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Cause and effect of overvoltage on the LV network

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Abstract

Research at the Australian Power Quality & Reliability Centre has identified sustained overvoltage to be a common phenomenon with serious impacts on a range of components connected to the electricity supply network. Whilst there are many causes for the issue it has been determined that the continued proliferation of distributed energy resources like small scale PV solar systems, may have considerable influence on the network's voltage. This paper investigates the reasons behind the continued increase in voltage levels and the impact it is having on connected devices. Research and experimental work has been carried out to quantify these effects showing that overvoltage scenarios can be detrimental to equipment lifetimes. The components of interest presented here are AC motors and Switch Mode Power Supplies. Suggestions to further revise the allowable voltage range in Australian low voltage distribution networks are also presented in the interests of mitigating the stress placed on components.

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Cause and Effect of Overvoltage on the LV Network

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***Abstract*—Research at the Australian Power Quality & Reliability Centre has identified sustained overvoltage to be a common phenomenon with serious impacts on a range of components connected to the electricity supply network. Whilst there are many causes for the issue it has been determined that the continued proliferation of distributed energy resources like small scale PV solar systems, may have considerable influence on the network's voltage. This paper investigates the reasons behind the continued increase in voltage levels and the impact it is having on connected devices. Research and experimental work has been carried out to quantify these effects showing that overvoltage scenarios can be detrimental to equipment lifetimes. The components of interest presented here are AC motors and Switch Mode Power Supplies. Suggestions to further revise the allowable voltage range in Australian low voltage distribution networks are also presented in the interests of mitigating the stress placed on components.**

***Index Terms*— AC Motors, Power Quality, PV Solar Inverters, Switch Mode Power Supplies (SMPS), Sustained Overvoltage**

I. Introduction

In Australia, the ideal voltage waveform is a 230 V_{RMS} sinusoidal wave at 50 Hz. Energy Distribution Network Service Providers (DNSPs) are required to maintain this waveform within an acceptable range of +10%, -6% of the nominal V_{RMS} value, allowing for a range of $216 < V_{RMS} < 253$ [1]. Although it is well understood that sustained overvoltage is likely to have an adverse effect on connected components, there has been little research that attempts to quantify the impact of increased component aging due to degradation. This project investigates the long-term effects that sustained overvoltage scenarios are likely to have on a range of connected equipment.

Industrial and consumer devices that rely on the distribution network for power have been designed to operate within designated voltage levels and tend to allow for some variation in input supply characteristics. It is common for consumer devices to have an operating voltage range of 110 – 240 V 50/60 Hz. This allows for equipment to operate in most countries without the need for redesign due to specific country standards. Operating outside of these values can result in unexpected behavior including brown outs due to undervoltage, or premature wear due to overvoltage.

Whilst the causes of sustained overvoltage can vary, the likelihood of equipment being exposed to sustained overvoltage is becoming more likely due to the increased implementation of Distributed Energy Resource (DER) plants, namely PV solar systems. PV inverters are a known cause of overvoltage and this is being exacerbated by the number of systems operating on local networks [2]. The impacts of sustained overvoltage on equipment can be varied, however, network components as well as consumer devices operating at higher voltage levels are likely to experience accelerated lifetimes, resulting in a definite financial impact on customers and DNSPs.

II. Overvoltage Due To Solar Inverters

Solar PV systems have experienced continued popularity in recent years. This can be attributed to an increase in social awareness regarding renewable energy, governmental support, rising costs of electricity and reduced costs for solar systems [3]-[4]. Regardless of the reasons why, the popularity boom has led to some difficulties for DNSPs in network balancing and voltage regulation [2]. The inherent operating characteristics of the small-scale PV generators installed in residential installations are such that the voltage at the inverter terminals will be higher than the incoming supply voltage. The difference between the voltage at the inverter terminals and the supply voltage is a function of the impedance of the circuit to which the inverter is connected. However, if the supply voltage is already at the upper end of the allowable voltage range, inverters will only compound the issue. There are concerns that continued rates of PV penetration are likely to maintain increased network voltage levels, potentially damaging network components [5]. It is also well understood that higher voltage levels can have significant impacts on consumer devices also [6]. Whilst the study in [6] investigates the effect of short term overvoltage, there is a significant lack of understanding regarding the increased ageing effect that sustained overvoltage has on such devices. This is explored further in Section III.

