms below:

- PV penetration: amount of PV capacity installed in a grid with respect to the load demand. It is commonly defined as either (1) the ratio of the PV installed capacity with respect to the peak load demand, or (2) the ratio of the total energy produced by PV with respect to the total energy consumed.
- Harmonics: components of voltage or current which are not at the power system frequency (see Section 4.4).
- Islanding: state when the main electrical grid is not present anymore, yet a distributed generator (such as a PV system) is still generating electrical power. Islanding is not desirable because it can pose danger to technicians who might not realise that the circuit is still powered. All commercial on-grid PV inverters now have anti-islanding protection.
- Transmission system/network: high-voltage (typically above 66 kV) electrical network which transfers the electrical power from centralised power plants to electrical substations.
- Distribution system/network: low-voltage (LV) and/or medium voltage (MV) network which transfers the electrical power from the transmission network to final consumers.
- Transients: short period of time (~10s) where the electrical voltage or current is disturbed.
- Voltage fluctuations/flickers: rapid fluctuation on the grid voltage which produces changes in light brightness (see Section 4.1.1).
- Power quality: ability of the grid to provide a stable and desired flow of power. This is typically measured based on the characteristics of the grid voltage, frequency and waveform.

This paper is the first part of a two-part review where the impacts of high PV penetration in distribution and transmission systems are reviewed. The second part of the review (Kumar et al., 2020a) then outlines the existing solutions in the literature and the way forward. Section 2 of this paper describes the need for an updated review of impacts of PV integration on the power systems' stability and reliability. Section 3 outlines the review methodology. Subsequently, the impacts of PV on voltage, frequency, protection, harmonics, rotor angle stability, and flexibility requirement are reviewed in Section 4. Section 5 elaborates how these impacts have been reported to limit PV penetration in power systems, while Section 6 gives an overview of the platforms and models used to analyse them. Finally the paper is concluded in Section 7.

2. The need for an updated review

The quest to quantify the impact of PV integration into the electrical grid has become popular only recently. Before 2010, there have been research works that analysed the PV grid integration, such as Asano et al. (1996) and Barker and De Mello (2000), but these efforts have been sporadic. This is also reflected in the number of review papers on the subject. In the early 2000s, most reviews were more focused on the off-grid applications of PV (Wichert, 1997; Phuangpornpitak and Kumar, 2007; Nema et al., 2009), as the cost of installing grid-connected PV is not yet competitive with conventional generation and not many people thought that PV would be a significant source of power. Yet, PV is now the fastest growing source of energy and shows no signs of stopping. As such, many researchers have been reviewing the potential impacts of PV on the power system and suggested measures to solve the potential challenges.

Early efforts have mostly analysed the impacts of distributed PV generation on the distribution systems, because the electricity price is the highest at the distribution level, and therefore where PV would first penetrate. Eltawil and Zhao (2010) reviewed the literature on PV adoption across the world, impacts of PV at high penetration and the islanding prevention methods. At the end, the authors recommended PV to operate at unity power factor to reduce the probability of islanding. Passey et al. (2011) focused on the impacts of distributed generation on low voltage (LV) networks and analysed the technical and non-technical factors – including the role of government, utility, and regulators – required to address the negative impacts. Karimi et al. (2016) identified voltage and harmonics caused by PV in distribution systems as the main challenges for PV integration. The authors also gave an overview of the methods to detect islanding, both passive and active, as well as hybrid methods. Meanwhile, Haque and Wolfs (2016) focused on overvoltage and voltage unbalance problems. The paper suggested the use of voltage regulating devices, both the traditional and emerging ones to solve these issues. Aziz and Ketjoy (2017) also found that voltage problems is the main limiting factor of increasing PV penetration and reviewed the PV penetration limits in low voltage

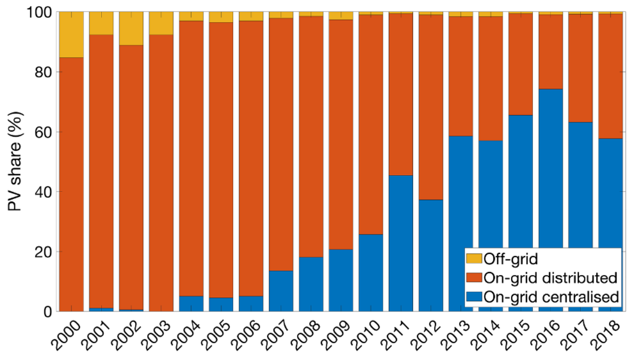

Fig. 3. Shares of global PV installations based on the type of grid connection. Data source: IEA (2019a), IEA PVPS (2016).

networks based on the voltage violations.

As the costs of PV continued to decrease, more and larger utility-scale PV projects began to flourish. Researchers started paying attention to the impacts of large-scale PV systems on the transmission network. Shah et al. (2015) reviewed the stability issues caused by large-scale PV in power systems and the PV models required for the analysis. Rakhshani et al. (2019) discussed possible contributions from large-scale PV to power system operations, such as by providing virtual inertia and regulating voltage. The shift in research focus from off-grid PV, to on-grid distributed PV, and then to on-grid centralised PV power plants, is in line with their evolving shares of the total PV installation across the world (Fig. 3).

The variability associated with PV has been a particular focus of interest among researchers. In Shivashankar et al. (2016), the impacts of intermittency of PV were surveyed, with particular focus on the voltage and frequency fluctuations. The authors suggested geographical dispersion, use of storage, and active power curtailment to smoothen the PV variation. ElNozahy and Salama (2013) have analysed the impacts of both small and large-scale on-grid PV system and predicted that cloud transients and the required increase in frequency regulation would be the factors limiting PV penetration. Seneviratne and Ozansoy (2016) reviewed the transmission system frequency response in case of sudden loss of a large traditional generator with increasing wind and PV penetration. Dreidy et al. (2017) argued that frequency is the most important technical issue limiting the adoption of PV and wind. The paper also reviewed the inertia and frequency regulation techniques for both of the renewable energy sources.

As PV inverters play a huge role in determining the impact of PV integration on the grid, many papers dedicated their efforts on reviewing the inverter development and various control and topologies available (Veena et al., 2014; Yang and Blaabjerg, 2015). There have also been works to evaluate the PV integration efforts in specific countries, e.g. Greece (Kyritsis et al., 2017), South Africa (Thopil et al., 2018), and Malaysia (Wong et al., 2014), taking into account the local standards and energy policies.

Many of the review papers are too broad, covering everything from the power production of solar cells to inverter topology and the PV impacts on the grid in a single paper, and not covering the topics with enough depth in the end. For example, Lai et al. (2017) described the development of PV in selected countries and the cell technologies available, on top of the PV stability and integration issues. Subsequently, the authors reviewed the development of energy storage systems and how they can mitigate the integration challenges. Lupangu and Bansal (2017) were even more ambitious in covering the cell technologies, maximum power point tracking (MPPT) modelling techniques, energy management methods, operations and management of PV systems, and even the energy policy. As such, the paper only briefly touched on the impact of PV systems on the grid. Obi and Bass (2016) reviewed the interconnection and safety standards, emphasised the need for steeper ramp up at high PV penetration as illustrated by the Californian 'duck curve' (Jones-Albertus, 2017), and also outlined the ways to increase PV efficiency and energy yield. Kumar et al. (2016) briefly reviewed the PV and wind technology, outlined the various issues they bring about, and described the methods – in particular optimisation methods – that have been proposed in the literature to solve them.

Some review papers focused on islanding of PV systems as an issue (Eltawil and Zhao, 2010; Passey et al., 2011), even though a rigorous study by IEA PVPS in a representative residential network in the Netherlands reported that the probability of islanding is 'virtually zero' (Verhoeven, 2002) and another IEA PVPS study estimated that the worst case risk of an electric shock due to islanding of PV system is less than 10^{-9} per year, three orders of magnitude lower than the existing risk for network operators and customers (Cullen et al., 2002).

Some papers did not clarify which issues are happening at distribution or transmission level. Moreover, almost all the review papers did not provide a guide on how to carry out the assessments, such as the list of tools and how to model the grid, which would allow the readers to perform their own studies and verify the findings reported in the literature.

In the past few decades, not only PV penetration has risen rapidly, the PV technology has also advanced with vast changes in the interconnection standards. For example, when it was first published in 2003, Institute of Electrical and Electronics Engineers (IEEE) Standard 1547 used to prohibit PV and other distributed energy resources (DERs) from providing reactive power support for voltage control (Ellis et al., 2012), but has since made reactive power capability compulsory in its full revision in 2018 (IEEE Standards Coordinating Committee 21, 2018).

Because of the aforementioned shortcomings, and because of the rapid development of PV technologies, a more instructive, structured, and updated review is warranted. This review paper seeks to cover the technical impacts of integration of PV in power system in depth, carefully analysing what contributes to those impacts as well as the level and timeframe at which they occur. This review not only covers the impacts and the possible solutions,[1] but also the tools and models that are employed to analyse them. Therefore, through this paper, the readers will not only understand the challenges of PV integration, but will also be able to verify them and further the research in this field.

This work focuses on the technical power system impacts of PV that might limit its penetration, but not on other types of impacts that come with PV integration, e.g. economic, environmental, and social. The readers are referred to Alqahtani et al. (2016), Denholm et al. (2014), Gowrisankaran et al. (2016), Mills et al. (2013) for explorations on the other types of impacts.

3. Review methodology and scope

Upon discovering the gaps in the literature explained in Section 2, a more comprehensive literature survey was conducted using a methodology described in Fig. 4 (the figure's layout was inspired by Ayoub (2019)). The initial scope and keywords were determined through the authors' previous works as well as through the assessment of the existing review papers in the field, elaborated in Section 2. The scope and keywords were iteratively adjusted based on the findings obtained throughout the review process. Google Scholar, one of the most prominent platforms to search for scientific works, has been used. On top of that, the relevant documents of leading institutions in power systems and solar energy integration, such as California Independent System Operator (CAISO), IEA PVPS, IEEE, National Renewable Energy

[1] The solutions to PV integration impacts are reviewed in 'Review of power system impacts at high PV penetration Part II: Solutions and the way forward' (Kumar et al., 2020a).

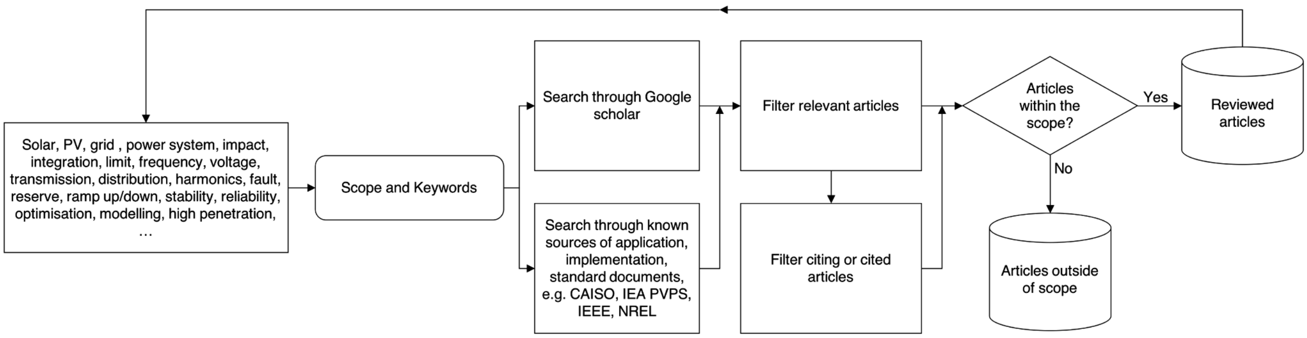

Fig. 4. Flowchart of this paper's review methodology.

Laboratory (NREL), etc., were also examined. The references from these documents, together with the articles that cited the documents, were also checked. The relevant articles were then reviewed and cited in this paper. The works that analysed the impacts of high PV penetration on power systems are listed in Table 1 on page 5, while other reviewed works are cited in the relevant sections of this paper. It should be noted that the impacts analysed are power system impacts that are/might be limiting PV penetration, and do not include communication, cyber security, economic, or environmental issues associated with PV installations. Electricity market has not been explored in detail in this paper, although some aspects were introduced and explained in various sections, particularly in Sections 4.2 and 4.6.

The tools and models described in Section 6 are not meant to be a comprehensive review, but rather serve as a starting point and reference for the readers who wish to study the power system impacts analysed in this paper. More detailed reviews on the different tools and models have been provided in the relevant subsections.

