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A review of smart inverter capabilities for managing high levels of distributed energy resource integration in South Africa's power grid

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Abstract

Distributed energy resources (DERs), including solar panels, wind turbines, and battery storage, are becoming more prevalent in power grids. This increased penetration necessitates a closer look at how they impact the grid's operation. Power grid operators face challenges in ensuring the secure operation of the network in the presence of DERs. This includes managing voltage fluctuations, integrating diverse energy sources, and preventing grid overloads. This paper reviews the impacts of DERs on power grid operation and discusses strategies for enhancing the integration of DERs in South Africa's grid. The strategies involve technology solutions, grid management techniques, and policy changes that facilitate the seamless integration of renewable energy sources. Smart inverters are highlighted as an essential component of the solution. Their advanced capabilities play a central role in managing voltage, frequency, and other aspects of power quality, which is critical when integrating DERs. The paper offers a comprehensive overview of the challenges of integrating inverter-based DERs into the power grid, highlighting lacks and deficiencies in existing South Africa power grid codes and standards and discussing solutions – thus paving a way for future investigations and developments. Eight international regulations are examined and compared, exposing the lack of a worldwide harmonisation and a consistent communication protocol. The paper calls for the evolution of power grid codes to adapt to the changing energy landscape and to harness the benefits of DERs and advanced smart inverter capabilities. This involves updating regulations and standards to ensure grid stability and reliability while accommodating renewable energy sources. The review can aid power utilities and regulators in making informed decisions in enhancing grid-connected DERs and ensuring safe and secure grid operation.

Keywords: *cyberattacks; smart grid; voltage control; reactive power*

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1 Introduction

The modern power grid requires advanced and flexible technologies to effectively manage the integration of distributed energy resources (DERs) (Lopes et al., 2007; Horowitz et al., 2020). These technologies must be capable of adapting to the evolving energy landscape. If not appropriately addressed, the limitations of conventional voltage control systems could hinder the widespread deployment of DERs in the future smart grid (Lopes, et al., 2007). The current voltage control systems were designed for centralised power generation and may not be equipped to handle the complex demands, such as reverse power flow, introduced by the widespread adoption of DERs within a smart grid context (Li et al., 2020; Liu et al., 2012; Muttaqi & Negnevitsky, 2015). To overcome these challenges, smart control methos need to be developed and implemented. These methods should be capable of efficiently managing voltage in a grid system that incorporates a diverse range of energy sources and technologies.

Traditional voltage regulation methods are designed to operate based on predefined network parameters (Li et al., 2020; Liu et al., 2012; Muttaqi & Negnevitsky, 2015). These methods may not be suited to the complexities introduced by the integration of DERs. To maintain power and voltage quality standards without significantly disturbing DER operation, tailored solutions are required. Various methods and devices have been proposed in the literature to improve voltage quality in the presence of DERs. These include step voltage regulators, static reactive power compensators, static synchronous compensators, transformer tap-changers, battery energy system and smart inverter technology (Gandoman et al., 2018; Li et al., 2020; Liu et al., 2012; Muttaqi & Negnevitsky, 2015). However, implementing these technologies requires new settings and refined coordinated control systems. International regulations and standards that govern the connection of DERs to distribution systems, including IEEE 1547:2003, IEEE 2030.5, IEC 61850, and IEC 61727, have been developed to include these new technologies (Albunashee & McCann, 2019; Martins et al., 2018; IEEE, 2018). Australia, Germany, and the USA are recognised as leaders in the integration of DERs into their power grids (REN21, 2020). They have made progress in implementing smart inverter technology to address technical challenges associated with DER integration. For example, in the USA, power utilities in regions like California and Hawaii are reshaping regulations to incorporate smart inverter technology at low voltage (LV) levels to support DER integration (NREL, 2014; CPUC, 2018; HEC, 2015). The Hawaiian Electric Rule 14H and California Rule 21 are examples of smart inverter standards that have been developed to define communication protocols and advanced functionalities for grid interconnected DERs (Berdner, 2015; CPUC, 2018; HEC, 2015; NREL, 2014).

South Africa has its own set of standards, such as NRS 097-2 and the South African Grid Codes for Renewable Power Plants (SAGCRPP), which specify grid-interconnection requirements for DERs (Berdner, 2015; NERSA, 2017; NERSA, 2019). The existing regulations are based on static limits, and may not support the country's ambition to achieve a significant share of small-scale DER systems at the LV level, as outlined in the Integrated Resource Plan (IRP) 2030 (Calitz & Wright, 2021; Owusu-Mante, 2020). This paper provides a review of existing local and international regulations from the perspective of coordination requirements between the traditional existing voltage regulators and smart inverter control and to determine opportunities for South Africa's advancement.

2 South Africa's energy context

South Africa benefits from an outstanding solar resource, with most areas receiving over 2 500 hours of sunshine annually. Solar radiation levels range between 4.5 and 6.5 kWh/m^2 per day, making it one of the world's highest solar potential regions. The South African government has set a goal to achieve net-zero emissions by 2050 (Calitz & Wright, 2021; Owusu-Mante, 2020). To reach this target, South Africa is actively working to transition to a low-carbon economy. This shift is essential for reducing the environmental impact of energy production and consumption. The government is making strategic investments in solar and wind energy projects. The IRP 2010, adopted in 2011, provides a comprehensive roadmap for South Africa's energy generation mix. It sets ambitious targets for renewable energy generation, aiming to achieve 17 800 MW of renewable energy capacity by 2030 (Owusu-Mante, 2020). This roadmap outlines the country's vision for a cleaner and more sustainable energy future. This transition to renewable energy not only helps reduce carbon emissions but also drives economic growth and job creation. The renewable energy sector can stimulate the economy and provide employment opportunities. It also enhances energy security by reducing reliance on fossil fuel imports and volatile energy markets.

In 2021, South Africa installed solar energy capacity of 2.91 GW, representing over 50% of its total renewable energy capacity (Calitz & Wright, 2021). As of 2024, South Africa is utilising only a small fraction of its vast solar energy potential, harnessing around 2% to 5% of its total solar resource (Mackenzie, 2024). Despite having some of the highest solar irradiance levels globally, the installed solar capacity remains significantly underdeveloped compared to its potential. Currently there is more than 94 MW of installed rooftop PV in South Africa, with rooftop solar capacity has increased by 349% in a little over a year (Ferris, 2023). Figure 1 shows the cumulative rooftop solar connected to the grid (Ferris, 2023).

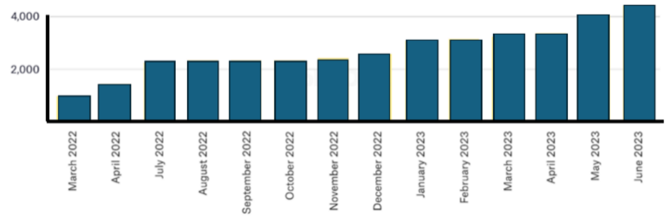

Figure 1: Cumulative rooftop solar connected to the South African grid (MW)

This underscores the country's commitment to expanding solar energy infrastructure. Both international and local financial institutions have invested in major solar projects. Prominent examples include the Redstone concentrated solar energy project, Amazon's solar plant, and Tronox Holdings' power purchase agreement. These projects showcase the diversity and scale of solar energy applications in the country and underscores the commitment to diversifying its energy mix and reducing its reliance on fossil fuels. Solar energy capacity is expected to continue expanding in the coming years and the solar energy segment is well positioned to dominate the renewable energy market and play a pivotal role in helping South Africa achieve its renewable energy targets. The abundant solar resources and the growing capacity make it a reliable and sustainable source of clean energy. This commitment to solar energy aligns with global sustainability objectives, contributing to the broader efforts to reduce carbon emissions and combat climate change.

This paper will explore the following research questions:

- What is the impact of DERs on power grid operations, and what strategies can be implemented to enhance their effective integration into the grid?
- What are the necessary features and capabilities of smart inverters for effectively coordinating voltage regulators and smart inverter-based DERs?
- How do international standards for integrating inverter-based DERs into power grids compare, and how can these standards be leveraged to improve existing South African grid regulations (grid code)?

3 Methodology

This literature review utilised various sources, including industry and government publications, academic technical papers, and public domain sources to conduct a comprehensive investigation.

The study analysed South African publications on the history and future power grid, selecting relevant ones based on subject matter, as illustrated in Figure 2. A database was created to summarize and report on the current situation of South Africa power system network and integration of DERs.

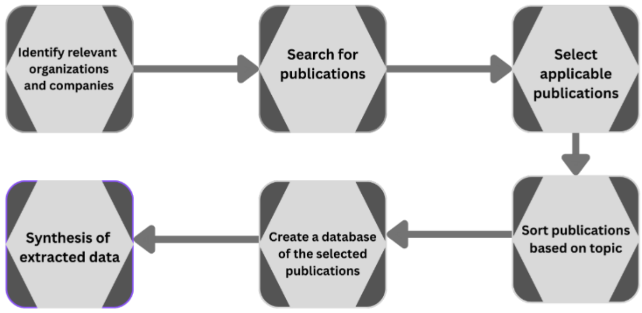

Figure 2: Selected procedure for South African publications

The selection of academic technical papers was mad according to guidelines from Kitchenham and Charters (2007), as illustrated in Figure 3.

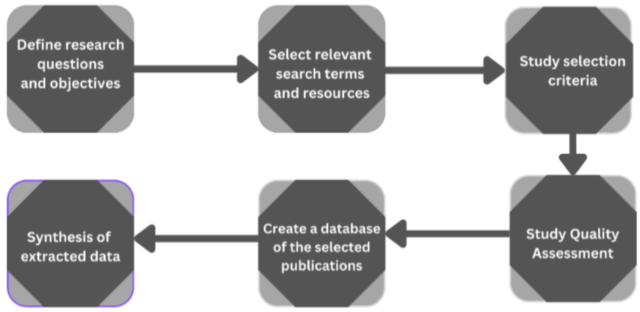

Figure 3: Procedure adopted for selection of academic technical papers

Academic technical papers were sourced from the Web of Science database, including MDPI, IEEE, Elsevier, and Springer, using specific criteria for inclusion and exclusion. Relevant studies were sorted based on publication date, title, abstract, conclusion, and content review, including insights on current practices and trends.