A. Model Simulation

In order to determine the level of influence a solar system may have on a network, a PSCAD model was created to simulate the Point of Common Coupling (PCC) between a small-scale system and the LV distribution transformer (Figure 1). This circuit has been adapted from a model supplied by Manitoba HVDC staff [7]. The inverter model is a 3-phase system with a solar array module and MPPT tracking. The nominal output of the system is 230 $V_{RMS\ L-N}$.

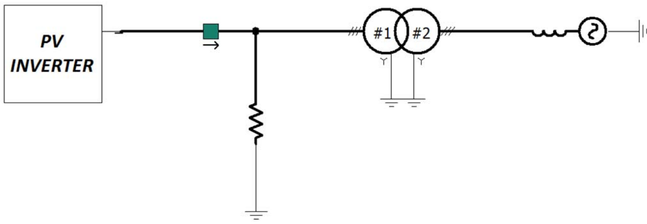

Figure 1. Computer Simulation Circuit

The model analyses the RMS voltage at the PCC between a LV grid connected PV inverter and the transformer. The model operates under normal conditions until $t = 7\ s$ at which point the inverter's breaker is activated, effectively taking the inverter offline. At this point in time, the resistive load is now supplied directly by the transformer. Inspection of Figure 2 at $t = 7\ s$ shows a clear drop in the RMS voltage. An approximate reduction of 12 V is seen at the PCC.

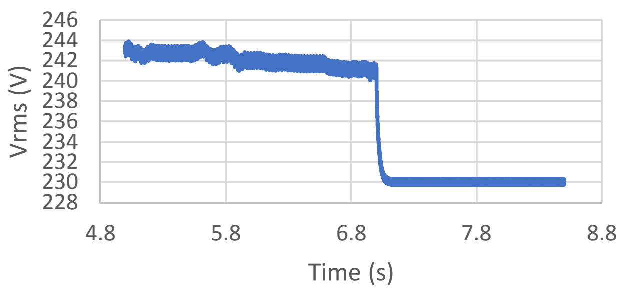

Figure 2. Simulation Results, Impact on V_{RMS} due to Inverter

The argument can be made that the increase in V_{RMS} remains inside the allowable operating range (<253 V) however it should be considered that this is a simple model only to ascertain whether a voltage rise is likely to occur due to the presence of a PV inverter system. The outcome presented in Figure 2 suggested that laboratory work was required to confirm the validity of the simulation.

B. *Laboratory Measurements*

To confirm the results of the model simulation, experimentation was performed in a laboratory environment. The circuit in Figure 1 was recreated in the laboratory, omitting the transformer. In its place was an arbitrary waveform generator supplying 230 V, representing the ideal voltage waveform seen at an LV power outlet.

A 2kW resistive load was first powered solely by the waveform generator. Two inverters were separately connected to determine the level of impact they had on the RMS voltage. The results of this are shown in Figure 3.

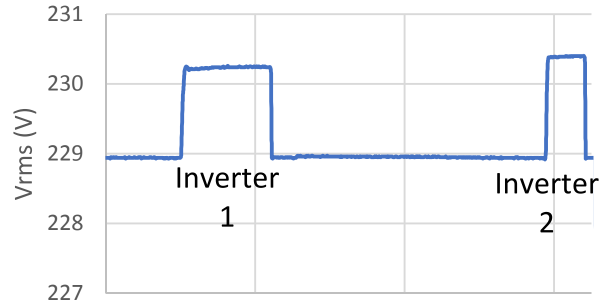

Figure 3. Inverter impact on RMS Voltage

This result shows a clear step increase in V_{RMS} due to the presence of the PV inverter. Much like the computer simulation results, the voltage rise remains well within the limits of an allowable working voltage. However, considering the test circuit represents an ideal, controlled scenario. This testing confirms the results of the computer simulation, suggesting that PV inverters can be expected to have an impact on RMS voltage levels.

C. *Grid Connected System Measurements*

To further investigate the impact of PV inverters on the supply voltage at an installation, o, measurements were taken at the Sustainable Buildings Research Centre (SBRC) at the University of Wollongong (UOW). The PV system inspected for this study is rated at 120 kWp and includes 6x 20 kW inverters. Figure 4 shows the V_{RMS} of the SBRC measured at the PCC of the 6 inverters supplying power from the PV inverter system. This measurement is recorded every 15 minutes and Figure 4 displays this data for the day April 6, 2017.