4. Impacts of PV integration into power system

The current electrical networks were built with dispatchable centralised generation in mind. As such, they are not necessarily able to handle the increasing variable distributed generation from solar PV (Passey et al., 2011).

The PV characteristics that bring about challenges for the power system integration can be mainly classified as: distributed, diurnal, converter-based, and intermittent.

Distributed: PV, due to its modularity, can be installed in small scale directly at the load. When installed behind the meter, the PV system might be invisible to the grid operators, and are non-dispatchable. In 2012, the European Network of Transmission System Operators for Electricity (ENTSO-E) estimated that 80% of installed PV are connected to the LV distribution system (Porter et al., 2012). When the PV generation exceeds the load, reverse power flow occurs. This might be a problem as the grid was designed for unidirectional power flowing from high to low voltage networks. Unbalanced installations of distributed PV across the phases can also cause voltage unbalance in the LV network.

Diurnal: PV generation is only available during the day. While this is beneficial for systems with peak load during the day, at higher PV penetration and especially in systems with evening peak load, PV necessitates high ramp rate/reserve requirement to transition from the low daytime net load to the peak evening load. This phenomenon is illustrated by the famous 'duck curve' shown in Fig. 5. In residential networks with very low daytime loads, high PV penetration can induce reverse power flow.

Converter-based: Unlike traditional generators, PV does not have a turbine or a rotor and hence, it has no kinetic energy or inertia either. Inertia is essential in maintaining the frequency and rotor angle stability during disturbances. Therefore, large shares of inertia-less PV in the power system might cause instability. Non-linear switching and operations of inverters can also contribute to harmonics and reduce the system's power quality.

Intermittent: Power generated from PV can change drastically within a very short time due to cloud movements; for instance, the generation of a 1.6 MW and 2 kW PV system can drop to half within 9 and 3 s respectively (Cormode et al., 2013). At high penetration, this rapid change in power can cause harmonic distortions and voltage flickers.

Fig. 6 illustrates the PV characteristics, as well as their significance and impacts to the power system. The timescales and the location (distribution or transmission system) of the impacts have also been indicated such that the readers can determine the tools and data required to evaluate a particular impact, as elaborated in Section 6.

Table 1 lists the references reviewed in this paper, the grid impacts of PV that they analysed, and the power system tools they employed (elaborated in Section 6.1). Some of the references have investigated the impacts of PV on transformer and line loading, as well as on non-technical impacts, which are not elaborated in Table 1 or in this paper. Increased transformer and line loading has not been a challenge to PV integration (Bernards et al., 2014; Hoke et al., 2013; Tie et al., 2015) – other impacts have been shown to be more pressing in the papers that investigated both – and thus was not included. The reference list is not exhaustive and may contain a bias based on the review methodology described in Section 3.

The following subsections review the reported impacts of PV integration into power system based on the category outlined in Fig. 6. It is important to note that all the impacts highly depend on the system characteristics (topology, impedance, loading level, etc.) as well as on the penetration and locations of PV in the system.

4.1. Voltage

Many works have cited voltage violations to be the most important factor limiting PV penetration (Aziz and Ketjoy, 2017; Kordkheili et al., 2014). Traditionally, in 415 V LV network, there are no voltage regulation devices as the network depends on voltage regulations at the 11 kV or higher voltage network. As such, many of the voltage violations occur at the LV networks.

4.1.1. Voltage fluctuation

Voltage fluctuation, sometimes also called voltage flicker, is 'a series of voltage changes or a cyclic variation of the voltage envelope' (IEEE, 2015). Typically, the magnitude of voltage variations still fall within the voltage limits (Power Quality World, 2011). Their most significant effect is flicker. IEEE Standard 1453-2015 (IEEE, 2015) defines flicker as 'the subjective impression of fluctuating luminance caused by voltage fluctuations.' The flickering of light can cause fatigue, is detrimental for health, and in some cases even cause epileptic seizures. It should be noted that in this paper, voltage fluctuation specifically refers to the fluctuation in the order of ms to the point it causes flicker. Transient voltage stability is discussed in Section 4.1.3 Voltage magnitude.

Table 1
The list of studies, the impacts analysed, and the tools employed

Reference	Impacts Analysed[a]	Tools Used[b]
ElNozahy and Salama (2013)	Voltage fluctuation, voltage unbalance, voltage magnitude, frequency, harmonics, rotor angle stability, islanding	–
Passey et al. (2011)	Voltage fluctuation, voltage unbalance, voltage magnitude, frequency, harmonics, islanding	–
Karimi et al. (2016)	Voltage fluctuation, voltage unbalance, voltage magnitude, harmonics, islanding	–
Cobben et al. (2008)	Voltage fluctuation, voltage unbalance, voltage magnitude, harmonics	Real measurements
Smith et al. (2017)	Voltage fluctuation, voltage unbalance, voltage magnitude, harmonics	–
Wong et al. (2014)	Voltage fluctuation, voltage unbalance, voltage magnitude	Experimental measurements
Kumar (2017)	Voltage fluctuation, voltage magnitude, frequency, protection, harmonics, rotor angle stability	MATLAB, PowerWorld, Simulink
Wu et al. (2016)	Voltage fluctuation, voltage magnitude, frequency, protection	MATLAB, PSS/E
Tan (2004)	Voltage fluctuation, voltage magnitude, frequency, rotor angle stability	EUROSTAG, PowerWorld, Simulink
Ackermann and Knyazkin (2002)	Voltage fluctuation, voltage magnitude, protection, harmonics	–
Kumar et al. (2016)	Voltage fluctuation, voltage magnitude, harmonics, rotor angle stability	–
Bank et al. (2013)	Voltage fluctuation, voltage magnitude, harmonics	Real measurements
Ebad and Grady (2016)	Voltage fluctuation, voltage magnitude	MATLAB, OpenDSS
Barker and De Mello (2000)	Voltage fluctuation, protection, harmonics, islanding	–
Thongpron et al. (2004)	Voltage fluctuation, harmonics	Experimental measurements
IEA PVPS (2014)	Voltage unbalance, voltage magnitude, frequency, harmonics, islanding	–
Ding and Mather (2017), Wang et al. (2019)	Voltage unbalance, voltage magnitude	MATLAB, OpenDSS
Haque and Wolfs (2016)	Voltage unbalance, voltage magnitude	–
Tie et al. (2015)	Voltage unbalance, voltage magnitude	OpenDSS
Schwanz et al. (2017)	Voltage unbalance	Not provided
Enslin (2009)	Voltage magnitude, frequency, protection, rotor angle stability	Not provided
Rakhshani et al. (2019)	Voltage magnitude, frequency, harmonics, rotor angle stability	–
Eltawil and Zhao (2010)	Voltage magnitude, frequency, harmonics, flexibility requirement, islanding	–
Ackermann et al. (2013)	Voltage magnitude, frequency, harmonics, flexibility requirement	DIgSILENT PowerFactory, Simulink
Eftekharnejad et al. (2013)	Voltage magnitude, frequency, rotor angle stability	DSATools, PSLF
Kumar et al. (2019)	Voltage magnitude, frequency, rotor angle stability	PowerWorld
Kumar et al. (2020)	Voltage magnitude, frequency, rotor angle stability	MATLAB, PowerWorld
Shah et al. (2015)	Voltage magnitude, frequency, rotor angle stability	–
Mukwekwe et al. (2017)	Voltage magnitude, protection, harmonics	MATLAB, Simulink
Kyritsis et al. (2017)	Voltage magnitude, protection	–
Thopil et al. (2018)	Voltage magnitude, harmonics	–
Lai et al. (2017)	Voltage magnitude, rotor angle stability	–
Aziz and Ketjoy (2017)	Voltage magnitude	–
Bernards et al. (2014), Kordkheili et al. (2014), Povlsen (2002), Thomson and Infield (2007)	Voltage magnitude	Not provided
Gandhi et al. (2016b)	Voltage magnitude	MATLAB
Heslop et al. (2014)	Voltage magnitude	DIgSILENT PowerFactory, MATLAB
Hoke et al. (2013)	Voltage magnitude	GridLAB-D
Maharjan et al. (2020)	Voltage magnitude	DIgSILENT PowerFactory
Shayani and de Oliveira (2010)	Voltage magnitude	MATPOWER
Tonkoski et al. (2010)	Voltage magnitude	MATLAB, PSCAD
Tonkoski et al. (2012)	Voltage magnitude	PSCAD
Zhang et al. (2010)	Voltage magnitude	PSLF
Miller et al. (2014)	Frequency, rotor angle stability, flexibility requirement	PLEXOS, PSLF
Tielens and Van Hertem (2016)	Frequency, rotor angle stability	–
Fritz (2016)	Frequency, flexibility requirement	Real measurements
Lew and Miller (2017), Ogimoto (2014), Porter et al. (2012)	Frequency, flexibility requirement	–
Alquthami et al. (2010)	Frequency	PSCAD, PSS/E
Ciapessoni et al. (2013), Miller et al. (2012)	Frequency	Not provided
Dreidy et al. (2017), Seneviratne and Ozansoy (2016)	Frequency	–
Yan et al. (2015)	Frequency	PSS/E
You et al. (2017)	Frequency	PLEXOS, PSS/E
Hooshyar et al. (2013)	Protection	PSCAD
Kavi et al. (2017)	Protection	MATLAB, Simulink
Phuttapatimok et al. (2008)	Protection	Experimental measurements, Simulink
Benhabib et al. (2007), Santos et al. (2015)	Harmonics	Not provided
Chidurala et al. (2016)	Harmonics	PSCAD, real measurements
Dartawan and Najafabadi (2018)	Harmonics	MATLAB, OpenDSS
Enslin and Heskes (2004)	Harmonics	MATLAB, real measurements, Simulink[c]
Langella et al. (2016)	Harmonics	Experimental measurements
Poosri and Charoenlarpnopparut (2016)	Harmonics	DIgSILENT PowerFactory
Rönnberg and Bollen (2016)	Harmonics	Real measurements

(*continued on next page*)

Table 1 (*continued*)

Reference	Impacts Analysed[a]	Tools Used[b]
Munkhchuluun et al. (2017)	Rotor angle stability	DIgSILENT PowerFactory
Arabali et al. (2012, 2016, 2014)	Flexibility requirement	Not provided
Deetjen et al. (2017, 2012)	Flexibility requirement	–
Ela et al. (2013)	Flexibility requirement	FESTIV, PLEXOS
Mills et al. (2013)	Flexibility requirement	CPLEX, own programme, PROMOD
Palmintier et al. (2016)	Flexibility requirement	FESTIV, GridLAB-D, IGMS, MATPOWER, PLEXOS
Pennock et al. (2016)	Flexibility requirement	PowerWorld
Wu et al. (2015)	Flexibility requirement	CPLEX, own programme
Cullen et al. (2002)	Islanding	–
Verhoeven (2002)	Islanding	Real measurements

[a] The impacts analysed are listed based on the categories provided in this paper (plus islanding, which has been thought to be a limiting factor to PV penetration previously); the references might have analysed other impacts not discussed in this paper, such as those on the electricity market or on carbon emissions.
[b] The tools used are listed in alphabetical order.'-' indicates that no power system tools (as elaborated in Section 6.1) were used, such as in the case of review papers and investigations using non-power-system tools like Excel. 'Not provided' means that usage of power system tools were implied, but no names were given in the papers.
[c] Simulink was not explicitly mentioned in the paper, but is usually used in addition to MATLAB to investigate harmonic contribution from PV inverters.

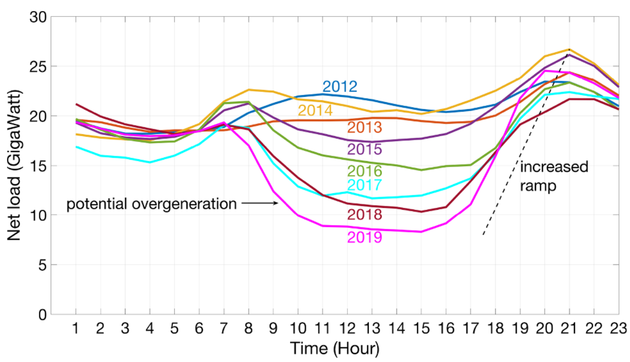

Fig. 5. The California Duck Curve. Data source: IEA (2019b), CAISO (2016).