4 Impact of DERs on grid operations

The following subsections discuss some of the key impacts of DERs on power grid operations. It should be noted that the provided literature on the impacts is not exhaustive.

4.1 Bidirectional power flow

Power system networks were originally designed with the assumption of unidirectional power flow, where electricity flowed from central generation sources to end-users. Voltage regulation primarily focused on managing voltage drop along ths distribution network. The integration of DERs disrupts the unidirectional power flow assumption. DERs introduce bidirectional power flow, meaning power can flow not only from centralised generation sources to end-users but also from DERs back into the power grid (Yan et al., 2014). With bidirectional power flow, voltage levels near DER installations can become higher than expected, especially when power flows from end-users toward the generation source. This can lead to voltage rise challenges. Traditional voltage regulators like step voltage regulators and on-load tap changers were designed to manage unidirectional power flow (Lopes et al., 2007). In this new bidirectional scenario, they are less effective in controlling voltage rise. When there is reverse power flow from DERs, voltage regulators may misinterpret the direction of power flow and adjust tap settings in the opposite direction. This can result in voltage rising above defined limits, potentially violating regulatory standards like NRS 097-2.

4.2 Voltage rise issue

This phenomenon occurs due to the bidirectional power flow and intermittent nature of DERs. The intermittent nature of DERs such as solar PV can lead to sudden increases in power injection during peak generation periods (Yan et al., 2014). If local demand is low during these times, the excess power from DERs can cause voltage to rise. Figure 4 shows a power system network feeder without and with a DER represented by the distributed generation (DG). The sending voltage V_S is given by Equation 1.

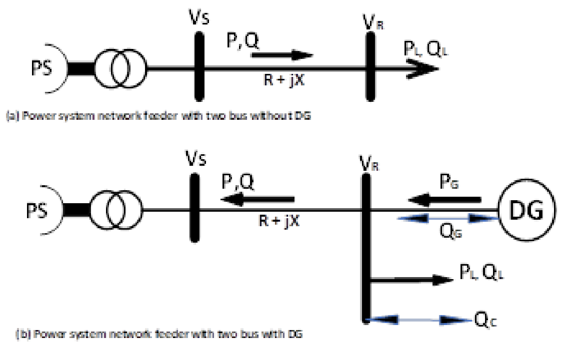

Figure 4: Bidirectional power flow

$$V_S = V_R + I\,(R + jX) \quad (1)$$

Equations 2 and 3 are also known:

$$V_S . I^* = P + jQ \quad (2)$$

$$I^* = \frac{P - jQ}{V_S^*} \; (3) \quad (3)$$

where V_R is the receiving end voltage, R is the resistance of the feeder, X is the reactance of the feeder, I is the current flowing in the feeder, P and Q are the real power and reactive power of the feeder respectively.

This implies Equation 5:

$$V_S = V_R + \frac{P - jQ}{V_S^*}(R + jX) \quad (4)$$

$$\Delta V = V_S - V_R = \frac{RP + XQ}{V_S^*} + j\frac{XP - RQ}{V_S^*} \quad (5)$$

Under normal conditions the angle between V_S and V_R is generally very small, which makes the imaginary part of Equation 5 close to zero. Taking Vs a reference bus and assuming that its magnitude is approximately equal to 1 gives Equation 6:

$$\Delta V \approx RP + XQ \quad (6)$$

If a DG is connected at the receiving end of the feeder as in Figure 4 (b), the active power P and reactive power Q in the feeder will be given as:

$$P = P_G - P_L \text{ and } Q = \pm Q_C - Q_L \pm Q_G \quad (7)$$

Q_C is the reactive power from the capacitor bank. This implies that the voltage seen at the generator in case of a reverse power flow will be given as Equation 8:

$$V_{GEN} = R(P_G - P_L) + X(\pm Q_C - Q_L \pm Q_G) \quad (8)$$

From Equations 3 and 6 it can be seen that during normal operational conditions of the power system network the current is unidirectional, as it will flow from generation to the end-user, and voltage is stable. However, when a DG is connected to the grid, the effect in the power flow affects the voltage profile as can be seen in Equation 8. In this case, the power flow through the feeder is bidirectional and V_{GEN} is dependent on the relative magnitude of the active and reactive power of the load, generator and losses in the network. Excessive injection of DER in the feeder is therefore a serious concern, as it will alter the voltage profile of the feeders. This can be addressed by lowering the voltage on the generation side; however, this approach will result in low voltages in some parts of the power system network feeders, as all buses are not equally affected by the integration of DER.

4.3 Voltage fluctuations

DERs, particularly PV systems, have power output that varies due to factors like weather conditions and fluctuations in sunlight intensity (Gandoman et al., 2018; Lopes et al., 2007; Yan et al., 2014). These variations can lead to rapid changes in the power injection from DERs into the grid. The rapid and unpredictable changes in power injection from DERs can lead to disturbances in the voltage profile of the feeder. This can have detrimental effects on both consumer appliances and the power system network. Traditional voltage control devices, such as voltage regulators and capacitor banks, are designed to respond to gradual changes in load. They typically have time delays ranging from 30 seconds to two minutes (Basso, 2014; EPRI, 2021a). In cases of high penetration of inverter-based DERs like PV systems, these control devices may not be able to respond quickly enough to the rapid power fluctuations. As the power output from PV systems changes throughout the day due to factors like cloud cover and the sun's position, voltage control devices would need to operate more frequently to maintain the desired voltage levels. This increased operational frequency can lead to excessive wear and tear on these devices, requiring more frequent maintenance or replacement. A case study that was carried out from the Fontana power grid in California (Mather, 2014) using real field data of voltage fluctuations caused by rapid changes in PV power output shows significant impact of cloud-induced power fluctuations, with some events causing a drop of more than 50% of the PV system's rated output per minute. While the passing of clouds causes severe fluctuations in PV output, it was noted that sunlight intensity changes were not strong enough to cause severe flicker, highlighting the distinction between rapid power fluctuations and flicker issues.

4.4 Voltage unbalance

Many DERs, especially residential solar PV systems, are connected to single phases of a three-phase network. If these DERs are unevenly distributed across the phases, it can cause one phase to have significantly different voltage levels from the others, leading to voltage unbalance. In other instances, the impedance of the distribution network can differ between phases, especially in older networks with asymmetrical layouts. When DERs inject power, these impedance differences can cause uneven voltage drops across the phases, exacerbating voltage unbalance. The voltage unbalance results in differences in phase-to-neutral and phase-to-phase voltages, which deviate from the ideal balanced condition where all phases should have the same magnitude and be 120 degrees apart. Uneven voltage levels can place stress on power system network equipment and appliances. For example, three-phase motors may experience uneven performance or potential damage due to voltage imbalances. Voltage unbalance can affect the efficiency and operation of equipment and appliances, potentially reducing their lifespan and causing operational issues (EPRI, 2021b; Sayed & Takeshita, 2010). Voltage unbalance requires a combination of smart planning, technology deployment, and operational strategies that optimises the placement and capacity of DERs across phases and implementation of effective control mechanisms that are able to adjust voltage levels across phases to ensure more balanced conditions (EPRI, 2021b). Utilising advanced technology, such as smart inverters and monitoring systems, can help detect and mitigate voltage unbalance. Smart inverters, for instance, can actively control voltage levels and balance power injection across phases.

4.5 Thermal rating criteria

Understanding the thermal ratings of power system components is crucial to prevent damage from overloading. This is because every component in a power system network, such as power lines, cables, and transformers, has a current-carrying capacity (known as the thermal rating). Exceeding this rating for an extended period can lead to permanent damage to the physical and electrical characteristics of the component. In other words, overloading components can cause lasting damage. Voltage levels are influenced by both active and reactive power flows. Increasing power flow through a line to support voltage levels at distant points in the network can increase the current closer to the thermal limit of the line or transformer. This increased current can lead to higher thermal loading, potentially exceeding the thermal rating of the equipment, even if the voltage is kept within limits. High penetration of DERs, especially during scenarios of maximum generation and minimum load, can result in increased current levels in certain parts of the network (EPRI, 2021b; Lopes et al., 2007). This can lead to situations where the voltage needs to be reduced in those parts of the network. However, reducing the voltage through reactive power absorption can increase the current, potentially violating thermal limits. DERs that are engaged in voltage regulation at the same bus as conventional voltage regulation devices can lead to potential conflicts (EPRI, 2021b). When both DERs and traditional devices attempt to regulate voltage simultaneously, it can result in maloperation or undesirable interactions within the power system. To address these challenges, effective control and coordination strategies are required. These strategies can help manage the interplay between DERs and conventional devices, ensuring that they work together harmoniously without causing issues in voltage regulation and system operation.

5 DER hosting capacity enhancement strategies

Hosting capacity is a critical metric that defines the maximum amount of generation or load that can be integrated into the power grid without compromising its reliability and power quality. Expanding the hosting capacity is advantageous for both power utilities and DER owners. The installation of DERs like rooftop photovoltaic systems, electric vehicles, and heat pumps can alter the load profiles of households and businesses, which in turn affects the overall demand on the distribution network. This shift can lead to challenges such as voltage violations and overloading of lines. To address these issues and accommodate higher levels of DER penetration, a range of technical solutions have been proposed. These solutions encompass both conventional and innovative approaches, all aimed at increasing the hosting capacity of distribution networks. Table 1 shows a matrix that outlines various techniques used to enhance DER hosting capacity in power grids, highlighting the different issues observed when implementing the techniques.

