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Summary of the economic impacts of power quality on consumers

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Abstract

The quality of the electrical supply has a direct impact on the correct function and operation of equipment connected to the public electricity supply network. There is an expectation that devices will operate as designed and that equipment lifetime should, statistically, be close to the designed value. The reliability of the network is generally assumed to be high enough so as to not cause unacceptable issues with regard to loss of production or loss of functionality. Quantifying the cost to the consumer when the supply power quality or reliability are not as expected is an important metric and can be used as business case to justify expenditure in order to improve the supply network. This paper explores the research associated with quantifying the cost of reliability and power quality. Several power quality disturbances are investigated and possible methods of quantifying both the effect and cost are presented. Due to the complex nature of equipment performance with regard to power quality, there is a need for extensive research in order to develop a generalised approach to lifetime and cost evaluation.

Keywords

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Summary of the Economic Impacts of Power Quality on Consumers

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***Abstract*— The quality of the electrical supply has a direct impact on the correct function and operation of equipment connected to the public electricity supply network. There is an expectation that devices will operate as designed and that equipment lifetime should, statistically, be close to the designed value. The reliability of the network is generally assumed to be high enough so as to not cause unacceptable issues with regard to loss of production or loss of functionality. Quantifying the cost to the consumer when the supply power quality or reliability are not as expected is an important metric and can be used as business case to justify expenditure in order to improve the supply network. This paper explores the research associated with quantifying the cost of reliability and power quality. Several power quality disturbances are investigated and possible methods of quantifying both the effect and cost are presented. Due to the complex nature of equipment performance with regard to power quality, there is a need for extensive research in order to develop a generalised approach to lifetime and cost evaluation.**

***Index Terms*—Power Quality, Power system economics, Quality of Service, Sags, Unbalance**

INTRODUCTION

Unlike reliability which deals with extended loss of supply where the impact is immediate and obvious, the impact of power quality (PQ) disturbances may not be immediately obvious. In addition, there are well structured regulatory incentives and penalties for reliability while there are few regulatory frameworks for PQ. For PQ, while limits may be regulated, there are generally no incentives and/or penalties for exceedance of these limits save for the possibility that an electricity supplier may be in breach of their licence conditions if PQ levels are not maintained within limits. As an example, the service target performance incentive scheme (STPIS) [1] framework in use in Victoria, Australia, contains a section related to quality of supply (Section 4). However, the framework states that "*No quality of supply parameters are currently specified for inclusion in the scheme.*"

The economic impacts due to PQ disturbances are wide and varied. In some cases the impact of the PQ disturbance is immediately obvious through equipment damage and/or loss of process. This is particularly the case for sags, interruptions and transients. In other cases, the impact of the PQ disturbance may only manifest over time. An example of this is the ageing of equipment. In this case, equipment deterioration may not be observed for some years if at all. In other cases, PQ disturbances will lead to additional losses which just become part of the everyday costs of doing business and are not considered further.

In [2] the authors state that the costs attributed to PQ can be broken down into direct and indirect costs. The various cost parameters detailed are very similar to those given in [3] and are as follows:

Direct economic impacts

- Loss of production
- Unrecoverable downtime and resources
- Process restart costs
- Spoilage of semi-finished production
- Equipment damage
- Direct costs associated with human health and safety
- Financial penalties incurred through non-fulfilment of contracts
- Environmental financial penalties
- Utility costs associated with the interruption

Indirect economic impacts

- The costs to an organisation of revenue/income being postponed
- The financial cost of loss of market share
- The cost of restoring brand equity

Social economic impacts

- Uncomfortable building temperatures which may reduce efficiency, health or safety
- Personal injury or fear
- Possible need to evacuate nearby buildings as a result of a failure of industrial safety