Lights can flicker because of the sudden rise or drop in voltage, which might occur because of frequent on-off operation of heavy loads, e.g. large electric motors or arc furnaces. However, the voltage fluctuations do not affect just lights. They might also interfere with sensitive electronic equipment relying on constant voltage such as medical equipment (Fluke, 2020) and cause consumers' equipment to malfunction (Remund et al., 2015).

Measurement of flicker can be a proxy to measure the voltage fluctuations and to set their limit. However, the standards and tools for flicker measurement have been designed for incandescent lamps and are not suitable for other lamp types that are common today, i.e. compact fluorescent lamp (CFL) and light-emitting diode (LED) (Remund et al., 2015).

PV systems in distribution feeder have the potential to cause noticeable flicker because of cloud movements (Rönnberg and Bollen, 2016) and because of the MPPT operations (Langella et al., 2016). Flickers might arise even when the PV generation is consumed locally and not exported to the grid (Bank et al., 2013). Nevertheless, the reported severity of the flicker problem varies. Smith et al. (2017) found that although the increase in voltage flicker is measurable, it is unlikely to violate any standard. Meanwhile, according to Ebad and Grady (2016), the 2% voltage fluctuation and flicker limit is violated at 20% PV penetration when the PV is concentrated in a single location. When the PV installations are well distributed, even at 50% PV penetration, they still manage to fulfil the voltage fluctuation constraints. Through

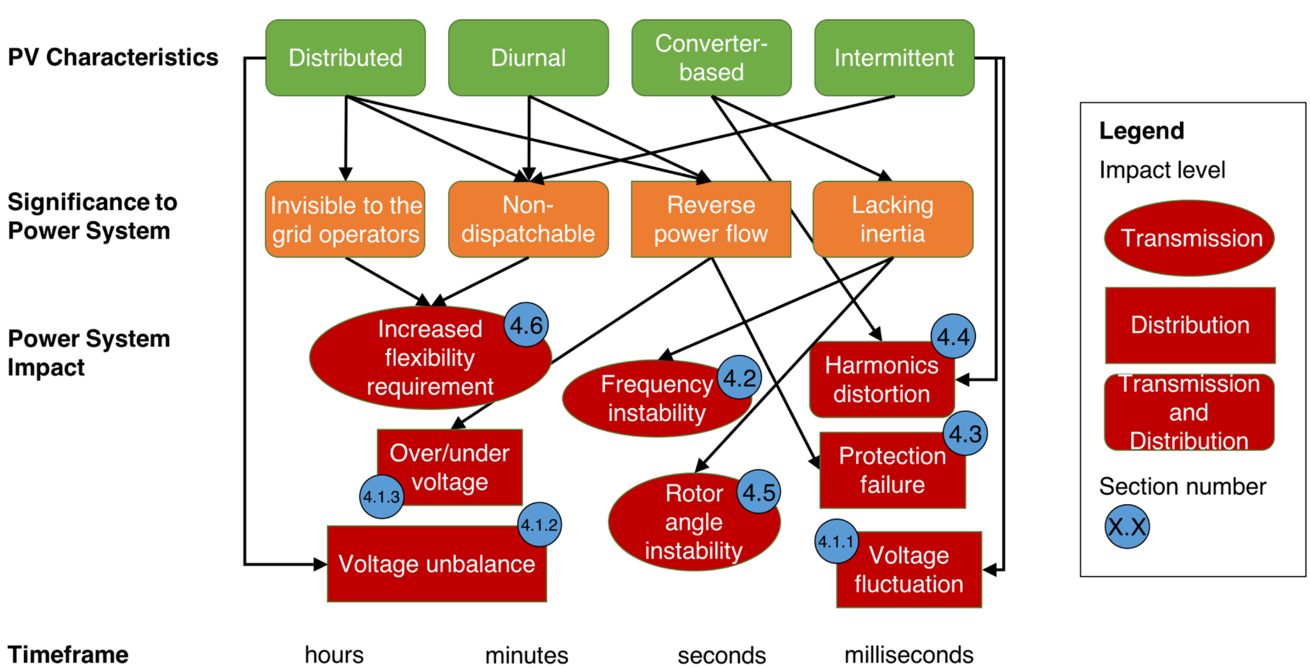

Fig. 6. Overview of power system issues caused by the integration of PV.

real measurement of a 3.6 kWp PV system, Wong et al. (2014) also found that the flicker at the point of common coupling (right after the inverter) exceeded the local limit of 1% during peak PV output.

Flicker is a localised problem for distribution systems as the effect of cloud movement is reduced over a large area at the sub-transmission and transmission systems. For example, a 13.2 MWac PV plant in Nevada experienced only 20% power ramp in 10s, even when there was a 75% change in irradiance within the same period for a particular sensorwithin the plant (Mills et al., 2011). Other studies have also confirmed that variability of a single PV system is smoothed out over many systems (Remund et al., 2015).

4.1.2. Voltage unbalance

Low voltage distribution systems run on three phases, but many small households, depending on the country, usually only have connection on one phase. Voltage unbalance occurs when the loading of the phases differ significantly. Even without PV installations, there may already be unbalance due to unequal impedances and loads across the phases. Unbalance can result in overheating and derating of induction motors, transformers (Lee, 1999), and of small three-phase generators (Passey et al., 2011).

Schwanz et al. (2017) studied the impact of residential PV installations on voltage unbalance in three distribution feeders: 6-customer and 28-customer networks in Sweden, as well as a 40-customer network in Germany. In the 100 kVA 6-customer network, the worst case voltage unbalance with no PV is slightly over 2%. This increases to almost 3% when each customer installs 6 kW PV on the same phase. Considering only the contribution from the 6 PV systems, the expected unbalance is about 1%. Similar results were obtained for the larger networks. It was also found that when PV is connected randomly to one of the phases, the level of voltage unbalance can decrease compared with that before the addition of PV. And when the PV penetration is increased from 75% to 100%, the voltage unbalance is actually reduced, as the larger number of PV has a better balancing potential.

The impact of PV to the system unbalance is sensitive to changes in the network configuration and to the existing unbalance of customers' connection and consumption (Schwanz et al., 2017). From 9-month measurements of a 3.6 kWp PV system in Malaysia, Wong et al. (2014) observed voltage unbalance beyond 2% – the local statutory limit – when the background unbalance is approximately 0.5%. The peak unbalance occurred during peak PV generation.

The voltage unbalance caused by PV affects the effectiveness of voltage regulation in the system significantly (Wang et al., 2019), which may even cause disconnection of PV systems due to unintentional impact from the voltage regulation scheme. Reactive power absorption and injection on one phase not only affects the voltage of that phase, but also of the other two phases. As such, coordination among the phases in voltage regulation is important to prevent and solve voltage problems effectively and efficiently. Injecting reactive power to one of the phases may actually solve an overvoltage problem in another phase.[2]

Lower but unbalanced PV penetration in LV network can cause more problems than higher but balanced PV penetration. As such, if in the planning studies, the utility or researchers consider only the impact of balanced PV penetration on the network, the overvoltage problems may be underestimated (Wang et al., 2019).

4.1.3. Voltage magnitude

Power system voltage is strictly regulated by the power system operators. In Canada, feeders of up to 50 kV should maintain steady state voltage within 0.917 to 1.042 p.u. (Tonkoski et al., 2012) as determined by American National Standards Institute (ANSI) C84.1. Similar standards exist in each country or area, such as EN 50160 for European LV network, which limits the voltage magnitude to be within ± 10% of the reference value (Markiewicz and Klajn, 2004). Many research papers have taken the acceptable range to be 0.9 to 1.06 p.u. (Povlsen, 2002), 0.90 to 1.05 p.u. (Richardson et al., 2012), and 0.95 to 1.05 p.u. (Zhang et al., 2018). When voltage varies dramatically, tap-changing transformers and other voltage regulators may need to be operated more frequently to keep the voltage within the allowable range, reducing their lifetime.

At low penetration, distributed PV can improve voltage profile and reduce losses in the system (Gandhi et al., 2016b). Nevertheless, at high penetration – when PV generation exceeds the local electricity demand and causes reverse power flow – it can also cause overvoltage problems. Overvoltage problems generally occur at peak PV generation when there is little or no load in the LV network (Aziz and Ketjoy, 2017; Povlsen, 2002). Aziz and Ketjoy (2017) found that overvoltage violations are often encountered in medium voltage (MV) network when PV penetration exceeds 20% because of the lack of flexibility of the transmission system to respond to PV power fluctuations due to cloud movement. Undervoltage, to the point of voltage collapse, might also occur when peak PV generation drops suddenly because of cloud movements or otherwise (Maharjan et al., 2020).

Many researchers have found that overvoltage problems would occur before overloading of the power system components. For instance, this was observed by Bernards et al. (2014) for typical LV networks in Netherlands. Tonkoski et al. (2012) analysed an LV network of 216 houses, and observed overvoltage when each house exports 1.87 kW (totalling ~22% of transformer rating). When the feeder impedance was doubled, the maximum export per house dropped to 1.10 kW. Colorado State University (CSU), while studying the impact of integrating 5.2 MWac PV system with minimum daytime load of 3.1 MVA, identified overvoltage as a potential problem in the 13.2 kV distribution system (Bank et al., 2013). Xcel Energy – the utility serving CSU – suggested, in the event of overvoltage, to adjust the voltage regulators setting and then use the inverters to absorb reactive power.

The location of the PV within the distribution system matters a lot (Hoke et al., 2013; Bernards et al., 2014). By analysing maximum PV penetration in 16 feeders representative of the U.S radial distribution feeders, Hoke et al. (2013) found that, in general, evenly distributed PV cause the least voltage problems and that the closer the PV is to the larger grid (as opposed to the end of the feeder), the better in terms of overvoltage problems.

Undervoltage and overvoltage situations might even happen at the same time when there is an existing voltage unbalance. For example, when an overvoltage on one phase is detected by a tap-changing transformer, the transformer changes its setting to reduce the voltage. This might cause the other two phases to experience undervoltage (Mukwekwe et al., 2017).

PV-induced over/undervoltage problems are unlikely to occur in the transmission system since voltage in the transmission system is more affected by the reactive power due to relatively low reactance values. Additionally, there are many more voltage regulators in the transmission system. As such, at the transmission level, the changes in PV active power affects the frequency of the system more than the voltage (explained more in Section 4.2). Nevertheless, while sustained over/undervoltage is not likely, transient over/undervoltage might occur. By simulating transmission-level faults, Eftekharnejad et al. (2013) observed that although system with PV (20% penetration) experienced similar settling time and voltage peak compared to the case with no PV, it experienced larger voltage dip, up to 5% lower. Should the fault cause large-scale disconnections of distributed PV, the system will go through even larger scale voltage oscillations. Zhang et al. (2010) also found that transient overvoltage following a fault increases with PV penetration and the distance of PV from the main system.

[2] This might be counterintuitive because using PV to inject reactive power to the system is associated with increasing its voltage, while reactive power absorption lowers its voltage. Nevertheless, this phenomenon occurs because of the relations among the three phases.

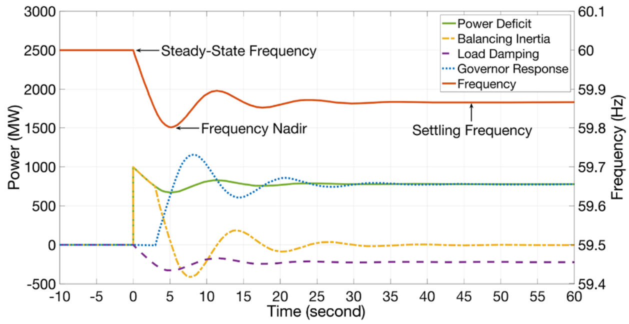

Fig. 7. Illustration of frequency support in North America power system. Governor response is synonymous with primary frequency support and frequency response. AGC is not shown in the figure. Reproduced based on NERC (2012).

4.2. Frequency

Frequency depends on the balance of supply and demand. When demand increases, the generation also has to increase to match it. When the demand and supply are not matched, the mismatch is reflected in a fluctuation of the system frequency through the following equation (Bebic, 2011):

$$J\omega\frac{d\omega}{dt} = P^{\mathrm{gen}} - P^{\mathrm{load}} + P^{\mathrm{import}} - P^{\mathrm{export}} \tag{1}$$

where J is the moment of inertia of all generators and ω is the equivalent angular velocity, which is proportional to frequency. The active power (P) symbols are self explanatory.