Table 1: Various techniques used to enhance DER hosting capacity in power grids

Technique	*Issue addressed*	*Observed issues*
Automatic voltage regulators	Maintains stable voltage levels in the grid	Can be slow to respond to rapid voltage changes; requires regular maintenance
Static var compensators	Provides reactive power support to manage voltage	High installation and operational costs; complexity in control
Distribution-level tap changers	Adjusts transformer taps to regulate voltage	Limited granularity; may cause wear and tear on transformers
On-load tap changers	Allows continuous voltage regulation under load	High maintenance requirements; potential for operational delays
Dynamic voltage restorers	Protects against short-term voltage sags/swells	Expensive; limited to addressing short-term disturbances
Demand response programmes	Adjusts load to maintain voltage stability	Requires customer participation; effectiveness varies with customer response
Battery energy storage systems	Provides fast frequency response capabilities	High cost of implementation; limited by battery capacity and lifespan
Inverter-based frequency regulation	DER inverters support grid frequency through active power control	Limited by inverter design and settings; potential for grid synchronisation issues
Virtual inertia	Emulates the inertial response of traditional generators using power electronics	Still in early stages of deployment; can be complex to implement effectively
Smart inverters	Provides both voltage and frequency stability, especially in islanded microgrids	Limited application to small or isolated grids; costly and complex to implement
Microgrid controllers	Coordinates voltage and frequency control within a microgrid	High setup costs; complexity in integrating with larger grid operations
Flexible AC transmission systems	Manages both voltage and frequency through dynamic control of transmission systems	Expensive to deploy; requires advanced control algorithms and infrastructure

The following subsections explore in detail some of the techniques used to enhance the hosting capacity of DERs in power grids.

5.1 Traditional methods

Traditional methods for enhancing hosting capacity involve network augmentation solutions. These include upgrades to transformers and conductors, along with the use of on-load and off-load tap changers, as well as capacitor banks (Capitanescu et al., 2014; Li et al., 2020; Lopes et al., 2007; Mather, 2014). These measures have been recognized as effective means to improve the capacity of distribution networks to handle increased levels of DERs. Voltage regulators play a crucial role in this process. These devices are designed to control the output voltage of distribution lines by automatically adjusting the level of voltage boost or reduction. However, with the integration of DERs, especially during periods of high generation, there is a risk of local voltage levels exceeding acceptable limits due to excess power injection (Muttaqi & Negnevitsky, 2015). This can lead to voltage violations, potentially impacting the stability of the grid. To address this issue, voltage regulators are deployed strategically (Muttaqi & Negnevitsky, 2015). They work by actively reducing the voltage at specific points in the distribution network. This is achieved through the injection or absorption of reactive power, a technique that helps to maintain voltage within an acceptable range, ensuring the stability and reliability of the grid even under conditions of high DER generation.

5.1.1 Tap changers

Conventional voltage regulation devices, particularly tap changers, play a crucial role in the integration of DERs into the power grid. These devices are instrumental in ensuring that voltage levels remain within acceptable limits, even with the fluctuations in power generation and demand introduced by DERs. Tap changers are electro-mechanical switching equipment that allow for the adjustment of a transformer's tap position while the transformer is loaded or with no load. This adjustment helps in maintaining the voltage supplied to the load within prescribed limits, compensating for over and under voltages that may result from variations in load (Liu et al., 2012). Essentially, they regulate the output voltage by altering the turns ratio of the transformer. By changing the tap position, the voltage ratio between the primary and secondary windings is modified, as shown in Figure 5.

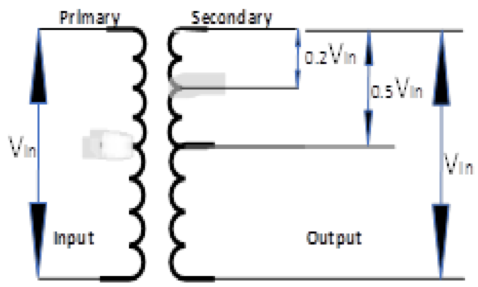

Figure 5: Tap changing position of a transformer

In the context of DER integration, particularly with renewable sources like solar PV, power generation can vary due to factors such as weather conditions. When DERs inject power into the power grid, especially during low load conditions, the local voltage can rise. The tap changer can respond by adjusting the transformer taps to lower the voltage, mitigating the voltage rise. In contrast, during periods of high demand or low DER output, the tap changer can increase the voltage by adjusting the taps, ensuring that the voltage at the end of the distribution line remains adequate. This variability can lead to voltage fluctuations in the distribution network. Tap changers respond dynamically to these fluctuations in voltage levels by adjusting the transformer's turns ratio. This compensates for voltage deviations caused by the fluctuating output of DERs. For instance, if the voltage tends to rise, tap changers can be adjusted to lower it, and vice versa. This ensures that the voltage supplied to the load remains stable and within the specified range, contributing to the reliable and secure operation of the power grid amidst the variability introduced by DERs.

5.1.2 Capacitor banks

Capacitor banks have traditionally played a vital role in addressing undervoltage issues by injecting reactive power and raising voltage levels along the feeder. However, with the increasing integration of DERs and their dynamic power output, traditional capacitor banks may face limitations in controlling voltage effectively. In scenarios of high DER power generation, traditional capacitor banks might not be well-suited to manage voltage due to the dynamic nature of DER power output (Horowitz et al., 2020; Li et al., 2019). During periods of high DER generation, voltage levels along the feeder can increase, and the use of fixed capacitor banks may inadvertently worsen the overvoltage problem. Moreover, switched capacitor banks, which typically operate in discrete steps, can struggle to respond quickly and accurately to rapidly changing load patterns and voltage fluctuations caused by variable DER power output. As a result, there is a growing interest in alternative approaches that utilise DER-based control algorithms. These algorithms harness the capabilities of smart inverters and controllable loads as more effective and flexible methods to regulate voltage variations, working in coordination with utility-owned assets, including capacitor banks.

5.1.3 Network reconfiguration

Network reconfiguration involves making changes to the connectivity of distribution feeders with the aim of optimising power flows, reducing losses, balancing loads, and enhancing overall reliability (Capitanescu et al., 2014). This strategy has been acknowledged as an effective means to increase the hosting capacity of DERs by improving voltage profiles and optimising network operation. Network reconfiguration can be divided into static (planning stage) and dynamic (operational stage) approaches. Static reconfiguration approach optimises the network configuration for specific conditions. It is typically performed during the planning stage and aims to achieve the most efficient and reliable network structure for anticipated scenarios. Dynamic reconfiguration adapts to changing scenarios in real-time, responding to variations in demand, generation, and other network conditions as they occur.

One option of network reconfiguration involves replacing existing conductors with ones of larger cross-sectional areas. This reduces impedance in the network, which can help manage voltage drop issues associated with high DER penetration. The goal is to minimise resistance losses in the distribution network and maintain voltage levels within acceptable ranges. Another approach is the replacement of distribution transformers with larger power ratings. This reduces impedance and improves voltage regulation in the network. While effective, the costs associated with these methods need to be carefully evaluated, particularly in scenarios involving distributed generation, to ensure they align with the overall cost-benefit analysis.

5.2 Emerging technologies

Emerging technologies are innovative approaches that are used to effectively tackle the challenges brought about by the integration of DERs into the power grid (Horowitz et al., 2019). These technologies harness advancements in control algorithms, data analytics, and real-time monitoring to significantly enhance the power grid's capacity to accommodate DERs while ensuring stable voltage levels, power quality, and overall reliability. The following subsections provide a summary of some of the key emerging technologies in this field. These technologies offer promising solutions to the complex task of seamlessly integrating DERs into the power grid while maintaining grid stability and efficiency.

5.2.1 Energy storage systems

Energy storage systems (ESSs) are integral components of the power grid, and various types are employed to enhance grid performance and accommodate DERs. The key types of ESS include batteries, flywheels, ultra-capacitors, and superconducting energy storage systems (Zeraati et al., 2016). ESSs serve as power smoothing devices, effectively mitigating abrupt changes in power output from DER units and assisting generators in ramping up or down their output. They play a pivotal role in providing power to DER units during their ramp-down phase or absorbing power when they ramp up. By controlling the rate at which DER power output varies, ESSs prevent sudden changes in DER power injection, making the operation of the power system more manageable, particularly during periods of high DER penetration (Wang et al., 2015; Varma & Singh, 2020). The rapid response from ESSs is particularly valuable as it helps in mitigating voltage violations and reducing the wear and tear on static voltage regulating devices. Effective control strategies are crucial for ensuring the efficient operation of ESSs. Simple control methods may not adequately address network events. For example, residential battery energy storage systems (BESSs) are often controlled using a basic strategy where they charge when production exceeds consumption (Ustun et al., 2019; Ustun et al., 2020). However, this approach may lead to BESSs being fully charged early in the day and not being able to respond effectively to network events when their support is most needed. Studies have shown that off-the-shelf residential BESSs, when used in this manner, may not significantly address voltage issues in distribution networks. This is often because these systems reach their upper storage limits early in the day and are unable to prevent excess power exports from PV systems during periods of light load and high voltage levels. To address these challenges, when applying ESS devices to curtail active power (or absorb active power), a volt-watt function curve can be used (Rashid & Knight, 2020; Ustun et al., 2020) as shown in Figure 6. This curve helps control the power output of the ESS to optimise voltage control within the network.

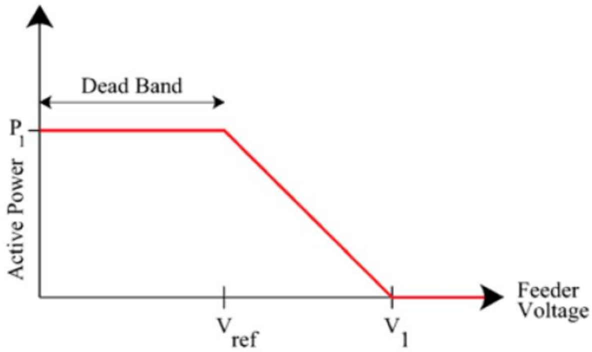

Figure 6: Volt/watt control curve

The curve starts at full power output (P_1) at the nominal voltage V (1.0 pu). As voltage increases past the threshold V_{ref} (e.g., V_{ref} = 1.03 V pu), the curve slopes downward, indicating a reduction in active power. The curve reaches a low point at a higher voltage V_1 (e.g., V_1 = 1.10 V pu), where power output is significantly reduced to zero. Proper utilisation and control of ESSs are essential for achieving their full potential in stabilising the grid, supporting DER integration, and ensuring power system reliability.