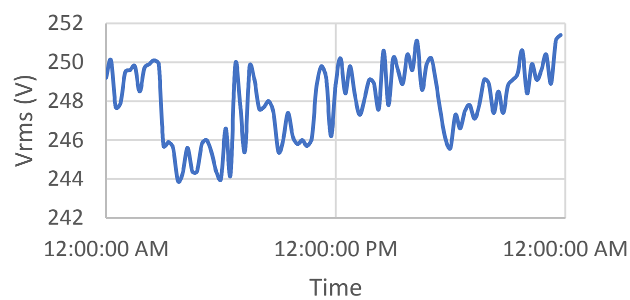

Figure 4. SBRC V_{RMS}, 24-hour period

Inspection of Figure 4 shows instantly that the SBRC is operating at any given time throughout the day no less than 6% above the nominal RMS voltage. Furthermore, there is ongoing fluctuations in the voltage across the entire 24 hours displayed. Further analysis is needed to be performed to determine whether the inverters are having a significant impact on the RMS voltage.

To do this, an average RMS value was taken over three random days throughout 2017. Each day was split into three sections;

- Pre-sunrise
- Day Time

- Post-sunset

Breaking the day up into 3 periods allows comparison of the RMS voltage when the inverters are injecting power into the grid and when they are on standby, the results are presented in Table I.

Table I. Average RMS Values

Section	Day 1 (January 27)	Day 2 (April 6)	Day 3 (May 8)
Pre-sunrise	245.6	247.0	248.0
Day Time	249.0	248.1	248.0
Post-Sunset	248.3	248.7	246.4

The results display a clear increase of V_{RMS} from morning to day time. There appears to be less of a difference when comparing day time to night. This can be due to a myriad of reasons, including network operations or customer loads, for example.

D. Analysis of Results

It can be seen through the computer simulation, laboratory results and implemented system measurements shown above that regulation of the distribution voltage levels can be made more difficult by the presence of PV inverters. The testing undertaken in this paper is of a small scale only to outline the effects that PV systems are likely to have on voltage regulation. Based on the common size of systems and line impedances, the overvoltage impact is most likely to be noticed within the installation locality rather than further along the distribution network.

Whilst the computer simulation provided sufficient evidence to perform laboratory work and further measurements, the increase of 12 V was not a realistic change compared to the results found in a controlled environment. The voltage changes observed for the laboratory measurements were minute in comparison, however, a clear step in V_{RMS} can be seen. Comparing to the measurements taken at the SBRC which operates at an increased voltage throughout the day, it is unclear from this study whether this is due to the presence of renewable generation or network operation. Further investigation needs to be performed to ascertain this, however the results presented in Table I suggest that there is a likelihood that the solar system influences the voltage level when injecting power into the network.

E. Impact

The impact that these results may have can be localised or widespread. For example, multiple inverters operating across a network may increase the number of tap changes required to maintain an acceptable voltage level. This can be influenced by the amount of renewable penetration online and weather events [8].

A localised effect of overvoltage may be increased aging of consumer devices. Components are likely designed to account for a limited amount of voltage variation, depending on the device's purpose and susceptibility to over/under voltage. Whilst a device may be able to withstand an elevated operating voltage, the design may only allow this for a short amount of time. What may occur is that certain components of the device may start to prematurely wear and increase the devices rate of degradation. This phenomenon will be explored further in section III.

F. Mitigation Techniques

Some previous works have suggested limitations be placed on the number of renewables that are able to be placed on any given feeder. The simulation presented in [9] suggests that an excess of 30 % renewable penetration could lead to voltage rises above the acceptable threshold. The project also outlines the use of battery storage or reactive power control could assist in maintaining a safe operating voltage. Another project suggests renewable plants to operate below the Maximum Power Point (MPP) to mitigate the effects of voltage rise [10].

Intuitively, it may be expected that network operators are responsible for the regulation of the voltage level, however, the continued uptake of renewable systems is making this task more difficult impacting both customer and network equipment. A holistic approach to the issue of voltage rise will see the most beneficial outcome across the network.