Traditionally, the frequency stability in power system is maintained through the system's frequency support, which is divided into three, from fastest to slowest: inertial support, primary frequency support (also known as frequency response), and automatic generation control (AGC). The frequency support (excluding AGC) is illustrated in Fig. 7 (NERC, 2012). In the figure, AGC is assumed to only kick in after the settling frequency, but there is bound to be overlap between the primary frequency support and AGC in real system operations, as the set points for AGC are updated centrally every 1–10 s (Rahman and Bouzguenda, 1994). In system frequency response, generally the inertial support and the primary frequency support are more important (Seneviratne and Ozansoy, 2016).

Before delving deeper into the details of the frequency support and how PV affects the frequency stability, it is important to mention the indicators of frequency stability. They are frequency nadir (the lowest frequency value in case of disturbance, which ideally is above the highest level of under frequency load shedding (UFLS)), rate of change of frequency (ROCOF) from the steady-state to nadir frequency, settling frequency, and the change of frequency from nadir to settling frequency.

The fastest type of frequency support is inertia, the balancing power that comes from the kinetic energy of the rotating generators. As can be inferred from Fig. 7, higher inertia reduces the ROCOF and increases the frequency nadir. A higher frequency nadir means that the UFLS mechanism is less likely to be triggered. The second type, primary frequency support, is used to maintain the system frequency through generator governor control, while AGC is an area-wide frequency droop control to maintain the frequency within allowable range.

Miller et al. (2012) found that the available spinning reserve and proportion of governor responsive generators can predict the frequency response better than the penetration of solar or wind. On top of those two, Seneviratne and Ozansoy (2016) mentioned that the following are also important parameters affecting the system frequency response: total system inertia, percentage MW trip size, distribution of spinning reserve, governor response time, and frequency capability of asynchronous generators. So far, most of the works in the literature have not considered all the system parameters simultaneously in analysing the impact of PV on system frequency response (Seneviratne and Ozansoy, 2016).

As PV penetration increases and the phasing out of fossil fuel generators continues, the inertia in the power system will decrease, and the ROCOF will increase. While traditional synchronous generators may have inertia constant of 2.5 to 6.5 Ws/VA (Seneviratne and Ozansoy, 2016; Tielens and Van Hertem, 2016) and most loads have less than 1 Ws/VA (Tielens and Van Hertem, 2016), PV system does not contribute to the inertial support at all. Moreover, since most PV systems are operating at MPPT, they do not have any reserve for frequency regulation. At the same time, the proportion of governor responsive generators also decreases with the addition of PV, even more so when PV replaces those generators. From the Western Wind and Solar Integration Study (WWSIS) conducted by NREL, for every additional 3 MW wind generation, on average, there are 2 MW and 1 MW reductions in thermal unit commitment and dispatch respectively (Miller et al., 2012). With respect to reserve, if the PV generation leads to dispatching down generation, the system now has more reserves and therefore may have better frequency response. However, if the PV generation leads to decommitting of the traditional generators, then the amount of reserve (and inertia) will decrease.

PV mainly affects the system frequency in two ways. Firstly, it worsens the system frequency response, leading to higher ROCOF and lower frequency nadir. Miller et al. (2014) simulated the tripping of nuclear generators and found that the ROCOF is 18% higher while nadir frequency lower when the wind and PV penetration is doubled to 37%. Miller et al. (2014) also noted that the amount of generation tripped is more important than the location. A simulated PV tripping at 20% PV penetration in New England transmission test system triggered UFLS even though it did not at 5% and 10% penetration (Alquthami et al., 2010). Enslin (2009) estimated that 20% of PV penetration in California will require 2% of peak demand to be available for frequency regulation, while 33% of PV penetration will require 4%; at the moment CAISO's frequency regulation requirement is at 1% of peak demand.

Although most works agree that PV worsens the frequency response, the exact extent of the impact of PV integration on the system frequency response is not clear. Miller et al. (2014) reported that doubling the wind and PV generation (to 37.3% instantaneous penetration) 'leaves the characteristics of the system response to large disturbance unchanged', suggesting that there is no sudden worsening of the frequency response as the amount of reserves and inertia goes lower. Miller et al. (2014) went on to postulate that for large US interconnections, the loss of inertia because of intermittent renewable generation is not significant up to 50% instantaneous penetration, as long as 'fast primary frequency-responsive' generators are available and that other local constraints such as voltage might be violated first before the system-wide frequency stability. Yet, You et al. (2017) reported that the capability of power systems to respond to frequency disturbance decreases non-linearly with increasing PV penetration. The paper found that the frequency response of Eastern Interconnection in the US markedly decreases when the renewable energy (RE) penetration increases from 60% (45% PV and 15% wind) to 80% (65% PV and 15% wind). ROCOF at 80% instantaneous RE penetration is more than twice the base case without PV (12.2 mHz/s vs. 5.0 mHz/s), even though at 60% the ROCOF is 9.7 mHz/s. The settling frequency is also found to be much lower.

Secondly, some of the PV inverters – especially those commissioned long ago – might not have under frequency ride through (UFRT) function and might be disconnected even before UFLS is triggered, exacerbating the unfavourable frequency event. For example, in Italy, PV systems which were commissioned before 31 May 2012 have to be disconnected from the grid when the frequency of the system goes below 49.7 Hz or above 50.3 Hz (Ciapessoni et al., 2013), even though the first UFLS is set at 49.0 Hz. Hence, although the UFLS was not initiated at first, the underfrequency transients may trigger secondary PV trip, worsening the power unbalance in the grid and triggering the UFLS (Yan et al., 2015; Miller et al., 2014). Yan et al. (2015) found that system with high wind and solar generation (30–70% of total load) and low ratio of synchronous generators (20–40%) can survive severe contingencies with proper UFLS scheme. However, should secondary PV tripping occur, the frequency nadir, ROCOF, and UFLS are worsened significantly – up to six times the amount of load shed. Similar observations are made by Miller et al. (2014) and Ogimoto (2014).

Nevertheless, tripping of distributed PV is not as bad as tripping of centralised generators of the same magnitude; all else being equal, tripping of distributed PV leads to better frequency nadir and settling frequency. This is partly because when distributed PV trips, the voltage in the distribution system drops (more power is flowing to the distribution system) and therefore the load power also drops (because of the voltage behaviour of the load) (Miller et al., 2014). Therefore, load voltage sensitivity is more important than load frequency sensitivity for frequency response.

Similar to voltage problems, the concern for frequency stability is also the greatest during light load conditions since there is much less generation at the time, but the size of potential disturbance remains the same (Miller et al., 2014).

4.3. Protection

Power system protection devices, e.g. breakers, fuses, relays, need to be coordinated correctly to ensure that electrical equipment is protected from overcurrent, particularly during a fault. In a three-phase system, a fault may occur among the phases or between one or more of the phases and the ground. As prolonged flow of fault currents can lead to severe damage of electrical components, fast protection scheme to isolate and remove the fault is crucial. Hence, accurate detection and isolation, along with coordination of protection devices, are necessary for protecting the power system components.

Currently, overcurrent relays (OCR) are being used to determine the location of the fault and isolate it using circuit breakers in most of the distribution lines worldwide. However, the presence of distributed generation in the system can alter the amount of fault current seen by the protection device. This might affect the efficacy of these OCRs in determining the location of the fault and in protecting the power system from fault currents, such as causing false tripping, blinding of protections, fuse recloser miscoordination and loss of coordination, among others (Kumar, 2017). However, many works found that the contribution of PV to the fault current is not significant enough to cause most of these problems as the contribution of fault current by the PV inverters are limited to 1 to 1.5 p.u. (Ackermann and Knyazkin, 2002; Bebic, 2011; Buchholz et al., 2006; Peng et al., 2009; Wu et al., 2016). Nevertheless, depending on the inverter protection mechanism, the fault current profile of a distribution system with high PV penetration can be very different from that without PV (Hooshyar et al., 2013), which might warrant a change in the relay and protection setting of the system.

Among the possible adverse impacts of distributed generation on OCR shown in Fig. 8, PV is likely to present a problem in microgrid/islanded mode (Fig. 8 (e)). In islanded mode, the short-circuit current seen by the relays R1 and R2 is much lower than that in grid-connected mode. As such, if the OCR setting remains the same in islanded mode as in grid-connected mode, there may be delayed or failure of protection (Kumar, 2017).

Phuttapatimok et al. (2008) studied PV systems' behaviour during a fault. From the moment of the fault until the PV detects it (PV has to detect an islanding condition and shuts down within 2 s according to IEEE Standard 1547 (IEEE Standards Coordinating Committee 21, 2018)), the PV system continues to supply power, contributing to the fault current. At 100% PV penetration, PV was found to contribute to 7% and 0.5% higher fault current when modelled as voltage source and current source (depending on the control mode of the inverter), respectively, compared to the case with no PV system. PV, when integrated in MV distribution lines, can also introduce more challenges to the already difficult task of high impedance fault detection (Kavi et al., 2017).

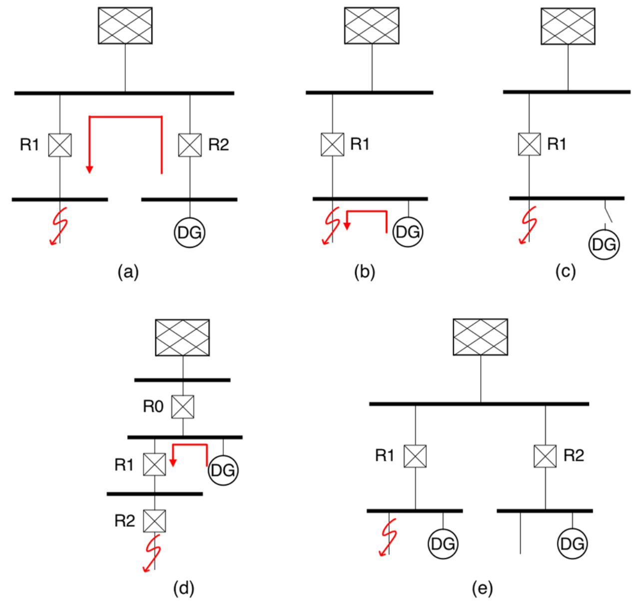

Fig. 8. Overview of how distributed generation (DG) can affect the overcurrent relay: (a) false tripping, (b) blinding of protection, (c) loss of distributed generation, (d) loss of relay coordination, and (e) unsuitable settings for islanded mode. Adapted from Kumar (2017).

The inverter current to the grid depends on the rating of the switches, control algorithm, irradiance, and PV array configurations, among others. PV inverters can also cause protection desensitisation, which has to be evaluated for each situation (Bebic, 2011).

4.4. Harmonics

The term harmonics refers to components of voltage or current which are not at the power system frequency (usually its integer multiples). In an ideal alternating current (AC) power system (all the loads in the system are either resistor, inductor, or capacitors), both the voltage and current vary in a purely sinusoidal manner. But when there are non-linear loads (e.g. fluorescent lighting, and LEDs) or power conversion of some kind (e.g. switches in the converters), they would change the sinusoidal nature of AC current and therefore the AC voltage. In today's power systems, electric power converters are the largest nonlinear loads. They are mostly used in industry in electrochemical power supplies, adjustable speed drives, and uninterruptible power supplies (IEEE, 2014). The harmonic currents cause heating in motors and generators, increase heating and voltage stress in capacitors, and might cause malfunctioning of electronics (Schwanz and Bollen, 2017; Wagner et al., 1993; Meyer et al., 2013).

Most harmonics are categorised into odd harmonics (150 Hz, 250 Hz, 350 Hz, and so on for 50 Hz system) and even harmonics (100 Hz, 200 Hz, 300 Hz, and so on). Traditionally, most of the harmonics in power systems are odd harmonics (Schwanz and Bollen, 2018). There are also other categories of harmonics, namely 'interharmonics' and 'supraharmonics'. Interharmonics are the distortions that are not integer multiples of the power system frequency, whereas supraharmonics are those whose frequency is in the range of 2 kHz and 150 kHz (Schwanz and Bollen, 2018). Both interharmonics and supraharmonics have been small traditionally.

With the rise of more non-linear components in the power system, the harmonic content might be growing. Most high efficiency fluorescent lighting and many LED lights contribute to supraharmonics

(Blanco et al., 2013a; Martinez and Pavas, 2015). And while the pulse-width modulation (PWM) mechanism of most PV inverters limit the low-order harmonics, they emit supraharmonics because of the high switching frequencies (Meyer et al., 2013; Smith et al., 2017).