5.2.2 Low voltage regulators

Low voltage regulators (LVRs) are essential devices designed to regulate voltage within a specified range around the nominal voltage on the low voltage grid (Takram et al., 2020; Torres et al., 2014). They have the capability to perform both boost operation (increasing voltage) and buck operation (decreasing voltage) to maintain voltage levels within acceptable bounds. The LVR is positioned on the low-voltage side of the distribution network, typically downstream from the transformer and can be located either upstream or downstream of DERs, depending on the specific application and needs. When placed upstream of DERs it controls voltage fluctuations before the power reaches the DERs and the end-users. Placing it downstream of DERs would enable it to manage the voltage fluctuations introduced by DERs, especially if they are causing overvoltage issues due to their fluctuating power generation output. LVRs typically operate within a specified range, which might be set at ±13% of the nominal voltage. They are known for their high regulation accuracy, often maintaining voltage within a very tight tolerance, such as ±1 volt (Kikusato et al., 2014; Takram et al., 2020). Some LVRs are equipped with bi-directional capability, allowing them to adjust voltage even when there is a reverse power flow from the DER unit into the power grid. This feature is valuable in scenarios where voltage regulation is essential, particularly during reverse power flow situations. LVRs offer a promising solution for voltage regulation in low voltage grids, especially in situations where voltage needs to be effectively managed. However, their cost can be a limiting factor, particularly in areas with low-density distribution networks. Balancing the benefits of voltage regulation with the associated expenses is a consideration for utilities and grid operators when implementing LVRs in their networks.

5.2.3 Flexible AC transmission system devices

The deployment of flexible AC transmission system (FACTS) devices in distribution networks represents an evolving research area with a focus on improving control and voltage regulation. Several common FACTS devices are being explored for application in distribution systems to enhance various aspects of grid performance, including voltage control, loss minimisation, and power quality improvement (Gandoman et al., 2018; Rezaeian-Marjani et al., 2020; Sayed & Takeshita, 2010; Yan et al., 2014). These devices have the potential to be valuable assets in distribution networks, and ongoing studies are exploring their effectiveness in addressing specific challenges. Research efforts are aimed at optimising the placement of FACTS devices, such as unified power quality conditioners, to achieve dual benefits. This includes enhancing photovoltaic hosting capacity, which is the capacity to integrate solar photovoltaic systems while simultaneously reducing energy losses (Gandoman et al., 2018). By strategically locating these devices, it becomes possible to boost the hosting capacity for distributed energy resources while minimising grid losses. Some studies explore the interaction between smart inverters, static var compensators, and dynamic voltage control (Gandoman, et al., 2018; Rezaeian-Marjani et al., 2020; Sayed & Takeshita, 2010). This research has demonstrated the potential to significantly increase the hosting capacity of distributed energy resources in the power grid. This enhanced interaction between devices offers a pathway to doubling the capacity of DERs, thus optimising their integration and management. These technologies offer advanced capabilities for optimising the distribution grid, and ongoing research is uncovering their benefits in terms of improved grid performance, reduced losses, and increased reliability. The application of FACTS devices in distribution systems represents a promising avenue for enhancing the integration of DERs while maintaining grid stability and power quality.

5.2.4 Smart inverters

Smart PV inverters have transformed the landscape of DER systems by offering advanced functionalities that enhance the stability, efficiency, and reliability of the power grid. Their evolution has enabled smart inverters to play a pivotal role in power grid management and the seamless integration of distributed energy resources, particularly solar photovoltaic systems (NREL, 2014; (UL, 2016; Xue & Guerrero, 2015). The development and adoption of smart inverter technology, supported by standards like UL 1741 SA and IEEE 1547-2018, mark a significant milestone in the integration of DERs into power grids (EPRI, 2016; IEEE, 2018). These devices are crucial components in enabling the transition to more sustainable and distributed energy systems while maintaining the stability and reliability of the grid. The development of smart inverters was prompted by the need to integrate higher levels of DER generation into the power grid safely and efficiently. Before 2017, traditional inverters used in DER systems had limited functionality and were not suitable for grid integration when the fraction of energy generated by DERs exceeded 15% of total energy consumption (NREL, 2014; Reno & Broderick, 2015). In response to this limitation, the state of California collaborated with Underwriters Laboratories to create the UL 1741 SA standard. This standard defined the requirements for smart inverters, which could be installed in much higher densities within the power grid. Smart inverters, as defined by the UL 1741 SA standard and other similar standards, offer advanced functionalities that contribute to the stability and reliability of the power grid. One notable feature is the ability to provide low- and high-voltage ride-through. This allows the inverter to remain connected to the grid during certain disturbances, helping to stabilise the grid instead of abruptly disconnecting, which could exacerbate disruptions. Smart inverters actively participate in power grid management. They can contribute to voltage and frequency regulation, which is critical for grid stability. These inverters can also provide ancillary services, such as reactive power support, to help manage grid conditions and improve overall power quality. The concepts and standards developed for smart inverters have not only been implemented at the state level but have also had a broader impact. They have been incorporated into national standards, such as IEEE 1547-2018, which provides guidelines and requirements for the interconnection of DER systems to the power grid on a wider scale. Their ability to actively participate in power grid management and support the integration of distributed energy resources, such as solar PV systems, makes them key players in the transition to a more sustainable and resilient energy system. The following section will look at smart inverter capabilities in detail.

6 Smart inverter capabilities

The Electric Power Research Institute (EPRI) has identified several high-priority power grid-supportive functions for smart inverters. These functions play a crucial role in enhancing the interaction between DERs equipped with smart inverters and the power grid. The following is an overview of these functions (EPRI, 2016; Horowitz, et al., 2019):

Immediate control: Smart inverters have the capability to quickly connect or disconnect in response to power grid conditions. This immediate control function allows them to respond rapidly to grid events, contributing to grid stability and reliability.

Frequency-related control: Smart inverters can adjust their power output based on measured high frequencies in the power grid. This function helps in maintaining power grid stability by responding to frequency fluctuations, ensuring that the grid operates within acceptable limits.

VAr management: VAr (volt-ampere reactive) management involves various methods of reactive power and voltage regulation using smart inverters. These methods include maintaining a fixed power factor, adjusting the power factor as needed, and providing VAr control to regulate voltage levels. Effective VAr management is essential for grid stability and voltage control.

Ride-through capability: Smart inverters are designed to remain connected to the power grid even during temporary fault events. This ride-through capability enhances power grid resilience by ensuring continuous operation despite disturbances. It contributes to minimising power interruptions.

Storage management: Smart inverters can manage energy storage systems, including charging and discharging. This function enhances the flexibility and efficiency of energy storage integration. By effectively managing energy storage, smart inverters support grid stability and enable the optimal use of stored energy.

Event-logging and status-reporting: Smart inverters are equipped with the capability to log events, modify settings, set alarms, and communicate operational status to the power grid operator. This data exchange helps ensure effective coordination between DERs and the power grid. Event-logging and status-reporting assist in monitoring and managing DERs in real-time.

These functions are becoming standardised as smart inverter functions and are being incorporated into grid code requirements and industry standards. For instance, the IEEE 1547:2018 standard and the IEC61850-90-7 standard include these functions to ensure the proper integration and interaction of DERs with the power grid. By adhering to these standards, smart inverters can contribute significantly to grid stability, reliability, and the efficient integration of renewable energy resources.

6.1 Standard reviews

This section presents an overview of how international and South African guidelines address the functions of smart inverters and their role in mitigating challenges associated with variable DER power generation. A similar study was done by Xavier et al. (2021), but the comparison was limited to two regions – USA and South Africa. This paper provides a comprehensive review of different standards of eight different regions and a comparison to the South Africa grid code is made. The NRS 097-2-1 and SAGCRPP play a crucial role in regulating the interconnection of DERs to the power utility network in South Africa (NERSA, 2017; 2019). They provide specific frameworks tailored to different generator capacity sizes, focusing on low-voltage embedded generators and medium-to-large-scale systems operating at medium and high voltages. These regulatory frameworks aim to ensure the safe and effective integration of DERs into the South African power grid. It is a significant step towards maintaining grid stability and reliability while accommodating the growing presence of distributed energy resources.

Table 2 shows different regions that have adopted various frameworks and standards to manage the challenges of DER integration. While the specifics vary, common themes include the need for smart inverters with advanced grid support functions, stringent voltage and frequency control requirements, and the harmonisation of standards across regions. These frameworks have been critical in ensuring that DERs contribute positively to grid stability, preventing issues such as voltage unbalance, frequency deviations, and other challenges associated with high levels of distributed generation. As South Africa continues to integrate more DERs into its power grid, learning from these global experiences will be essential in developing effective and resilient standards.