III. Effects of Sustained Overvoltage

The effects of overvoltage on equipment can vary quite dramatically depending on the conditions and the device under consideration. Research has been carried out previously to determine the impact that severe overvoltage may have on everyday household items. The study presented in [6], whilst interesting, imposed some scenarios that are very unlikely to occur on the supply network, $V_{RMS} > 20$ % of ideal. This work only focused on the immediate effects of short term overvoltage experienced by the test devices without considering the increased degradation rate due to sustained overvoltage scenarios.

To better understand the impacts of accelerated degradation, testing has been carried out at the Australian Power Quality & Reliability Centre (APQRC) in an attempt to quantify the effect that overvoltage has on customer equipment. Two case studies are presented below.

A. Case Study 1 - Switch Mode Power Supplies

Through an in-depth research project, it was found that sustained overvoltage is likely to have significant impact on Switch Mode Power Supplies (SMPS). SMPS are common devices that power electronic devices and can be found in use throughout many industries and households. The most common failure mode of these devices is the failure of the Electrolytic Capacitors (EC) [11]. An examination of the most common designs of SMPS found that a significant number of these devices are connected to the network through a bridge rectifier paired with an LC filter, using an EC. The rectifier-LC filter combination uses the sinusoidal voltage waveform to supply the subsequent circuitry with a near-DC voltage waveform, Figure 5.

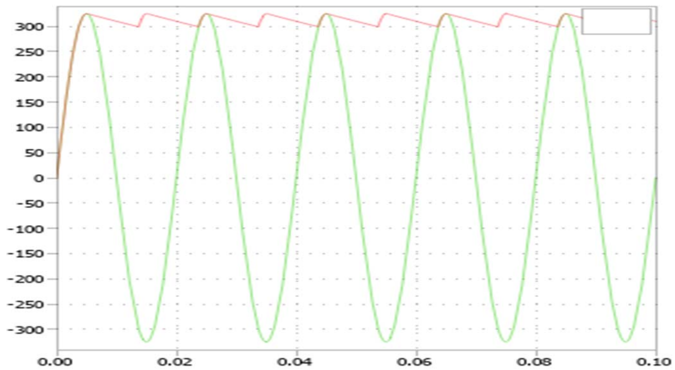

Figure 5. Supply and output waveform of rectifier-LC filter combination

Where V_{in} (Green) is the voltage applied to the overall system and V_c (Red) is the voltage waveform across the filter capacitor that supplies the rest of the SMPS system, shows the expected output of a bridge rectifier with an LC filter.

Given the fact that most SMPS design have similar front-end topology, a test device was then designed to place focus on the EC and expose it to different voltage levels to determine if there was a relationship between the operating voltage and the rate of degradation. To do this within a reasonable timeframe, the capacitors were exposed to an elevated operating temperature. This uniformly increases the rate of degradation by influencing the electrolytic evaporation process that occurs over a long period of time within the component [11].

ECs can be represented as the equivalent circuit shown in Figure 6. This can be further simplified by removing the Equivalent Series Inductance (ESL) as it is generally not of significant value compared to the Equivalent Series Resistance (ESR) [12].

Figure 6. Electrolytic Capacitor Equivalent Circuit [13]

As capacitors degrade, the ESR increases and the capacitance decreases. A failed capacitor can be said to have failed once $ESR = 2.8 \times ESR_0$ or the ESR has increased to 2.8 times the original values [13].

Throughout experimentation the capacitors were placed at an increased operating temperature of 160 °C. Different voltage levels ($230 < V_{RMS} < 270$) were applied to the system and the experiment was left to run. At 24-hour intervals the capacitors were returned to room temperature and their ESR measured and compared to the original value. This was repeated until a significant number of capacitors had failed or a clear degradation trend had been recognised.

B. Results

To accurately quantify the impact that voltage magnitude has on the degradation rate, Product Lifecycle Management (PLM) software was used. This is software that, among other uses, assists in determining the failure rate and models of Accelerated Life Tests (ALT). The PLM software was used to determine the acceleration factor that the voltage level has on the expected Time To Failure (TTF), shown in Figure 7.