Harmonics in the system is usually measured through total demand distortion (TDD) and total harmonic distortion (THD). The former is the root mean square (RMS) ratio of harmonic content, excluding inter-harmonics, to the maximum demand current, while the latter is the RMS ratio to fundamental current (IEEE, 2014). Standards such as UL1741 in the US and AS4777.2 in Australia limit the THD from inverter current to be less than 5%, more stringent than the requirement for loads (Passey et al., 2011).

The total voltage and current harmonics in power systems are limited by the IEEE Std 519-2014, which is the revised version of the IEEE Std 519-1992. The new standard requires the harmonic measurement of daily and weekly 95th and 99th percentile, which so far cannot be simulated using commercially available tools (Dartawan and Najafabadi, 2018). Dartawan and Najafabadi (2018) noted that the limits for weekly 95th and 99th in IEEE Std 519-2014 are much more restrictive than those in the 1992 version. Even after fitting passive shunt harmonic filters, there are still individual even harmonic limits that were violated in the weekly analysis for a 180 MW solar farm. Simulation results may also differ from field measurements since the network impedance changes with system reconfiguration and other unpredictable events (Dartawan and Najafabadi, 2018). To perform impact assessment, it is essential to have an accurate estimate of the grid's equivalent harmonic impedance (Santos et al., 2015).

It is found in the literature that the harmonic limits are only violated at relatively higher PV penetration. Some parts of Australia already have PV penetration of 30% since 2013 and so far harmonics have not been a problem (IEA PVPS, 2014). In fact, the authors found that air conditioning contributes to higher harmonics than PV does. Nevertheless, Poosri and Charoenlarpnopparut (2016) found that in an LV distribution system with 60% PV penetration with respect to the transformer rating, the THD is over the 5% limit, even with inverter whose THD current is below 2%. Another study simulated the harmonics in 96-house network in the Netherlands (Benhabib et al., 2007) and observed that at 100% PV penetration, THD exceeds 5% even when there is no non-linear load. The addition of non-linear loads further increase the current and voltage THD. The non-linear loads also interact with harmonics from PV in a way that is not clear yet. The interaction, coupled with the fact that the harmonic contributions from inverters differ significantly for different models and manufacturers (Smith et al., 2017), makes the harmonic analysis difficult.

Thongpron et al. (2004) found that PV power quality is lower at low irradiance. Even though the absolute values of the harmonic currents are larger with higher irradiance, their THD is higher at low irradiance. Odd harmonics were also found to be more prominent at low irradiance.

Single-phase PV inverters also contribute to supraharmonics at 15–20 kHz (Smith et al., 2017; Meyer et al., 2013). For three-phase inverters, although the switching frequency used to be around 2 kHz, more and more commercial inverters have switching frequencies around 20 kHz (Smith et al., 2017). The frequencies may continue to change as the inverter technology keeps on developing. The supraharmonics emission is predicted to further increase in the future because of emissions from appliances, including but not limited to industrial converters, street lamps, electric vehicle (EV) chargers, PV inverters, household devices, and power line communication for smart meters (Rönnberg and Bollen, 2016).

Meyer et al. (2013) measured the supraharmonics in laboratory and 25 sites and found that the lowest harmonics is at the LV side of transformers while the highest is at the inverter point of connection (up to 5 V). Even within the distribution system, the high frequency distortions seem to be a localised phenomenon which do not propagate far.

The magnitudes of the supraharmonics and interharmonics arising from PV installations themselves may be small, but their possible resonance – amplifying the distortions – or interference are still unknown (Rönnberg and Bollen, 2016). The impact of such resonance may not be negligible since distributed PV systems are located close to low-voltage devices. As there are more power electronics in the power system (both in demand and supply side), the impact and the interaction of harmonics emission and background voltage distortions become more complicated (Blanco et al., 2013b). Thus far, it has been reported that supraharmonics might have caused clocks to run too fast, flickering lights, and appliances turning on by themselves (Rönnberg and Bollen, 2016; CENELEC SC 205A, 2015).

In large-scale PV plants, especially those using similar or same type of inverters, the harmonic currents are added arithmetically. The grid-side filters can cause resonance at low-order harmonics; the frequency decreases as the number of inverter increases (Smith et al., 2017). Harmonics from large PV plants are unlikely to interact with electrical appliances as they are usually located far away from load centres. Nevertheless, a resonance might still occur among the harmonics emission from the inverter, capacitance of cables in the grid, and the inductance of transmission transformer (Schwanz and Bollen, 2018). To estimate the resonant frequency accurately, it is crucial to determine the values of resistances, capacitances, and inductances around the resonant frequencies, which may also be frequency dependent (Schwanz and Bollen, 2018).

Cobben et al. (2008) studied the impact of PV on power quality in four urban areas (one in Germany and France each, two in the Netherlands) with high PV penetration. While three sites do not have any problems related to power quality, the holiday park "Bronsbergen" experienced violation in 11th and 15th harmonics because of resonance effect at PV penetration of approximately 80% with respect to transformer capacity. Similar harmonics violation was also observed by Enslin and Heskes (2004) in a suburb of Netherlands because of resonance frequency around the 23rd harmonic from distributed PV installations.

As converter technologies develop and proliferate further, new measurement techniques and standards have to be developed to truly understand the impacts of harmonics on power systems and how they interact with existing load and grid equipment.

4.5. Rotor angle stability

Rotor angle stability refers to the power system ability to maintain synchronism of the generators, i.e. each of their electromagnetic torque and mechanical torque (Kumar et al., 2016). Rotor angle instability may lead to partial or full blackout of the power system (Rakhshani et al., 2019).

Rotor angle stability can be divided into small-signal (steady-state) stability and transient stability, where the former refers to the system's ability to maintain synchronism after small disturbances around the operating point and the latter is more concerned about large disturbances. The time frame for the transient stability is generally 3–5 s, and may extend to 10–20 s for larger systems.

As the number of PV systems grow in a power system, it reduces the share of the synchronous generators and therefore the amount of inertia in the system, making it harder for the remaining generators to maintain synchronism (Kumar et al., 2019). That being said, unlike the impact of PV on the system's frequency stability, the impact of PV on rotor angle stability is still inconclusive (Tielens and Van Hertem, 2016).

At higher penetration, relative rotor angles are likely to experience larger oscillations and make the system less stable (Eftekharnejad et al., 2013; Kumar et al., 2020; Tan, 2004), but whether the impacts of PV are positive or negative depends on system topology, as well as on the fault type and location (Eftekharnejad et al., 2013). The lower the fault impedance of the system, the higher the magnitude of oscillation in generator rotor angle (Tan, 2004).

Munkhchuluun et al. (2017) found that the presence of PV in the system actually improves the small-signal stability, although it also increases the oscillation frequency, which reduces the damping ratio. However, when PV is replacing generators equipped with power system stabilisers (PSS), the effect depends on the perturbation location. When the perturbation location is close to the newly added PV replacing the generators with PSS, small signal stability is improved, but when it is far away, the stability reduces (Munkhchuluun et al., 2017).

Munkhchuluun et al. (2017) also found that the higher the PV penetration, the less stable the system is to transient conditions which occur in critical locations in the network. At 45% PV penetration, the system collapses after a three-phase short-circuit fault due to rotor angle instability, even though the system recovers at lower penetration. In less critical points, the transient stability improves.

4.6. Flexibility requirement

As explained in Section 4.2, the generation and load need to be balanced at all times. While the short-term fluctuations in power balance are handled by the frequency support, longer-term fluctuations are typically handled by regulating reserves or load following. Before the rise of intermittent renewable generation, power system operators need to forecast only load and adjust the generation according to the real load. The increase in variability (the rapid change in PV and wind generation) and uncertainty (the fact that their generation cannot be forecasted perfectly) has necessitated increase in the flexibility requirements. Flexibility can be provided by both demand and supply sides, such as in the forms of demand response, storage, and fast-ramping (also fast-starting) generators. Traditionally, the system flexibility is measured through the operating reserve availability.

Power system operating reserves can be classified based on the conditions when they are deployed, as shown in Fig. 9. Nevertheless, the definitions, classification, and requirements of reserves vary widely for different utilities in different countries (Ela et al., 2011a; Rebours and Kirschen, 2005) and can continuously evolve as the needs of the power systems change. For example, Singapore Energy Market Authority (EMA) has combined the definition of secondary and primary reserve, and increased the reserve requirements, to handle frequency events faster (EMA, 2017). Operating reserves are generally offered in the electricity market as ancillary services. Because of that, the works which analyse flexibility requirements from PV penetration typically

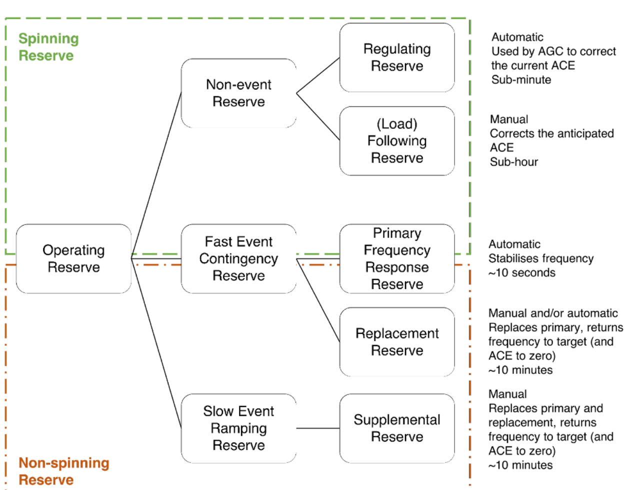

Fig. 9. Classification and brief explanation of different types of reserves, based on information from Ela et al. (2013), Muzhikyan et al. (2019), Rebours and Kirschen (2005), US Department of Energy (2011). Both replacement and supplemental reserves are also called secondary and tertiary reserves depending on the electricity markets. ACE stands for Area Control Error, a measure of power system reliability.

also analyse the impacts of PV on the electricity market (Arabali et al., 2012), which comprises energy and ancillary service market. Nevertheless, the impacts of PV on electricity market are not the focus of this paper as they do not theoretically limit the PV penetration.

Solar is better correlated with load than wind is (Bebic, 2011) and hence does not increase the net load variability as much and is easier to integrate into the system. In the case of Italy, PV has been found to require reserve only 9% of rating (vs. 54% for wind) because maximum PV generation is predictable and varies according to season and time of the day, whereas maximum wind generation can happen anytime (Ogimoto, 2014). In 2012, CAISO found that 80% of the load-following requirements are attributable to loads while the rest to wind and solar variations (Porter et al., 2012). At the time, PV – excluding distributed generation – and wind installations are 1.8% (4.5%) and 9.3% (23.5%) of the peak (minimum) load respectively.

At low PV penetration, the fluctuation of PV due to cloud movements can be absorbed by the load-following mechanism and primary reserve of the traditional generators (see Fig. 9). However, as PV penetration increases, this may no longer be sufficient. Through one month of 1-s-resolution measurements of a 1.6 MW PV plant's AC power production in Arizona, the fluctuations were found to reach 800 kW in 20 s (0.01% of the time) (Cormode et al., 2013). From Smooth PV studies (Ackermann et al., 2013) on European Power System, in one-minute timescale, there can be up to 15.9%, 5.5%, and 2.7% of variations due to cumulous clouds for 10, 1,000 and 100,000 km^2 of PV respectively. Meanwhile, many transmission system operators in Germany and the US require maximum PV ramp rate of 10% of rating within a period of 1 min (Vahan and Booth, 2013). For systems with no fast ramping generation (such that maximum net load change is 1% of load per minute), a study on cloud-induced PV fluctuations by Jewell and Unruh (1990) concluded that 1.3%, 6.3%, 18.1%, and 35.8% of PV penetrations are acceptable for PV system located in a central station, a 10 km^2, a 100 km^2, and a 1,000 km^2 area.