Table 2: DER integration frameworks and standards of different regions

Standard	*Focus*	
China (GB/T 19964-2012) (China National standard GB/T 19964-2012, 2012)	Managing integration of DERs, particularly wind and solar connections into the grid	
	Grid stability	Emphasis on hierarchical grid management and regional energy trading markets and deployment of high-voltage transmission systems to manage stability across regions
	Voltage regulation	Voltage support requirements for DERs focused on reactive power provision
	Frequency control	Employs a centralised frequency control strategy with frequency response obligations for large-scale DERs and hybrid control systems are used to coordinate frequency response between regional grids
	Overall integration	The GB/T 19964-2012 Code promotes a consistent approach to DER integration across China, focusing on regional coordination of energy flows and enhancing grid reliability
California (CA Rule 21) (CPUC, 2018)	Smart inverters and grid support functionalities.	
	Grid stability	Requires smart inverters to provide grid support functions such as Volt-Var, Volt-Watt, and frequency-watt control. This enhances grid stability by allowing DERs to actively participate in voltage and frequency regulation
	Voltage regulation	Inverters must respond to voltage fluctuations, helping to maintain voltage within acceptable limits, particularly in areas with high DER penetration
	Frequency control	Includes requirements for frequency-watt response, where inverters adjust power output based on grid frequency, aiding in frequency stabilisation
	Overall integration	CA Rule 21 has become a model for other regions, setting a high standard for the technical capabilities of DERs and their role in grid management
Hawaii (HE Rule 14H) (Berdner, 2015)	Integration of high levels of DER, particularly solar PV	
	Grid stability	Similar to CA Rule 21, but with a stronger focus on handling the challenges of extremely high DER penetration (up to 100% in some areas). Inverters are required to have advanced grid support functions to mitigate issues like the "Nessie curve."
	Voltage regulation	Inverters must manage voltage fluctuations, which are frequent due to Hawaii's high solar penetration and variable generation
	Frequency control	Emphasises frequency response capabilities to counteract the effects of rapid changes in generation due to cloud cover and other factors
	Overall integration	HE Rule 14H has proven effective in managing a grid with one of the highest solar penetrations globally, making it a critical case study for other regions with similar conditions (CEI 0-21, 2019)
Germany (VDE-AR-N 4105:2018) (VDE-AR, 2018 No. 4105)	Integration of DERs, particularly in residential and small commercial settings	
	Grid stability	Requires DERs to contribute to voltage and frequency stability through reactive power support and other grid-friendly functions
	Voltage regulation	The standard mandates reactive power control at the point of connection, helping to manage voltage at both local and regional levels
	Frequency control	Includes robust frequency response requirements, with DERs expected to adjust output based on frequency deviations
	Overall integration	Germany's standards are crucial for managing its high levels of renewable energy, particularly solar and wind. The framework ensures that even small-scale DERs contribute to overall grid reliability

Standard	Focus	
Australia (AS/NZS 4777.2:2020) (AS/NZS 4777.2:2020, 2020)	Integration of rooftop solar and other small-scale DERs	
	Grid stability	The standard requires smart inverters with capabilities like Volt-Watt and Volt-Var response, which help stabilize the grid in areas with high solar penetration
	Voltage regulation	Inverters must manage voltage at the connection point, crucial for avoiding over-voltage issues common in networks with high rooftop solar adoption
	Frequency control	Inverters are required to provide frequency support by reducing or increasing output in response to frequency changes
	Overall integration	Australia's framework has been effective in managing the challenges of high rooftop solar adoption, making it a model for regions with similar residential solar trends
Italy (CEI 0-21) (CEI 0-21, 2019)	Integration of DERs into the low-voltage grid	
	Grid stability	Mandates anti-islanding protection and grid support functions, ensuring that DERs contribute positively to grid stability
	Voltage regulation	Includes requirements for reactive power control, helping to maintain voltage levels in urban and rural networks
	Frequency control	DERs are required to support frequency stability, particularly in response to sudden changes in generation or load
	Overall integration	Italy's standards are effective in managing DERs in densely populated areas, ensuring that the grid remains stable despite high levels of distributed generation
New Zealand (Electricity Industry Participation Code - EIPC) (AS/NZS 4777.2:2020, 2020)	Managing the integration of DERs, particularly wind and solar, into the grid	
	Grid stability	Requires DERs to support grid stability through voltage and frequency response functions
	Voltage regulation	DERs must manage voltage at the connection point, critical for ensuring stability in a grid with high renewable penetration
	Frequency control	Emphasizes the role of DERs in maintaining frequency stability, particularly in response to rapid changes in renewable generation
	Overall integration	New Zealand's approach has been effective in balancing renewable energy with traditional power sources, providing a stable and reliable grid despite high levels of DER integration
Europe (ENTSO-E Network Code on Requirements for Generators) (ENTSO-E, 2013)	Harmonised standards across Europe for all generators, including DERs	
	Grid stability	The code provides a unified approach to DER integration across multiple countries, ensuring that DERs contribute to grid stability through frequency and voltage support
	Voltage regulation	Requires DERs to manage voltage fluctuations, crucial for maintaining a stable grid across diverse regional grids
	Frequency control	Establishes strict requirements for frequency response, with DERs expected to provide support during frequency deviations
	Overall integration	The ENTSO-E Network Code promotes a consistent approach to DER integration across Europe, facilitating cross-border energy flows and enhancing grid reliability

6.1.1 Voltage and frequency regulation

The inclusion of voltage and frequency regulation functions in smart inverters is crucial for ensuring stable grid operation and maintaining acceptable voltage levels, especially in the context of integrating DERs The specific regulation modes and functions may vary depending on the standard. The IEEE 1547-2018 standard specifies that DERs must have the capability to regulate voltage through reactive power support, utilising functions like volt-VAr (voltage-reactive power) and volt-watt (voltage-active power) modes. This allows DERs to either absorb or generate reactive power depending on the voltage level to maintain grid stability. Frequency regulation is supported through functions like frequency-watt control, where DERs adjust their active power output in response to frequency deviations. The frequency operating range is typically from 57 Hz to 62 Hz, allowing for automatic load shedding or generation curtailment when necessary. Similarly, the Australian grid code requires DERs to provide voltage support using volt-VAr and volt-watt response functions. DERs are expected to dynamically control reactive power output to maintain stable grid voltage, especially in regions with high DER penetration. DERs must stay connected within a wide frequency range (45 Hz to 55 Hz) and actively participate in frequency control. This involves adjusting power output based on the grid frequency, helping to manage both under-frequency and over-frequency conditions. The SAGCRPP standard allows for both reactive and active power compensation, encompassing volt-VAr and freq-watt modes, for systems in Category A3, B, or C.[1] However, NRS 097-2-1 does not cover any voltage or frequency regulation methods. These modes and functions provide flexibility in how smart inverters can assist with voltage and frequency regulation, helping to address the challenges posed by variable DER power generation and maintain the stability and reliability of the power grid. The differences in coverage between standards, such as SAGCRPP and NRS097-2-1, reflect the varying regulatory approaches for different types of systems. These standards play a critical role in shaping how smart inverters are used and regulated in the context of distributed energy resources.

6.1.2 Voltage and frequency ride-through capability

Smart inverters have defined modes of operation during these disturbances, such as mandatory operation, momentary cessation, and continuous operation (EPRI, 2016). This flexibility allows them to adapt to the severity and duration of the disturbance, ensuring a more stable grid response. The maximum ride-through times specified in various grid codes are important parameters, as they determine how long smart inverters should remain connected and assist in managing grid stability during disturbances. These standards help ensure consistent and reliable performance of smart inverters in response to grid events, contributing to power grid stability and reliability. This strategy ensures that smart inverters remain connected for a specified period, preventing simultaneous disconnections that could exacerbate the disturbance. It is noteworthy how different grid codes like GB/T 19964-2012, AS/NZS 4777.2:2020, CA Rule21 and HE Rule14H have defined specific modes of operation for smart inverters during ride-through periods, tailoring their response based on the severity and duration of the disturbance. California's Rule 21 and Hawaii's Rule 14H have established clear requirements for how smart inverters should operate during disturbances, and these requirements involve transitioning between different modes, depending on the severity and duration of the disturbance. The Chinese standard requires that large-scale wind and solar power plants must remain connected during voltage dips as low as 15% of the nominal voltage for a defined duration of 2 seconds. The frequency ride-through requirements specify that DERs must stay connected within a frequency range of 49.5 Hz to 51.5 Hz, with tolerances for more severe events depending on the grid's stability needs. This ensures that DERs do not disconnect during short-term disturbances. The CEI 0-21 standard emphasises that DERs must withstand voltage sags down to 15% of nominal voltage for a few seconds without disconnecting from the grid. The standard focuses on ensuring that DERs continue providing reactive power support during such disturbances. Italy's requirements allow DERs to remain connected within a frequency range of 49 Hz to 51 Hz, with additional conditions for supporting grid stability during significant frequency deviations. The Australian standard requires small-scale DERs (such as rooftop solar PV) to stay connected during voltage sags as low as 20% of nominal voltage for up to 0.2 seconds. For longer events, the voltage threshold is adjusted. DERs must remain operational within a frequency range of 45 Hz to 55 Hz, providing grid support during frequency fluctuations. The standard also mandates reactive power provision during such disturbances. Similar to Australia, New Zealand's standards align with the AS/NZS 4777.2 requirements. By specifying maximum ride-through times, grid codes provide a framework for how long smart inverters should remain connected during disturbances, ensuring that they contribute to grid stability while not exposing themselves to unnecessary risks. The variations in maximum ride-through times across different grid codes highlight how regional regulations and grid conditions can influence these requirements. For instance, a shorter ride-through time of 200 milliseconds in the NRS097-2-1 and SAGCRPP standards may be sufficient for addressing certain types of disturbances that are more localized or transient in nature. On the other hand, longer ride-through times of 1.5 to 2 seconds, as specified in CA Rule 21 and HE Rule 14H, provide additional flexibility for smart inverters to withstand short-term voltage and frequency variations, reducing the likelihood of unnecessary disconnections and power grid instability (EPRI, 2016); (Reno & Broderick, 2015); (UL, 2016). These longer ride-through times are particularly important in regions with a high penetration of distributed generation, where the coordination of responses to disturbances is critical to maintaining grid stability. In the case of over-frequency conditions, the SAGCRPP standard's maximum trip time of 5 seconds acknowledges the need for larger generating units to ride through disturbances and minimize the risk of disconnections and power outages. It is essential to have such standards in place to ensure that smart inverters act in a coordinated and effective manner during grid disturbances. The choice of specific ride-through times is influenced by a combination of factors, including the characteristics of the local grid, the prevalence of DERs, and the overall grid stability requirements. These variations in ride-through times across different standards reflect the need to strike a balance between maintaining grid stability and ensuring the reliability of DER systems.