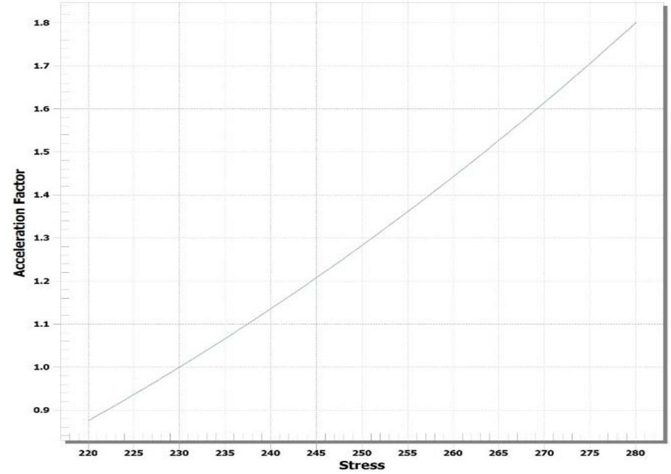

Figure 7. Acceleration Factor Due to Voltage Level

Figure 7 suggests that an SMPS designed for 230 V operating at 250 V, an increase of 8.7 % and inside the allowable supply range as per [1], will experience an acceleration factor of almost 1.3. For example, a system that has an expected lifetime of 10,000 hours, is likely to lose more than 2,000 hours of operating time due to the elevated operating voltage. Perhaps this result may be of little importance for small or relatively inexpensive equipment, however, there are a vast number of common devices that are powered by SMPS and premature failures can quickly become a significant financial burden if the cause is left untreated.

This result should be seriously considered as front-end LC filters are used in more than just SMPS systems. Most PV inverters supply power to the grid through the use of filters using ECs also [14]. This assists in filtering out high frequency transients on the voltage and current waveform.

As mentioned above, there continues to be significant additions of renewable energy systems being implemented both nationally and internationally. These systems are likely to increase the voltage level on the network and further work needs to be completed to determine the effect this may have on a wide range of common inverter systems.

C. Case study 2 - AC Motors

Case study 2 relates to the effects of overvoltage on AC induction motor operating temperature. Motors are used throughout the industrial, commercial and residential sectors. To gain a comprehensive understanding, three motors were tested for their response to overvoltage scenarios.

1) Single Phase Motors

Single phase motors can be found commonly in residential and commercial applications. Devices that commonly use single phase motors are desktop and ceiling fans, automatic garage doors, washing machines and so on.

Two desktop fans were tested in this experiment across a range of operating voltages ($200 < V_{RMS} < 260$). The fan speed was measured using a tachometer, motor winding temperatures were monitored using a thermocouple attached to the stator of the motor and power consumption was measured using a PQ monitoring device. Figure 8 displays the stator winding temperature measured for each fan for each input voltage level. A clear increase in temperature is observed as voltage increases. The relationship appears to be relatively linear. It was also noticed that the power consumed and fan speed increased linearly in response to the voltage increase.

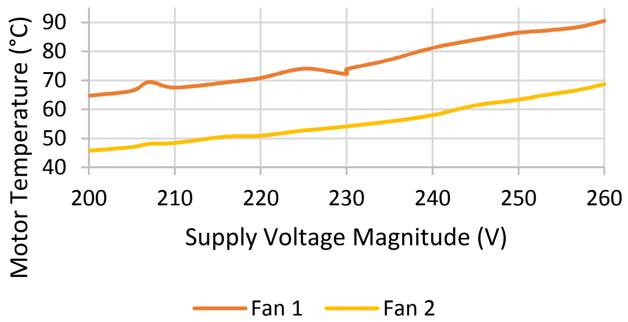

Figure 8. Temperature rise due to voltage magnitude

2) Three Phase Motors

The second test performed on AC motors was exposing a three-phase motor to increased winding voltages. The test device was a 5.5 kW, 415 $V_{RMS\ L-L}$ three-phase motor. The output shaft was attached to a 7.5 kW DC generator connected to a high-power resistor bank providing a 5.5 kW load for the motor. Once again, motor temperature was measured using thermocouples attached to the motor stator winding. The motor stator winding temperature for each applied voltage level is shown in Figure 9.