The diurnal nature of PV also poses a problem for the power system: PV generation increases the net load gap from the middle of the day to the peak load in the evening, as exhibited by the 'duck curve' shown in Fig. 5, which was first predicted by NREL in 2008 (Denholm et al., 2008) and then reported by CAISO (and given its name) in 2013 (CAISO, 2016). The duck curve phenomenon is happening faster than predicted, and not only during cool but sunny day in March, but also in winter (John, 2016). The lowest net load in California was predicted to be 15 GW in 2016 from 20 GW in 2011, yet the actual minimum daytime load in March 2016 was slightly lower than 14 GW (John, 2016), and even reached as low as 11.7 GW in May 2016, already lower than the 2020 prediction (CAISO, 2016). The 2019 data (IEA, 2019b) showed that the minimum load kept on falling, as illustrated in Fig. 5. The ramp rates were also more severe than predicted; the months of winter – during periods of low load with high PV generation – being the most severe. The phenomenon is not unique to CAISO either. Simulations conducted by Ma et al. (2012) found that the regulating and following reserves capacity and ramp rate (the increase/decrease in required capacity per unit time) requirements are higher in the winter months for the case of Southern Nevada System.

In power systems with less flexibility, the increase in net load gap might necessitate the usage of contingency reserves. But, should another contingency event occur, there may be a lack of reserves, reducing the power system reliability (Porter et al., 2012). The issue is exacerbated when the power system operators do not have access to the PV systems' specifications and the required weather data or forecasting capability to accurately predict the PV generation. The invisibility of distributed PV was found to increase the CPS2[3] violations by 26% and

[3] Control performance standard (CPS) 2 is a measure of power system reliability formulated by North American Electric Reliability Corporation (NERC) (Jaleeli and VanSlyck, 1999). CPS2 is determined based on the fulfilment of

11% compared with perfect forecast and persistence forecast,[4] respectively, for the case of Sacramento Municipal Utility District (SMUD) in California (Palmintier et al., 2016).

On top of the ramp rate and reserves capacity, many works have proposed other flexibility metrics in an effort to quantify impacts of PV. Deetjen et al. (2017) introduced a few flexibility requirement metrics, namely 1-h and 3-h ramp rate, ramp factor, ramp acceleration, as well as 1-h and 1-day volatility. In their study on Electric Reliability Council of Texas (ERCOT) grid, all the metrics were found to increase with increasing PV penetration beyond 1 GW (with February evening peak load of ~40 GW), but not with increasing wind penetration (Deetjen et al., 2017). Adding 14.5 GW of solar increases the maximum ramp rate experienced by the grid significantly, up to 4.9 GW/15 min (~25% of net load at that time). Similar conclusions were found for European countries by Huber et al. (2014), where in a 100% renewable case (28% wind and 42% PV), the required 1-h ramp can reach as high as 40% of peak load.

To help manage the variability and uncertainty of renewable generation and load in real-time electricity market, flexible ramping product (FRP) was proposed in 2015 (CAISO, 2015). Since 2016, FRP has been incorporated in the unit commitment (UC) and economic dispatch (ED) formulations of Midwest ISO (MISO) and CAISO in the US (Westendorf, 2018).The formulations and implementations of FRP in the electricity market, and how they differ from the operating reserves are explained in CAISO (2015), Cornelius et al. (2018), Wang and Hodge (2017). To implement FRP successfully, the ramping requirements have to be calculated accurately, a nontrivial task and is a topic of many ongoing researches (Cui and Zhang, 2018; Deetjen et al., 2017; Wang and Hodge, 2017).

Although predictable, solar eclipse may also pose problems as PV penetration keeps on increasing. During the solar eclipse in March 2015 in Europe, Germany alone experienced 9 GW drop in power within 75 min out of 37 GWp installed capacity (Fritz, 2016). While this was handled without problem with sufficient reserve planning at the time, as more and more traditional generators will be replaced with increasing PV penetration, this may not be the case in the future.

Therefore, flexibility is important in integrating PV into power system. If there is not enough flexible generation, e.g. for systems dominated by nuclear and coal, then PV might need to be curtailed often (Mills et al., 2013).

As in the case of other impacts, the impacts of PV on flexibility requirements also depend on many parameters. Larger and more interconnected grid, as well as more distributed PV installations reduce the flexibility requirements (Arabali et al., 2012; Huber et al., 2014). Nevertheless, the geographic smoothing effect decreases as PV penetration becomes higher (Huber et al., 2014). Panel orientations and the use of trackers[5] also play a role – south- and southeast-facing arrays in Texas are found to lower the flexibility requirements (Deetjen et al., 2017).

5. Limits of PV penetration

As PV penetration keeps on increasing and the impacts on power systems become more severe, it is natural to ask whether there will be technical constraints which limit the maximum allowed capacity of PV. This section explores the electrical difficulties that high PV penetration would bring into the grid. Case studies indicating the maximum allowed penetration are presented to have an understanding on the current perspective.

Based on the impacts mentioned in Section 4, different studies have taken place to estimate what would be the maximum allowed PV penetration – also known as hosting capacity – that will still assure a proper grid operation. In general, many researchers have agreed that PV penetration below 15% of peak load does not bring significant impact to the grid (Bank et al., 2013; Aziz and Ketjoy, 2017). By analysing the voltage and current limits, Hoke et al. (2013) found that in almost all scenarios, maximum PV penetration was above 30% for typical distribution systems in the US. In more than two third of the cases, the maximum PV penetration was found to be greater than 90%. Likewise, Thomson and Infield (2007) also concluded that for typical distribution grids in the UK with high PV installed capacity (up to 50% penetration level), the voltage increase in the grid is not substantial (normally below 2 V) and thus will not be a significant problem.

Most studies have concluded that voltage issues would be the limiting factor to PV integration, but the maximum penetration in the literature varies a lot depending on the power system parameters and PV location. Aziz and Ketjoy (2017) found that only 2.5% PV penetration can already violate the grid voltage limitations if all the PV is installed at the same point. However, this work showed that PV penetration values as high as 110% can be achieved while fulfilling the voltage constraints if these PV systems are installed in different (evenly distributed) points. In another analysis, Kordkheili et al. (2014) considered three scenarios in determining the maximum PV penetration in a Danish distribution grid: installing the PV panels evenly distributed throughout the feeder, installing them together close to the grid and installing them at the end of the feeder. Maximum PV penetrations of 129.6%, 205% and 81% were achieved, respectively. Similarly, Hoke et al. (2013) also concluded that the maximum PV penetration generally decreases with distance from the feeder.

Tie et al. (2015) considered voltage profile and imbalance, thermal limits at the transformer and feeder and losses in the grid to determine the maximum PV penetration in traditional residential grids in Malaysia. They concluded that the key limiting factors will be the voltage rise (at around 60% to 70% PV penetration) and imbalance (already detected at around 10% PV penetration). Similar conclusion was also obtained by Haque and Wolfs (2016).

In Shayani and de Oliveira (2010), the PV penetration limits were studied considering not only the voltage increase but also the conductor ampacity limit. They considered a simplified radial distribution grid for their simulations and concluded that even a PV system with a power twice the loads can be installed without going beyond the maximum allowed grid voltage.

Cobben et al. (2008) analysed the maximum PV penetration for different locations in Europe according to voltage and harmonics. It was found that harmonics is generally not a concern and that PV can reach values as high as 110% of the transformer rating before violating any voltage constraints. The authors concluded that, as a rule of thumb, PV penetrations of up to 70% in urban areas in Europe should not cause problems for the grid.

In Tonkoski et al. (2010), simulations were performed at the residential level to analyse the variation on grid voltage based on the PV penetration. They concluded that, PV systems of around 2.25 kW per household on typical distribution grids are not expected to elevate their voltage to values beyond the desired range (assuming that the base load of the residencies tends to be above 500 W). However, they also mentioned that particular studies should be conducted for feeders with the following characteristics: PV installed capacity per household beyond 5 kW; long/weak grid lines; high impedance at the distribution transformers; and high PV capacity installed far from the transformer.

Few studies thus far have reported other factors as the limiting factors to PV penetration. In Chidurala et al. (2016), the harmonics

(*footnote continued*)
area control error (ACE) requirements for 10-min periods over a month. A CPS2 score of $\geqslant 90\%$ is acceptable. Meanwhile ACE indicates a power balance in a particular area. ACE is calculated every few seconds; the lower the ACE, the more reliable the system is. NERC has since replaced CPS2 with Balancing Authority ACE Limit (BAAL) (NERC, 2013).

[4] Readers are referred to Yang et al. (2018) for review on solar forecasting.

[5] For evaluation of the different PV trackers' performance, readers are referred to Rodríguez-Gallegos et al. (2020).

level were studied as the PV installation limitation on the IEEE 13-bus distribution system (5 MVA, 4.16 kV). Here, the authors showed that in general, as the number of PV systems increase, the THD also rises, thus limiting the maximum amount of PV capacity. With 5 PV systems of 330 kW each, THD in some of the phases already exceed the 5% limit.

All of the works mentioned above have focused on the distribution systems since the voltage concerns generally occur at the distribution level, as previously mentioned in Section 4.1. At the transmission level, many works are concerned with the increasing requirement for grid flexibility. Should the extra cost for higher flexibility be charged to PV owners/operators, PV will become less economical. The PV integration costs increase with higher penetration because of the more demanding requirements for balancing reserve to address the variability of PV (Wu et al., 2015). In fact, it was found the monetary value of PV generation drops approximately 30% when it generates about 15% of total electricity consumption (Hirth, 2013). However, this is not a technical theoretical limit and will change as the price of PV continues to fall and as some forms of carbon pricing begin to be implemented.

Denholm and Margolis (2007) simulated the limits of PV in ERCOT. Depending on the flexibility of the power system (e.g. the minimum loading constraints), PV curtailment is already significant at 20% penetration by electricity produced as the net load in the middle of the day can become negative. When the minimum loading is 40% of peak load, PV starts being curtailed when the capacity is about 20% of peak load. Without storage and load shifting, even for power system with 100% flexibility (no minimum loading constraints), 50% PV penetration by electricity consumption seems to be the technical limit (equivalent to PV capacity thrice the peak load). Without new measures such as demand response or load shifting, additional PV generation will mostly be curtailed.

To increase the PV penetration limit, many measures have been proposed in the literature, such as curtailing the PV generation (Pukhrem et al., 2016; Tonkoski et al., 2010), installing voltage regulators (Haque and Wolfs, 2016) and energy storage systems (Shivashankar et al., 2016), among many other methods. These measures to solve the problems that come with PV integration are reviewed in the second paper of this review (Kumar et al., 2020a).

6. Modelling for grid stability & reliability assessment with PV

To analyse the impact of PV on the power system and determine its maximum penetration, researchers have employed various tools, models, and assumptions, which are elaborated here to enable readers to determine the tools and data that they need for their specific purposes. These models and tools are important as they determine the accuracy and validity of the results obtained, as well as to analyse the possible solutions reviewed in the second part of this paper (Kumar et al., 2020a). Section 6.1 gives an overview of the software and platforms to conduct the power system studies while Section 6.2 outlines the PV and grid modelling methods that have been frequently utilised in the literature.

6.1. Various power system tools for grid assessment

The choice of platforms and models depends on the aim of the study. As shown in Fig. 6, the impacts of PV integration on power system can be divided based on the location (distribution or transmission level) and the time resolution.

Low resolution studies generally also aim to measure the impact of PV on power system economics, i.e. distribution system operational cost or transmission-level electricity market, on top of the technical impact. These types of studies are usually conducted using optimisation tools, both generic (Section 6.1.1) and power system specific (Section 6.1.2). Higher resolution studies, on the other hand, require much more detailed power system modelling and dynamics, which are not available in optimisation tools. As such, they require the use of power system analysis tools (PSAT)[6] (Section 6.1.3) or real time simulator (RTS) (Section 6.1.4).

The tools which have been used by the references are outlined in Table 1. The number of appearances in the table does not necessarily indicate the general popularity of the tools among power system researchers and practitioners. As the references are all publicly available journal/conference articles and reports, the use of the tools in the industry may not be appropriately reflected. Additionally, many of the references did not mention the tools that they have used. Moreover, while some of the tools are more frequently used to analyse the impacts of PV on power systems, others might be more common in formulating and testing the possible solutions.

This subsection is not meant to be a comprehensive review of the tools used in power system analysis, but rather as a starting point for readers to weigh the different tools and determine their suitability. More comprehensive reviews of the different types of tools have been provided in the following subsections when available. Table 2 summarises the comparison of the different tools in evaluating the power system impacts.