6.1.3 Communication

The implementation of standardised communication protocols for smart inverters is a crucial aspect of modern power grid management, particularly in regions with high penetration of DERs. These communication protocols enable seamless interaction between smart inverters, distribution operators, and other power grid entities, facilitating real-time monitoring, control, and coordination. China primarily employs protocols based on IEC 61850 and DL/T 645 for DER communication, with extensions for DER-specific functions. The focus is on integrating smart inverters into grid operations using protocols that support real-time monitoring, remote control, and data acquisition. Italy's grid code CEI 0-21 emphasizes the use of IEC 61850 and Modbus protocols for smart inverter communication. These protocols support DER integration into the grid by allowing real-time monitoring, remote settings adjustments, and automatic control based on grid conditions. Australia's DER standards require the use of protocols like IEEE 2030.5 (often referred to as the Common Smart Inverter Profile or CSIP), Modbus, and IEC 61850. In California, the adoption of IEEE 2030.5 (SEP2) as the default communications protocol for smart inverters provides a standardized framework for communication between DER-based smart inverters and distribution operators (Basso, 2014). This protocol allows for the exchange of important performance data, operational instructions, and control commands. It plays a pivotal role in integrating smart inverters into the power grid, enabling fine-grained control and monitoring. Similarly, Hawaii mandates communication capabilities for inverter systems to control active power output and facilitate coordination with distribution operators, as stipulated in NRS 097-2-1. The use of Distributed Network Protocol 3 (DNP3) for information exchange, as required for large DER inverter-based systems exceeding 1 MVA by the SAGCRPP standard, ensures reliable communication between smart inverters and distribution network operators (NERSA, 2019); (NERSA, 2017). DNP3 is a widely recognised and robust protocol used for monitoring and controlling remote devices, making it a suitable choice for power grid management. IEEE 1547: 2018, a comprehensive standard for interconnecting DERs, offers flexibility in the choice of communication protocols, including IEEE 2030.5 (SEP2), IEEE 1815 (DNP3), and SunSpec Modbus (Sadan & Renz, 2020). This flexibility allows for compatibility with various communication infrastructures and offers options for different smart inverter configurations. The communication protocols mentioned, such as IEEE 2030.5 and DNP3, are essential tools for maintaining grid stability, enabling real-time adjustments, and ensuring power quality. These standards facilitate the integration of DERs into the power grid while promoting interoperability and coordination among grid assets. Overall, standardised communication protocols are a critical component of modern grid management, enabling the efficient and effective operation of power grids with high levels of DER penetration.

6.1.4 Return to service

The inclusion of protective functions in smart inverters to detect and respond to system parameters that exceed specified limits is essential for maintaining grid stability and safety (IEC, 2004); (Li et al., 2020; Pamshetti & Singh, 2019). When voltage or frequency parameters deviate outside acceptable ranges, smart inverters are programmed to disconnect the system to prevent any potential harm or disruption to the power grid. Upon detecting such an event, smart inverters initiate a disconnection process to ensure the safety and integrity of the power grid. The disconnection process is a precautionary measure aimed at protecting both the DER system and the grid. To prevent the system from immediately re-energising the grid after a disconnection, smart inverters incorporate a time delay function. This time delay serves a crucial purpose by allowing the grid's voltage and frequency to fully stabilise before the DER system or smart inverter reconnects to the power grid. It helps avoid rapid and potentially harmful reconnections. The specific time durations for the waiting period after voltage and frequency stabilisation vary based on different standards (IEEE, 2018); (NERSA, 2019); (NERSA, 2017). These standards provide guidance on the appropriate time delays that strike a balance between ensuring grid stability and preventing equipment damage. It is important to highlight that the adequacy of the return-to-service time should be carefully considered in the context of specific grid conditions and the characteristics of DER systems. A return-to-service time that is too short may lead to the Germany "yo-yo effect" (Uphoff & Dirks, 2012; Döring, 2013) characterised by rapid disconnections and reconnections, which can exacerbate grid instability. The yo-yo effect refers to the challenges that were faced by Germany's power grid due to the large fluctuations in renewable energy generation, particularly from wind and solar sources. This effect is a consequence of Germany's ambitious energy transition, known as the *Energiewende,* which has led to a significant increase in the share of renewable energy in the power mix. The yo-yo metaphor describes the rapid disconnections and reconnections of the power grid caused by frequency and voltage instability in the grid as a result of the rapid and unpredictable changes in power supply from integrated DERs. The conventional power generators, which are slower to ramp up or down, struggle to compensate for these fluctuations resulting in a yo-yo effect also known as the German "50.2 Hertz" problem . In China, DER systems, particularly wind and solar plants, are allowed to reconnect to the grid only after grid parameters (voltage, frequency) stabilise within a specified range. The DER must wait until grid voltage and frequency are within acceptable operating limits, typically within ±5% of the nominal values. The reconnection process is often gradual to avoid sudden influxes of power. The Italian CEI 0-21 standard specifies that DERs must wait for a minimum delay after a disturbance before reconnecting to the grid. The time delay usually ranges from 180 to 300 seconds. Before returning to service, the DER must ensure that grid voltage and frequency remain within specified limits (typically within ±10% of nominal voltage and within the frequency range of 49.5 to 50.5 Hz). The standard emphasises a controlled, gradual ramp-up of power to avoid sudden stress on the grid. In Australia, the AS 4777.2 standard governs the reconnection of small-scale DERs like rooftop solar systems. The standard mandates a waiting period of 60 seconds to several minutes before DERs can reconnect after a fault. Similar to other regions, DERs can only reconnect once grid voltage and frequency stabilise within predefined thresholds (typically within ±5% for voltage and within the frequency range of 49.5 to 50.5 Hz). The standard also requires a gradual reconnection process, typically ramping up output slowly over a few minutes to avoid causing grid instability. Balancing the return-to-service time with grid stability is a critical aspect of designing and implementing smart inverters and DER systems. It ensures that these systems positively contribute to the overall stability and reliability of the power grid, enhancing its safety and performance.

6.1.5 Ramp rates

Ramp rates, both normal and soft-start, play an important role in the operation of DERs and smart inverters when connecting to the power grid (CPUC, 2018); (HEC, 2015). These ramp rates help manage the transition of power output levels, ensuring grid stability and reliability. Normal ramp rates help manage gradual changes in power output during continuous operation. They are designed to facilitate smooth transitions between different power output levels as solar or wind plants vary their generation. These normal ramp rates are crucial for maintaining stable grid operation during steady-state changes in power generation. Soft-start ramp rates, on the other hand, are specifically used when a DER reconnects to the power grid after a disconnection due to a grid disturbance. These ramp rates control the rate of power output increase to prevent sudden surges in power that could destabilise the grid. Different standards and guidelines specify the allowable ramp rates, and they serve distinct purposes in various grid interconnection scenarios. In California, CA Rule21 sets a default soft-start ramp rate of 2% of the maximum current output per second, which can be customised with mutual agreement (EPIC, 2018; Jones-Albertus, 2017). In Hawaii, HE Rule14H specifies a default soft-start ramp rate of 0.33% of the maximum current output per second, also customisable through mutual agreement (John, 2014; HEC, 2015). IEEE 1547:2018 allows for an adjustable ramp rate with a rate of change of active power that cannot exceed the average nameplate power rating of the DER over a specific time frame, typically set at 300 seconds. The German standards, particularly VDE-AR-N 4105, set ramp rates for active power output to prevent sudden changes in generation. For grid-connected DERs, the ramp rate for active power changes is typically limited to 10% of nominal power per minute. Similarly, China's grid code, GB/T 19964-2012, mandates that DERs, particularly large wind and solar farms, limit ramp rates to manage grid stability. Common requirements are a maximum ramp rate of 10% per minute, with more stringent conditions in regions with high renewable energy penetration. SAGCRPP in South Africa mandates rapid restoration to 90% of the active power level within one second. NRS097-2-1, another South African guideline, requires a gradual ramping up of power output from 0% to 100% within 1–10 minutes, increasing by 10% per minute to ensure a controlled reintegration of the DER into the grid (NERSA, 2019); (NERSA, 2017). The choice of ramp rate and its customisation from default values should be made with mutual agreement between the distribution provider and the DER owner, considering the specific grid conditions, the characteristics of the DER systems, and the need to balance stability and reliability.

7 Discussion and future directions

The German power grid stability issue serves as a valuable case study, emphasising the need to consider the systemic impact of DERs, establish proactive regulations, implement coordinated control strategies, seek cost-effective solutions, and strike a balance between regulation and innovation (EPRI, 2016; Döring, 2013; Uphoff & Dirks, 2012). The lessons learned are relevant for regions worldwide as they seek to integrate increasing levels of renewable energy sources and maintain a reliable and stable power grid. While regulations are crucial for ensuring power grid stability, they should also allow for innovation and flexibility. Striking a balance between stringent regulations and enabling technological advancements is essential. Regulations should encourage the development and deployment of smart inverter technology that enhances grid stability without stifling progress. The Germany "50.2 Hertz" incident highlights the significance of adopting a system-level perspective when dealing with a high penetration of DERs. It is crucial to consider the collective behavior of multiple inverters within a distribution network rather than focusing solely on individual inverter compliance. Understanding how these systems interact and their impact on grid stability is vital. The need for coordinated control and communication among smart inverters is evident. Coordinated response mechanisms can help prevent unintended consequences, such as simultaneous disconnections that can lead to grid instability. It emphasises the importance of advanced control strategies that enable inverters to work together harmoniously (EPRI, 2016). Retrofitting existing inverters to accommodate advanced coordination functionality proved to be costly (Döring, 2013; EPRI, 2016; Uphoff & Dirks, 2012). In Australia after the adoption of the new regulation AS/NZS 4777.2:2015 it was identified that as much as 40% of grid-connected inverters installed with rooftop solar PV systems since 2016 may not comply with some of the mandatory settings prescribed in AS/NZS 4777.2:2015 and the relevant distribution network service provider connection agreements. This has caused issues for grid reliability and security that, without rectification, will limit consumers' choice to invest in DER. This highlights the importance of considering interoperability and advanced functionality when selecting and installing new inverters. Investing in technology that can adapt to changing grid conditions can help avoid expensive retrofits in the future. Implementing a centralized control approach using smart inverters with ride-through mechanisms can significantly enhance power grid stability and mitigate issues such as frequency deviations, as exemplified by the "50.2 Hertz" problem (Ding & Baggu, 2018; EPRI, 2021a; Pamshetti & Singh, 2019). Centralised control allows smart inverters to collectively respond to power grid events and address stability concerns that could lead to major blackouts. By coordinating the response of multiple smart inverters, it becomes possible to maintain grid stability even during disturbances, and empowers smart inverters to collectively respond to power grid events, effectively addressing stability concerns that could lead to major blackouts (Ding & Baggu, 2018; Pamshetti & Singh, 2019). Notably, regulations like CA Rule21 and HE Rule14H provide detailed guidelines for reactive and active power setpoints, offering utilities the flexibility to fine-tune and reprogramme these parameters through the IEEE 2030.5 communication protocol. This protocol, established as the standard in California and Hawaii, supports performance monitoring, remote software updates, and the potential for future centralised control of smart inverters. Implementing communication settings akin to IEEE 2030.5 in South Africa could yield similar benefits, enhancing performance monitoring and enabling coordinated control of multiple smart inverters. This framework could ultimately pave the way to a more resilient and stable power grid.