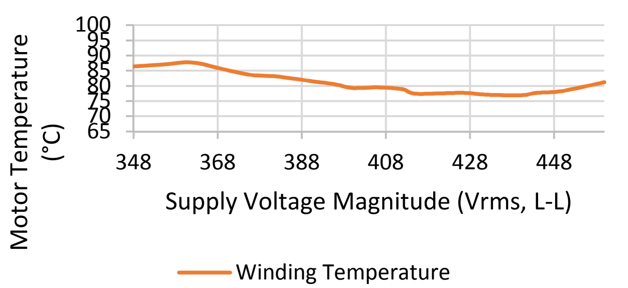

Figure 9. Temperature rise in three phase-motor

Interestingly, Figure 9 shows that the three-phase motor has a different response to overvoltage than the single-phase counterpart. Temperature rises are experienced at both under and overvoltage. The maximum temperature, 87.7 °C, is seen when $V_{supply} = 0.905V_{nominal}$ and the minimum temperature, 76.9 °C, is seen when $V_{supply} = 1.01V_{nominal}$ where $V_{nominal} = 400\ V_{RMS\ L-L}$. As the motor is rated higher than the nominal network line to line voltage, it can be expected to operate more efficiently at the 415 V magnitude. A noticeable positive gradient in temperature can be observed as the voltage continues to increase however. Figure 10 displays the effect that voltage magnitude has on the output power and efficiency of the motor. The curve shape of efficiency loosely resembles an inverse of the temperature profile seen in Figure 9. This could be expected as temperature increases occur as a result of inefficiencies in a motor.

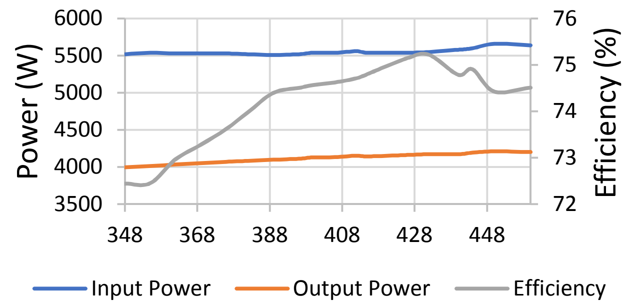

Figure 10. Power and efficiency of three phase-motor

D. Analysis

The effect of overvoltage on AC motors appears to be varied. The single-phase motors presented a linear increase in temperature, output speed and power consumption. The three-phase motor under test experienced a non-linear response to the voltage variation. It should be considered that the motor is rated to 415 $V_{RMS\ L-L}$ and the temperature did increase at the higher voltage range. Motor efficiency was also dependent on the magnitude of voltage and found that this decreased once V_{supply} became greater than 8 % of nominal.

IV. Future Work

Whilst the work completed for this paper focusses on an important area of power quality, sustained overvoltage, the results are only preliminary indicators of the potential impact it may have on the supply network and connected devices as a whole. Further work is required to fully understand the severity of the impact that this disturbance is likely to have. There is a possibility that some devices, designs or components are better equipped to deal with sustained overvoltage scenarios than others.

Of particular importance however, is the effect of sustained overvoltage on common solar inverters. As these devices continue to be connected to the distribution network in increasing numbers, a deep understanding of how they affect and are being effected by the supplied power quality is required. The same can be said for battery inverters which are a similar device to the solar inverter. Work also needs to be completed to confidently determine the impact on an inverter of other PQ disturbances such as voltage transients and harmonics.

Regarding the AC motors that have been tested, insulation derating starts to occur once the motor windings reach a certain temperature. This can have a detrimental impact on the lifetime of the motor, resulting in significant financial burden, particularly in the industrial sector. Impacts across all sectors suggest that a tighter regulation of allowable voltage levels is required. The deviation of voltage magnitude from ideal impacts not just the customer but the network also. These effects may not be noticed instantly however the long-lasting effects could be severe.

V. Conclusion

Voltage disturbances can take many forms, each with varying impacts on the supply network and the connected devices. Overvoltage scenarios are commonplace on the LV network and have been seen to be influenced by the continued support for renewable energy generation.

It can be suggested based on the results shown in Section II that the increased uptake of small scale PV solar systems have influenced the voltage levels on the LV network. Whilst the cases presented in Section II could be considered to have a relatively small impact, the systems are only indicative of a larger and more prominent system spread across entire regions, each likely to contain numerous DER plants operating at different levels, impacting the network hardware attempting to maintain a safe working voltage. The effects of sustained overvoltage can be widespread and varied. Whilst further work needs to be completed to better understand the complete effect this disturbance is likely to have, the results shown in Section III indicate that if an overvoltage scenario is left untreated, financial burdens could be unduly placed on customers within the residential, commercial and industrial fields. A tighter regulation of the voltage levels could be beneficial for both the customer and distribution companies; however, further research must be performed to attain a cost-benefit analysis of this action.

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