6.1.1. Generic optimisation tool

Some optimisation tools used for power system analysis are generic and are also used widely in other fields. In the field of power system, their application include energy management over a day or more, impact analysis at the transmission or distribution level, and generation planning over many years. As the name suggests, optimisation tools are used to optimise objective functions subject to the appropriate constraints. Some examples of objectives include maximising PV penetration, minimising power loss, operational cost, voltage deviations, etc. At the transmission level, the optimisation is sometimes divided into unit commitment (UC) and economic dispatch (ED). UC formulation is not generally present in the distribution system as traditional generators are rarely located there. The optimisation algorithms are categorised into exact and metaheuristic algorithms (Gandhi et al., 2016a; Song, 2013).

On the one hand, exact optimisation algorithm is an optimisation algorithm that will yield an optimal solution as long as the problem is convex. Since it reliably and quickly arrives at the solution for convex problems, exact optimisation is often preferred. Nevertheless, for non-convex problems, such as AC optimal power flow (OPF) (explained more in Section 6.2.1), it might take exponential time to solve it and might be trapped in local optima (Zhu et al., 2016). On the other hand, while the results metaheuristic algorithms are not always consistent, they can produce good enough solutions in reasonable amount of time. As such, metaheuristic algorithms are frequently used in solving complex combinatorial problems. A review of the applications of exact and metaheuristic algorithms in power dispatch optimisation is provided in Gandhi et al. (2016a), Song (2013).

Using generic optimisation tools, hourly, daily, and seasonal variations in solar irradiance can be represented, but they cannot capture the impact of variations of solar irradiance at shorter timescales since more detailed power system dynamics are required. Uncertainty of irradiance or PV generation can be taken into account through stochastic or robust optimisation. The PV power is usually modelled without taking into account the detailed working of the cell or the inverter.

Two of the most popular tools are MATLAB[7] and GAMS.[8] Among researchers, MATLAB is generally preferred as it is much more versatile

[6] PSAT mentioned throughout this paper strictly refers to the abbreviation for Power System Analysis Tool, a category of power system tools elaborated in Section 6.1.3. It does not refer to Power System Analysis Toolbox, a toolbox in MATLAB, or to the software by DSA tools, both of which have the same acronym.

[7] https://www.mathworks.com/products/matlab.html.

[8] https://www.gams.com/.

Table 2
The abilities of selected power system tools to analyse the PV impacts on power systems. All the different PSATs and RTSs are able to study all the impact categories, therefore they have been been combined into a single entry on the table.

	Voltage			Frequency	Protection	Harmonics	Rotor Angle	Flexibility
	Fluctuation	Unbalance	Magnitude		Coordination		Stability	Requirement
MATLAB[c]	☒	✓	✓	☒	☒	☒	☒	✓
GAMS	☒	✓	✓	☒	☒	☒	☒	✓
MATPOWER	☒	☒	✓	☒	☒	☒	☒	✓
FESTIV	☒	☒	☒	☒	☒	☒	☒	✓
PLEXOS	☒	☒	☒	☒	☒	☒	☒	✓
PSATs	✓	✓	✓	✓	✓	✓	✓	✓
RTSs	✓	✓	✓	✓	✓	✓	✓	✓

[c] The MATLAB's capabilities listed here do not include Simulink. Simulink is treated as a PSAT and is able to analyse all the power system impacts explored in this paper.

and can also be combined with Simulink, MATLAB's graphical programming environment that can act as PSAT. Because of MATLAB's flexibility, it has been employed in many papers working on new algorithms (e.g. to solve power dispatch) or incorporating new power system characteristics (Gandhi et al., 2018, 2020; Huang et al., 2016; Bingane et al., 2018; Cuevas et al., 2019). GAMS focuses on solving optimisation problems using exact optimisation, ranging from linear programming (LP) to mixed integer nonlinear programming (MINLP) solvers. Each solver requires a different licence, so it may be prohibitive for many researchers. CPLEX[9] is one of the most popular solvers in GAMS to solve UCED problems. MATLAB and GAMS have also been used in a specialised optimisation tool called FESTIV, as explained in Section 6.1.2. Other generic optimisation tools include AIMMS[10] and Pyomo.[11]

6.1.2. Power system optimisation tool (PSOT)

PSOTs are more specific than generic optimisation tools in the sense that they provide ready-made power-system-related functions and calculations for the users. The main PSOT types are production cost model for operational optimisation, and capacity expansion planning model for investment/planning optimisation (Anderson et al., 2016; Helistö et al., 2019).

On the one hand, the capacity expansion model is about planning power system of the future, i.e. optimising the upgrades and retirements of power plants, transmission lines, and other power system components. The optimisation normally simulates a large transmission system 20–30 years into the future in meeting its various energy targets and power system constraints. On the other hand, production cost model PSOT is used to solve UCED in electricity (energy and ancillary services) market. The output of the capacity expansion model can also serve as an input for the production cost model to verify its feasibility. This type of PSOT is usually employed by ISO and regional transmission organisation (RTO) for market scheduling (Anderson et al., 2016). Helistö et al. (2019) gave an overview how the different operational and investment optimisation PSOTs were used in the literature and highlighted the different challenges which arise because of the modelling parameters.

Only examples from the production cost model are elaborated in this section as the review paper is not concerned with power system planning. Among the different PSOTs, Flexible Scheduling Tool for Integrating Variable Generation (FESTIV),[12] MATPOWER,[13] and PLEXOS[14] have been used more frequently than the rest in renewable integration studies. This is because of their sub-hourly time step which allow the three tools to analyse the operational implications of the variability and uncertainty of PV and wind generation with greater accuracy. In addition, unlike other production cost modelling tools, FESTIV also incorporated AGC (every 4–6 s) into its multi-timescale UCED formulations. FESTIV model is developed by NREL in MATLAB, and uses CPLEX solver in GAMS to solve the UCED problems (Ela et al., 2011b). All three use exact optimisation to solve the OPF problems.

As implied in Table 2, both PLEXOS and FESTIV are more suitable for studying the flexibility requirements of PV and impacts of PV on the electricity market, but not other impacts. They lack the high time resolution which PSATs are capable of, and is required to analyse voltage fluctuations, harmonics, and protection miscoordination. Both PLEXOS and FESTIV employ DC OPF model (see Section 6.2.1), rendering them unable to analyse voltage issues.

Meanwhile, MATPOWER, an open-source MATLAB package for power system simulation (Zimmerman et al., 2011), enables the users to choose between DC and AC OPF (their differences are elaborated in Section 6.2.1). Their equations are formulated as linear programming (LP) and quadratic programming (QP) respectively. Nevertheless, the AC OPF is run in single phase, making voltage unbalance analysis unfeasible.

Anderson et al. (2016) have compared 16 PSOTs for the North American electricity markets and noted which studies and utilities have employed which tools. On top of the commercial and open source software, individuals and institutions have also created their own tools to suit their needs. For example, Etingov et al. (2012) developed a tool for the US Department of Energy to evaluate the uncertainty ranges of the flexibility requirements using Microsoft Visual Studio, Oracle, and MATLAB. On top of FESTIV, NREL also developed Integrated Grid Modelling System (IGMS) to measure the impact of distributed PV on the transmission system (Palmintier et al., 2016) by co-simulating FESTIV (for UC, AGC, and electricity market), MATPOWER (bulk AC power flow, including calculation of voltage and reactive power dispatch), and GridLAB-D (3-phase unbalanced AC power flow as well as modelling power system devices and appliances). IGMS is capable of simulating transmission and distribution system at the same time (up to 1.4 million nodes for the case of SMUD).

6.1.3. Power system analysis tool (PSAT)

Unlike the aforementioned optimisation tools, PSATs can analyse power system dynamics in much greater details and much higher time resolution (in the order of ms). As such, they require more in-depth

[9] http://ibmdecisionoptimization.github.io/docplex-doc/mp.html.
[10] https://www.aimms.com/.
[11] http://www.pyomo.org/.
[12] https://www.nrel.gov/grid/festiv-model.html.
[13] https://matpower.org/.
[14] https://energyexemplar.com/solutions/plexos/.

modelling of the components, as elaborated in more detail in Section 6.2. For instance, they need accurate model of the inverter and its control; usually in-built models are already provided in the software. Many PSATs can also be used for UCED and capacity expansion, but they are generally not as popular as optimisation tools for these purposes.

Ringkjøb et al. (2018) reviewed 75 modelling tools for energy and electricity systems, of which 13 are PSAT. The authors indicated their availability, whether they are commercial, open source, or free for demo. In Bam and Jewell (2005), 23 PSATs were reviewed and the authors elaborated how to evaluate and choose a suitable PSAT. Some of the most commonly used PSATs in the literature include DIgSILENT PowerFactory,[15] MATLAB Simulink,[16] OpenDSS,[17] PowerWorld,[18] PSCAD,[19] and PSS/E.[20]

In general, a PSAT is used to simulate power system components, rather than optimise specific objectives. If the users would like to carry out optimisation or other tasks which cannot be accommodated within the PSAT, sometimes it has to be used in combination with an optimisation tool. For example, DIgSILENT PowerFactory was used in combination with MATLAB by Heslop et al. (2014) to determine PV penetration limit for low voltage feeder in Australia. In Ebad and Grady (2016) and Ding and Mather (2017), MATLAB and OpenDSS were utilised to estimate maximum PV penetration and its impact on distribution feeders.

It must be noted that the simulation techniques used in different PSAT might be different and therefore they might produce different results (Alquthami et al., 2010). With regard to PV generation, PSATs usually only use historical or user-generated irradiance/generation data and it is difficult to take into account the uncertainty.

6.1.4. *Real time simulator (RTS)*

With higher computational capability provided by the dedicated processors, RTS is able to produce more accurate results faster (in real time) compared with PSAT. RTS tends to have a hardware-in-loop (HIL) function as well, such that it can be used for testing and prototyping control mechanism or hardware, such as a PV inverter. Moreover, RTS is commonly used for transient simulations as it can simulate time steps in the order of microseconds (μs). Common commercial RTSs are RTDS,[21] eMEGAsim[22] and HYPERSIM[23] by OPAL-RT, and Typhoon HIL.[24]

The use of higher time resolution simulator is important as low time resolution leads to an overestimation of maximum RE penetration in the grid (Ringkjøb et al., 2018); with lower time resolution (longer time-step) some of the impacts mentioned in Section 4 cannot be observed, as seen in Fig. 6 and Table 2. Consequently, this leads to an underestimation of the infrastructure required to accommodate the RE. Therefore, RTS, which can have time steps in the order of μs is an important tool in analysing the impact of PV on power system. Nonetheless, because of the higher cost (the use of RTS often requires dedicated and specialised hardware), RTSs are not as commonly used as PSATs or optimisation tools.

The RTS hardware, software, and communication interface have been reviewed by Omar Faruque et al. (2015), while its applications in power and energy sector were reviewed by Guillaud et al. (2015).

[15] https://www.digsilent.de/en/powerfactory.html.
[16] https://www.mathworks.com/products/simulink.html.
[17] https://sourceforge.net/projects/electricdss/.
[18] https://www.powerworld.com/.
[19] https://hvdc.ca/pscad/.
[20] https://pss-store.siemens.com/.
[21] https://www.rtds.com/.
[22] https://www.opal-rt.com/system-emegasim/.
[23] https://www.opal-rt.com/systems-hypersim/.
[24] https://www.typhoon-hil.com/.

6.2. *Models for grid assessment*

Measuring the impact of PV in the grid require at least a few models, i.e. power flow model, PV generation model, grid model, and model of the distribution and penetration of PV in the grid. In general, the higher the resolution (the shorter the time step) of the simulation, the more detailed and accurate the models have to be. This section is not meant to be a comprehensive account on all the models. Similar to Section 6.1, it is a brief overview of the various PV and grid models that have been employed by the reviewed papers.

This section (and the paper) is not concerned with the exact modelling of solar cells or modules (interested readers are referred to Rodríguez-Gallegos et al. (2018d) for more details). Neither is this paper concerned about shadowing, tilt and azimuth angle of the PV panels (readers are referred to Rodríguez-Gallegos et al. (2018a) for the influence of tilt and azimuth angle on PV power production).