The "duck curve" and "Nessie curve" are concepts that were introduced in California and Hawaii respectively (Jones-Albertus, 2017; John, 2014). They both illustrate the challenges associated with high penetration of DER systems in the power grid (Jones-Albertus, 2017; Roberts, 2016). The duck curve illustrates the challenges of integrating solar power into the grid, with a focus on the dip in demand and the steep ramp-up required for conventional power generators. It gives a graphical representation of the net electricity demand over the course of a day, after accounting for solar power generation showing the difference between total electricity demand and the amount of solar power being generated. The duck curve was first observed in California and is widely used to describe the impact of solar energy on the electricity demand curve throughout the day. In California, the demand was seen to be high in the early morning and late evening when solar generation is low, creating the "head" and "tail" of the duck. As solar generation increases during the day, especially around midday, the net demand for electricity from conventional power generators decreases, forming the "belly" of the duck. In the late afternoon and early evening, solar generation decreases rapidly while demand remains high or even increases, creating the steep "neck" of the duck. This created two challenges in managing DER systems in the power system network. The first was the need to quickly ramp up power production by conventional power generators as a result of the steep increase in demand for non-solar electricity in the evening. This ramp up requirement can be very challenging for traditional thermal power plants. The second challenge was overgeneration risk during midday, where supply from excess solar generation exceeds demand, potentially requiring curtailment of solar power. The "Nessie curve," is an extension or evolution of the duck curve concept, and was adopted by the Hawaii state utility and grid planners. Unlike the duck curve, Hawaii's curve showed enough solar power generation coming into parts of its power grid to start feeding back power in certain distribution circuits on sunny days and driving system-wide demand curves below zero on certain peak days. An additional challenge was introduced in Hawaii due to the reverse power flow causing lots of technical and operational challenges in the power grid.

These curves reflect the net load demand on the utility network over a 24-hour period, taking into account the difference between electricity load demand and PV generation output. Both California and Hawaii have recognised the need to adapt their standards and regulations to address the challenges associated with high PV penetration and ensure power grid stability. This necessitated changes in standards in California and Hawaii reflect the need to adapt regulations to accommodate the evolving energy landscape, enable advanced grid-supportive technologies, and ensure the reliable integration of DERs into the power grid. The efforts were proactive steps to prevent grid instability and the need for costly retrofits, as seen in other regions, like Germany. As the penetration of PV and wind energy rises, coal-fired plants face the need to ramp up quickly, a process that is costly and environmentally detrimental. Deploying multiple smart inverters equipped with normal and soft-start ramp rate functionalities can help alleviate the impacts of DER intermittency and the daily transition between PV and conventional sources. Although smart inverters may not entirely resolve challenges like the duck curve, they can alleviate the strain on conventional power sources, thus promoting a smoother transition towards renewable energy

In summary, adopting flexible and forward-looking smart inverter regulations, along with communication protocols like IEEE 2030.5, can greatly enhance power grid stability, facilitate the integration of DERs, and contribute to a cleaner and more sustainable energy landscape. These measures not only mitigate the adverse effects of variable generation but also foster resilient and adaptive energy systems that are better equipped to handle future challenges.

8 Conclusion

This paper discusses the increasing importance of voltage management in distribution networks due to the proliferation of distributed energy tesources (DERs). It highlights various techniques used to address these challenges, including capacitor banks, on-line tap changers, voltage regulators, and smart PV inverters. Each of these techniques has its own advantages and disadvantages. Capacitor banks are cost-efficient and effective for voltage control. However, they lack flexibility and the ability to handle power flows in both directions, which can potentially lead to power quality issues. While voltage regulators have their benefits, lowering voltage levels can increase current and power losses. Therefore, they should be used judiciously to balance voltage control with energy efficiency. On-load tap changers are a traditional solution but can experience frequent action due to intermittent DERs, which may reduce their lifespan and effectiveness.

The literature emphasises that the choice of technology depends on the specific characteristics of the power system network and the merits of each technique. In the context of managing voltage in distribution systems with DERs, smart PV inverters are recommended for their rapid volt-var control capabilities. They can support reactive power and provide an alternative to relying solely on traditional voltage regulators. The use of smart technologies like smart PV inverters have become increasingly important for efficient voltage management and ensuring secure network operations. This necessitates the need to change the existing power grid codes to accommodate the use of smart technologies, such as smart inverters, to enhance the operation and contribution of DERs. Historically, international standards and power grid codes limited the role of smart inverters in voltage regulation. However, recent standards, such as IEEE 1547–2018 and the Australian standard AS 4777.2:2020, are evolving to allow smart inverters to actively regulate voltage by adjusting reactive and active powers.

Smart inverters offer advanced functionality to address power grid challenges associated with the growth of DERs at both local and regional levels. Mandating existing standards like NRS097 and SAGCRPP to incorporate advanced smart inverter functions can help South Africa avoid the retrofitting costs that other regions faced. It is suggested that using frameworks like CA Rule21 and HE Rule 14H as potential models for South Africa's smart inverter design qualification would help in addressing technical challenges and their financial impact that might be faced as integration of DER levels increase in the power grid. This paper provides valuable resource for power utilities and regulators, providing them with insights to make informed decisions for improving grid-connected DERs and ensuring the safe and secure operation of the grid.

Notes

1. *Category A3: 100 kVA – 1 MVA.* This sub-category includes renewable power plants (RPPs) of Category A with rated power in the range from 100 kVA but less than 1 MVA. In line with the current Renewable Power Plant Grid Code, embedded generators smaller than 1000 kVA connected to low-voltage form part of Category A generators.
   Category B: 1 MVA – 20 MVA. This category includes RPPs with rated power in the range equal or greater than 1 MVA but less 20 MVA.
   Category C: 20 MVA or higher. This category includes RPPs with rated power equal to or greater than 20 MVA.

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References

Albunashee, H. & McCann, R. A., 2019. DER coordination strategy for Volt/VAR control using IEC61850 GOOSE protocol. *51st North American Power Symposium, NAPS 2019*, 13 - 15 October, pp. 0 -4.

AS/NZS 4777.2:2020, 2020. *Grid connection of energy systems via inverters, Part 2: Inverter requirements,* s.l.: SA/SNZ .

Basso, T., 2014. *IEEE 1547 and 2030 Standards for Distributed Energy Resources Interconnection and Interoperability with the Electricity Grid,* USA: NREL/TP-5D00-63157.

Berdner, J., 2015. *Advanced Inverter Status, CA & HI,* USA: NREL.

Calitz, J. & Wright, J., 2021. *Statistics of utility-scale power generation in South Africa in 2020,* South Africa: http://hdl.handle.net/10204/11865.

Capitanescu, F., Ochoa, L. F., Margossian, H. & Hatziargyriou, N. D., 2014. Assessing the potential of network reconfiguration to improve distributed generation hosting capacity in active distribution systems. *IEEE Transactions on Power Systems,* 3(1), pp. 346 - 356.

CEI 0-16, 2019. *Reference technical rules for the connection of active and passive consumers to the HV and MV electrical networks of distribution Company,* Italiano: CEI - Comitato Elettrotecnico.

CEI 0-21, 2019. *Reference technical rules for the connection of active and passive users to the LV electrical Utilities.,* Italiano: CEI - Comitato Elettrotecnico.

China National standard GB/T 19964-2012, 2012. *Technical requirements for connecting photovoltaic power station to power system,* s.l.: China Electricity Council.

CPUC, 2018. *Rule No. 21: Generating Facility Interconnections,* California, USA: California Public Utilities Commission.

Ding, F. & Baggu, M., 2018. *Coordinated Use of Smart Inverters with Legacy Voltage Regulating Devices in 675 Distribution Systems with High Distributed PV Penetration — Increase CVR Energy Savings.* IEEE Transactions on Smart Grid, https://doi.org/10.1109/tsg.2018.2857410.

Döring, M., 2013. *Dealing with the 50.2 Hz problem.* [Online] Available at: https://www.modernpowersystems.com /features/featuredealing-withthe-50.2-hz-problem/ [Accessed 16 July 2023].

ENTSO-E, 2013. *Requirements for Grid Connection Applicable to all Generators,* Brussels, Belgium: European Network of Transmission System Operators for Electricity.

EPIC, 2018. *EPIC 2.03A: Test Smart Inverter Enhanced Capabilities – Photovoltaics (PV): Smart Inverter Modeling Report.* [Online] Available at: https://www.pge.com/assets/pge/docs/vanities/PGE-EPIC-Project-2.03a.pdf?vnt=epicinterim report-SmartInverters [Accessed 16 July 2023].

EPRI, 2016. *Advanced grid support functions for smart inverters: toward a unified regulatory framework in Europe,* California, USA: EPRI.

EPRI, 2021a. *Coordinated Voltage Regulator and Smart Inverter Settings with High Levels of DER,* California, USA: EPRI.

EPRI, 2021b. *System Design Practices with Penetration of DER: DER Impact on Feeder Voltage Regulation Design,* California, USA: EPRI.

Ferris, N., 2023. *Weekly data: South Africa's unprecedented rooftop solar boom.* [Online] Available at: https://www.energy monitor.ai/tech/renewables/weekly-data-south-africas-unprecedented-rooftop-solar-boom/?cf-view [Accessed 09 08 2024].

Gandoman, F. et al., 2018. Review of FACTS technologies and applications for power quality in smart grids with renewable energy systems. *Renewable and Sustainable Energy Reviews,* Volume 82, pp. 502 - 514.

HEC, 2015. *Rule No. 14H: Interconnection of Distributed Generating Facilities with the Company's Distribution System,* Hawaii, USA: Hawaiian Electric Company.

Horowitz, K. A. et al., 2020. Techno-economic comparison of traditional upgrades, volt-var controls, and coordinated distributed energy resource management systems for integration of distributed photovoltaic resources. *International Journal of Electrical Power & Energy Systems,* Volume 123, p. 106222.

Horowitz, K. A. et al., 2019. *An overview of distributed energy resource (DER) interconnection: Current practices and emerging solutions,* California, USA: NREL Technical Report.

IEC, 2004. *Photovoltaic (PV) systems – Characteristics of the utility interface,* s.l.: IEC - International Electrotechnical Commission.

IEEE, 2018. *IEEE Std 1547-2018: IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power System Interfaces,* : The Institute of Electrical and Electronics Engineers, Inc..

John, J. S., 2014. *Hawaii's Solar-Grid Landscape and the 'Nessie Curve'*. [Online] Available at: https://www.greentechmedia .com/articles/read/hawaiis-solar-gridlandscape-and-the-nessie-curve. [Accessed 16 July 2023].

Jones-Albertus, B., 2017. *Confronting the Duck Curve: How to Address Over-Generation of Solar Energy.* [Online] Available at: https://www.energy.gov/eere/articles/ confronting-duck-curve-705 howaddress-overgeneratio n-solar-energy.
[Accessed 17 July 2023].

Kikusato, H., Takahashi, N. & Yoshinaga, J., 2014. Method for instantly determining line drop compensator parameters of low-voltage regulator using multiple classifiers.. *IEEE PES Innovative Smart Grid Technologies Conference Europe*, 12 - 15 Oct, pp. 1-6.

Kitchenham, B. & Charters, S., 2007. *Guidelines for performing systematic literature reviews in software engineering,* Keele University and Durham University Joint Report: Technical Report EBSE 2007-001.

Li, C., Disfani, V. R., Haghi, H. V. & Kleissl, J., 2020. Coordination of OLTC and smart inverters for optimal voltage regulation of unbalanced distribution networks. *Electric Power Systems Research,* Volume 187, p. 106498.

Li, C., Jin, C. & Sharma, R., 2019. Coordination of PV smart inverters using deep reinforcement learning for grid voltage regulation. *2019 18th IEEE International Conference On Machine Learning And Applications (ICMLA)*, 16 - 19 Dec, pp. 1930-1937.

Liu, X., Aichhorn, A., Liu, L. & Li, H., 2012. Coordinated control of distributed energy storage system with tap changer transformers for voltage rise mitigation under high photovoltaic penetration. *IEEE Transactions on Smart Grid,* 3(2), pp. 897-906.

Lopes, J. A. P. et al., 2007. Integrating distributed generation into electric power systems: A review of drivers, challenges and opportunities. *Electric Power Systems Research,* Volume 77, p. 1189–1203.

Mackenzie, W., 2024. *Africa solar PV market outlook 2024.* [Online] Available at: https://www.woodmac.com/reports/power-markets-africa-solar-pv-market-outlook-2024-150293562/ [Accessed 09 08 2024].

Martins, J., Gomes, V. & T, M., 2018. On the use of IEC 61850-90-7 for smart inverters integration. *9th International Conference on Intelligent Systems 2018*, 25 - 27 September, pp. 722-726.

Mather, B., 2014. *NREL/SCE High-Penetration PV Integration Project: Report o Field Demonstration of Advanced Inverter Functionality in Fontana,* California, USA: National Renewable Energy Laboratory (NREL).

Muttaqi, K. & Negnevitsky, M., 2015. A coordinated voltage control approach for coordination of OLTC, voltage regulator, and DG to regulate voltage in a distribution feeder. *IEEE Transactions on Industry Applications,* 51(2), pp. 1239-1248.

NERSA, 2017. *NRS 097-2-1: 2017 Small-scale embedded generation Section 1: Utility Interface,* South Africa: Eskom.

NERSA, 2019. *Grid Connection for Renewable Power Plants (RPPs) connected to the Electricity Transmission System (TS) or Distribution System (DS) in South Africa: Version 3.0,* South Africa: Eskom.

NREL, 2014. *Advanced Inverter Functions To Support High Levels Of Distributed Solar,* California, USA: National Renewable Energy Laboratory (NREL).

Owusu-Mante, S., 2020. *South Africa's 2019 IRP renewable energy targets.* [Online] Available at: https://www.climate policylab.org/communityvoices/2020/5/13/south-africas-2019-irp-renewable-energy-targets [Accessed 20 July 2023].

Pamshetti, V. B. & Singh, S. P., 2019. Optimal coordination of PV smart inverter and traditional volt-VAR control devices for energy cost savings and voltage regulation. *International Transactions on Electrical Energy Systems,* 29(7), pp. https://doi.org/10.1002/2050-7038.12042.

Rashid, M. & Knight, A. M., 2020. Combining volt/var volt/watt modes to increase pv hosting capacity in LV distribution networks. *2020 IEEE Electric Power and Energy Conference, EPEC2020*, 9 - 10 Nov, pp. 1 - 5.

REN21, 2020. *Renewables 2020 Global Status Report,* Paris, France: REN21 Secretariat.

Reno, M. J. & Broderick, R. J., 2015. *Technical evaluation of the 15% of peak load PV interconnection screen.* Los Angeles, USA, 2015 IEEE 42nd Photovoltaic Specialist Conference (PVSC).

Rezaeian-Marjani, S., Galvani, S., Talavat, V. & Farhadi-Kangarlu, M., 2020. Optimal allocation of D-STATCOM in distribution networks including correlated renewable energy sources. *International Journal of Electrical Power & Energy Systems,* 122( ), p. 106178.

Roberts, D., 2016. *Why the 'duck curve' created by solar power is a problem for utilities.* [Online] Available at: https://www.vox.com/2016/2/10/10960848/solar-energy-duck-curve [Accessed 16 July 2023].

Sadan, N. & Renz, B., 2020. New DER Communications Platform Enables DERMS and Conforms with IEEE 1547–2018 Requirements. *In Proceedings of the 2020 IEEE/PES Transmission and Distribution Conference and Exposition (T&D)*, Chicago, IL, US, 12 - 15 October, pp. 1 - 5.

Sayed, M. A. & Takeshita, T., 2010. All nodes voltage regulation and line loss minimization in loop distribution systems using UPFC. *IEEE Transactions on Power Electronics,* 26(6), pp. 1694-1703.

Takram, M. A., Hwang, I. C. & Ha, S., 2020. Architectural advancement of digital low-dropout regulators. *IEEE Access,* 8( ), p. 137838–137855.

Torres, J. et al., 2014. Low drop-out voltage regulators: Capacitor-less architecture comparison. *IEEE Circuits and Systems Magazine,* 14(2), pp. 6 - 26.

UL, 2016. *The rise of smart inverters: building the 21st century electrical grid.* [Online] Available at: https://www.ul.com /news/rise-smart-inverters-building-21st-century-electrical-grid [Accessed 16 July 2023].

Uphoff, V. & Dirks, H., 2012. 50.2 Hz modification also applies to existing facilities. *Sun and Wind Energy,* Volume 2, pp. 86 - 91.

Ustun, T. S., Aoto, Y., Hashimoto, J. & K, O., 2020. Optimal PV-INV capacity ratio for residential smart inverters operating under different control modes. *IEEE Access,* Volume 8, pp. 116078-116089.

Ustun, T. S., Hashimoto, J. & Otani, K., 2019. Impact of smart inverters on feeder hosting capacity of distribution networks. *IEEE Access,* Volume 7, pp. 163526-163536.

Varma, R. & Singh, V., 2020. Review of studies and operational experiences of PV hosting capacity improvement by smart inverters. *2020 IEEE Electric Power and Energy Conference (EPEC2020)*, 9 - 10 Nov, pp. 1-6.

VDE-AR, 2018 No. 4105. *Power generation systems connected to the low-voltage distribution network-Technical minimum requirements for the connection to and parallel operation with low-voltage distribution networks,* VDE-AR: Informationstechnik, VDE Verband der Elektrotechnik Elektronik. eV.

Wang, Y., Tan, K., Peng, X. Y. & So, P. L., 2015. Coordinated control of distributed energy-storage systems for voltage regulation in distribution networks. *IEEE transactions on power delivery,* 31(3), pp. 1132-1141.

Xavier, R., Bekker, B. & J, C. M., 2021. *Smart inverters in LV networks: A review of International Codes and Standards and Opportunities for South Africa.* Potchefstroom, South Africa, 2021 Southern African Universities Power Engineering Conference/Robotics and Mechatronics/Pattern Recognition Association of South Africa (SAUPEC/RobMech/PRASA).

Xue, Y. & Guerrero, J. M., 2015. Smart inverters for utility and industry applications. *International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management*, 19 - 20 May, pp. 1-8.

Yan, R., Marais, B. & Saha, T. K., 2014. Impacts of residential photovoltaic power fluctuation on on-load tap changer operation and a solution using DSTATCOM. *Electric Power Systems Research,* Volume 111, pp. 185 - 193.

Zeraati, M., Golshan, M. E. H. & Guerrero, J. M., 2016. Distributed control of battery energy storage systems for voltage regulation in distribution networks with high PV penetration. *IEEE Transactions on Smart Grid,* 9(4), pp. 3582-3593.