6.2.1. *Power flow model*

Optimal power flow (OPF) model is an optimisation problem to determine the generators' operating points which fulfil the power balance constraints and transmission line constraints, among others. OPF formulation is mainly categorised as AC OPF and DC OPF. AC OPF is nonconvex problem with binary and continuous variables. It includes the calculations of active power, reactive power, complex voltage, and power losses across the system simulated. Due to its complexity, it takes relatively long time to solve an AC OPF problem. Different AC OPF algorithms have varying efficacy at different levels, e.g. Newton-Raphson algorithm is more suitable for meshed transmission system, while Backward Forward Sweep suits radial distribution system more (Teng, 2003). There are numerous ongoing works in simplifying AC OPF formulations to reduce their computational time and improve their scalability (Huang et al., 2016; Bingane et al., 2018). Most works have employed the single-phase equivalent of the AC OPF model, assuming that all the phases are balanced. The three-phase power flow is almost exclusively used in papers which are specifically analysing the voltage unbalance in the system.

On the other end of the complexity scale, there is DC OPF. DC OPF formulation is linear and does not include reactive power, voltage, and line losses (although it still includes the line limit constraints). As such, it can be solved much more quickly and is often used for electricity market clearing by ISOs.

One of the important choices in power system analysis using generic optimisation tools is the choice of OPF model as it affects the possible impacts analysed and the feasible level of details. The OPF in PSOTs, PSATs, and RTSs are generally predetermined. In general PSOTs use DC OPF modelling (except for MATPOWER) while PSATs and RTSs use AC OPF.

6.2.2. *PV generation model*

Depending on the level of details desired and platforms used for the modelling, PV generation can be modelled using simple equations or a complex model involving equivalent model of solar cells, as well as inverter and its control scheme, among others.

For optimisation tools, it is generally not necessary to include the inverter control model or its dynamic behaviour. Most works in the literature used formulas that only depend on the PV rating, irradiance, and ambient temperature (Skoplaki and Palyvos, 2009). An example of such formula (Rodríguez-Gallegos et al., 2018c):

$$P_t^{\mathrm{PV}} = \frac{P^{\mathrm{PV,rating}} G_t}{1000}\left(1 + \gamma\left(T_t^{\mathrm{cell}} - 25\right)\right)\eta^{\mathrm{PV,inv}} \tag{2}$$

where P_t^{PV} and $P^{\mathrm{PV,rating}}$ are the instantaneous power and rated power of the PV system. G_t is the irradiance received by the PV system at period t. γ is the power temperature coefficient of the solar cell. $\eta^{\mathrm{PV,inv}}$ is the inverter efficiency and T_t^{cell} is the temperature of the solar cell, calculated using the following formula:

$$T_t^{\text{cell}} = T_t^{\text{amb}} + \frac{G_t}{800}(T^{\text{NOCT}} - 20) \tag{3}$$

where T_t^{amb} is the ambient temperature and T^{NOCT} is the nominal operating cell temperature. G_t, P_t^{PV}, and T_t^{amb} can either be real or forecasted value, depending on the purpose of the simulation/optimisation.

It should be noted that the value of G_t in Eq. (2) depends on the tilt angle of the PV modules in the system, among other factors. As such, there may be a need to transpose the irradiance data to a different tilt angle. Readers are referred to Yang (2016) for a review of different transposition models, and to Yang and Liu (2020) for the different sources of solar radiation data across the world and how to obtain them.

Although simulations in distribution system can use the same weather data (G_t and T_t^{amb}) for the different PV installations in the system, that is an oversimplification in the transmission system. When the simulation is conducted over multiple years (usually more for planning purposes rather than power system impact analysis), the module degradation needs to be included (Rodríguez-Gallegos et al., 2018b).

When there are many PV installations in the power system, it is often not possible to model each PV installation in the system individually; they have to be aggregated. For simulations in PSAT, the aggregate PV systems have to also be connected to the grid through accurate aggregate equivalent impedances (Bebic, 2011). To analyse the impact of PV at higher resolution (shorter periods), then the dynamics of the PV array, MPPT algorithm, and of the inverter need to be modelled accurately. Lappalainen and Valkealahti (2017) found that the average rate of change of PV output power (of 32 kWp PV) due to moving clouds is approximately 3%/s while the maximum reaches 75%/s. Through one-second real PV generation measurements over a year, Marcos et al. (2011) found that a 48 kWp system experienced a maximum of almost 60%/s while a 9.5 MWp system has less than 5%/s. However there is virtually no difference in the rate of change of power over 5 min among the different size PV plants. Similarly, from a case study in Hawaii, Remund et al. (2015) found that fluctuations above 8 min are no longer smoothed out by the distribution of PV systems.

Thus, to analyse the impact of PV in high resolution without real PV power data or irradiance data from dense network of sensors, the cloud movements have to be modelled. The cloud movement models have to also take into account the location of the systems, as different locations have different climates and cloud movement patterns. For example, Southeast Asia, and the tropics in general, are much cloudier than the desert regions and the solar irradiance is much more fluctuative (Wong et al., 2014).

On-grid PV inverters usually have two-stage topology: the PV module interface (boost converter) and the grid interface (grid converter). Other topologies are also available and many works have reviewed the development of on-grid PV inverters (Yang and Blaabjerg, 2015; Arulkumar et al., 2016; Ankit et al., 2018). Standards to model PV inverters have been recommended since nearly a decade ago (Bebic, 2011), but to the best of the authors' knowledge, there is still no such standard today.

PV is typically assumed to have an MPPT control. Perturb and observe (P&O) and incremental conductance are the most commonly applied MPPT algorithms (Xiao et al., 2013; Tan, 2004) although there have also been many works that proposed more advanced algorithms for MPPT (Esram and Chapman, 2007). Tan (2004) showed through the experimentally-validated model that although power also drops instantaneously when irradiance suddenly drops, it only rises steadily over a few seconds in case of sudden irradiance spikes. This is because of the behaviour of the MPPT controller. Sudden changes in grid voltage causes sudden drop in PV power.

Remund et al. (2015) surveyed existing methods to model PV variability and concluded that Dispersion Factor method (DFM) (Hoff and Perez, 2010) and Wavelet Variability Model (WVM) (Lave et al., 2013) to be suitable in analysing the variability of PV generation and its impact on power system. In particular, WVM only needs irradiance data from a single sensor if the correlation scaling factor is known, and only up to 6 sensors otherwise. DFM was verified with real PV generation data in Switzerland, the UK, the US, and Japan while WVM was verified with sensors in Hawaii (Remund et al., 2015). All other things being equal, the higher the wind speed, the higher the correlation across distances (Remund et al., 2015). In other words, in regions with high wind speeds, the PV installations need to be further away from each other to have the same correlations as in regions with low wind speed.

Ebad and Grady (2016) developed moving cloud shadow model at 1 s simulation step, which allows a much more detailed analysis even when real PV data are not available at high resolution. Nonetheless, the model has not been rigorously tested against real data and is not able to model the small fluctuations in PV power.

6.2.3. Grid model

Depending on the aim of the researchers, the analysis may incorporate a distribution grid, a transmission grid, or both. Utility-scale PV (in the order of MW) are usually connected at the transmission level, whereas smaller systems that are directly connected to customers' loads are connected at the distribution level.

A distribution system is usually radial with voltage between 400 V (LV) to tens of kV (MV). There is commonly no traditional generator; there is a slack bus representing the larger grid (transmission system) instead. This slack bus is often assumed to be able to inject or absorb any power from the distribution system, i.e. that it is perfectly flexible.

A transmission system, on the other hand, typically has many types of generators, such as coal, nuclear, combined cycle, and hydro power plants.

There are many publicly available grid models from IEEE, EPRI, CIGRE, and other institutions, for both distribution systems (EPRI, 2013; IEEE PES PSACE Committee, 2017; LIINES, 2019) and transmission systems (IEEE PES-Power System Stability Subcommittee-Test Systems for Voltage Stability and Security Assessment Task Force, 2015; LIINES, 2019; Grigg and Wong, 1999). Many works modify the generators' composition from the test systems to better represent the system that they want to analyse.

As important as the electricity network model are the load and generator data. The test systems typically only have one value for the load in different buses, therefore, in the absence of real measurements, the load variations throughout a day or other length of interest need to be constructed. Real high-resolution load data are rare. Combination of high-resolution load and PV generation data from the same location are rarer still. As such, many researchers have assumed constant load for short periods of study (within one hour) or use hourly load data for longer studies. Some works have also transplanted real one-minute variability data from one study period to hourly load data from another period with RE generation (Mills et al., 2013). The load model, e.g. whether the load changes with voltage or frequency, is also important. In fact, the impact of changing the load model is more significant than modifying the PV penetration, especially for transient conditions (Miller et al., 2014). Researchers and utilities alike typically assume the load profiles to be the same for each node in the grid (Palmintier et al., 2016).

Generators' data such as the ramping limits, fuel consumption, startup and shutdown costs are usually provided by utilities and available in the test system databases. Generic generator models are available in PSAT. The grid requirements also need to be specified, such as the voltage limits, and minimum spinning reserve. This information is available from the network utility.

If the impact study is done for future scenarios, then the data should incorporate load growth, addition and retirement of generators, transmission lines, etc. It is standard practice to scale the historical load data to future predictions published by utilities, government bodies, or research institutes.

6.2.4. PV distribution and penetration model

It is critical to have realistic PV penetration and distribution to analyse the impact of increasing amount of PV in a particular system or area. To do so, many works follow the official forecast or roadmap for renewable penetration, taking into account the shares of distributed and utility-scale PV.

Tan et al. (2017) presented a systematic approach to model the distribution of PV – both the utility scale and the residential rooftop – in the U.S. Western Interconnection using publicly available data. The irradiance data has been obtained from National Solar Radiation Database (NSRDB).[25] The load, generation, as well as PV location and penetration have been determined based on statistics, goals, and predictions stated on Western Electricity Coordinating Council (WECC) and Solar Energy Industries Association (SEIA) documents. Based on the data, the scenarios, evaluation metrics, power flow models, and dynamic models were prepared to make sure that the model and therefore the subsequent study were realistic. Both the rooftop and utility-scale PV were distributed to each area proportional to their technical potential – estimated using the NSRDB data.

In Ding and Mather (2017), the PV locations were selected randomly from candidate customers in each of the 17 distribution feeders analysed. Then, the size of each PV system was determined based on the California Solar Initiative's installed PV systems dataset. This procedure was conducted for every customer penetration level analysed – from 2% to 100% in steps of 2%.

The distribution of PV can also be modelled using optimisation. In You et al. (2017), PV distribution in Eastern Interconnection of the US was optimised using PLEXOS to minimise the system total cost while increasing the PV penetration.

Finally, as mentioned in various parts of Section 4, other parameters, such as the generators units that are committed, also affect the impacts of PV. One way to find out which units would be committed with higher PV penetration is by running UCED optimisation to minimise the energy cost subject to constraints. The resulting commitment and dispatch can then be used for stability studies and other analyses.

7. Conclusion

Solar energy, especially in the forms of photovoltaic (PV) systems, has become a prominent energy source. In many countries, grid-connected PV systems have proliferated and reached unprecedented penetration level. The high PV penetration can have serious implications on the stability and reliability of power systems. In this paper – the first part of a two-part review – the characteristics of PV systems that bring challenges for power system integration have been identified. Subsequently, their impacts on the power systems' voltage, frequency, protection, harmonics, rotor angle stability, and flexibility requirement have been examined in detail. The observed PV penetration limits in the literature have also been reviewed. In addition, to allow the readers to further the research in this field, this paper also gives an overview of the tools and models commonly used in PV grid impact analysis.

Although the transition to fossil-fuel-free world and the increased adoption of PV will not be stopped by the impacts mentioned in the paper, understanding the problems and implementing the solutions will certainly make the transition easier and less costly. Most of the changes are not abrupt and measures to solve the challenges of PV integration, as reviewed in the second paper of this review, can be implemented progressively.

As mentioned in almost all the papers reviewed, the impacts of PV on the power system and the effectiveness of the solutions highly depend on the PV penetration level and its location, as well as on the power system characteristics. To date, the different impacts have to be analysed using different tools with different inputs at different timescales. Thus far, there has been no unifying work that analyses the importance of the different impacts for a particular system and which systems' characteristics will exacerbate which impacts. Insights on what issues are likely to emerge in what kind of systems are much needed to accurately determine the maximum PV penetration limit in a particular system. More research in this direction is necessary. Moreover, researchers and practitioners are encouraged to identify the tools, models, and data that they have used, and, when possible, to share them. This will allow comparisons of the tools' effectiveness and of the impacts of PV in different networks.

Even though this paper focuses on the power system challenges related to increasing PV penetration, the energy practitioners and policy makers have to look beyond the power system impacts, such as impacts on the environment, natural resources, and society, among others.

Declaration of Competing Interest

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

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