Most of the literature which can be cited concerning the economic impact of PQ disturbances indicates that the costs associated with PQ can be very large. In [3] the authors claim that a number of studies have been examined in order to provide quantitative data on the cost of PQ. According to the study, at the beginning of the 1990s the cost of poor PQ to global industry was estimated to be in the region of a few tens of billions of dollars. More comprehensive studies suggest that this had risen to a few hundreds of billions of dollar in 2003. It is fair to assume that this figure has only increased in the years since 2003. The study in [4], which reports the results of a survey of 985 businesses in the USA, states that for disturbances other than sags, the cost per year to the US digital economy and industrial companies is an additional $6.7 billion. Overall, the study states that "*data suggest that across all business sectors, the U.S. economy is losing between $104 billion and $164 billion a year to outages and another $15 billion to $24 billion to PQ phenomena*"

For literature related to individual disturbances, estimates of the costs associated with interruptions, voltage sags and harmonics dominate the published research. It is not surprising that interruptions and sags receive considerable treatment as the outcomes due to interruptions and sags, i.e. loss of supply (interruption) or effectively a loss of supply (sag), are immediate and obvious. In many studies, the costs associated with harmonics appear to be very high and it is difficult to reconcile these costs with the relatively low number of complaints received for harmonics and the relatively low harmonic levels observed in distribution networks.

There are few studies which have examined the costs to industry and the community as a result of steady state voltage magnitude variance, voltage unbalance levels, flicker and transients. For steady state voltage, the lack of research is possibly due to the non-linear nature of the impact of the disturbance on equipment and the fact that over-voltage stress mainly leads to loss of life over an extended timeframe. Unbalance has not been highly investigated due to the fact that the impact is almost universally on 3-phase induction motors. The penetration level of these devices is relatively unknown and therefore, the cost of the effect of unbalance on these devices is uncertain. For flicker, it is likely that the difficulty in determining the principally non-technical costs associated with this disturbance limits the research possibilities. Transients do not receive significant attention due to the fact that even basics such as measurement methods and limits for transients are not well understood, let alone their impacts on equipment.

Much of the available literature is focused on qualitative disturbance impacts. Relatively few studies give quantitative figures and those that do are generally concerned with case studies as opposed to suggesting methodologies which may be applied across a wide range of scenarios.

Using Australian distribution network performance data from the results of the Long Term National Power Quality Survey (LTNPQS) project [5] managed by the University of Wollongong, the current research identifies the most important PQ disturbances from an economic point of view for Australia. The research examines the impact on equipment and processes only; it does not consider any costs associated with mitigation. In all cases, a review is made of the qualitative and quantitative economic impact of PQ disturbances and limitations in the published literature are identified. In many cases, generic quantitative methods for determining the economic impact of some PQ disturbances are not available. To address these knowledge gaps, novel new methods of determining quantitative economic impacts are suggested.

The research reported in this paper examines the economic impacts related to the following PQ disturbances:

- Steady state voltage
- Voltage unbalance
- Voltage harmonics
- Flicker/voltage fluctuations
- Voltage sags (also known as dips)
- Interruptions

Other disturbances such as swells, transients and inter-harmonics and noise have not been examined in detail as these disturbances only occur very rarely and are unlikely to be a major source of costs associated with PQ.

ECONOMIC IMPACTS BY DISTURBANCE

A. *Steady State Voltage Magnitude*

Steady state voltage magnitude is one of the most basic power quality parameters and quantifies the magnitude of the rms voltage supplied to equipment. For the purposes of this paper, steady state voltage magnitude refers to long term (minutes or hours) sustained voltage magnitudes as opposed to transient events.

The Australian LV voltage range as specified in AS 60038 [6] is 230 V +10%/-6%. A further 5% reduction in voltage is allowed in the customer premises giving an overall range of 230 V +10%/-11%. Most equipment will be connected at low voltage (LV) and has been designed to operate correctly and efficiently within a specified steady state voltage range. If the supplied voltage is outside of this design range, equipment may not operate correctly, may be inefficient or may be damaged. In particular, equipment insulation and capacitors are very sensitive to voltage levels. Sustained high voltage levels (over-voltage) stresses insulation and leads to premature failure. For sustained low voltage levels (under-voltage), equipment may draw additional current which may lead to additional component stress.

In [3], for sustained high voltage levels (over-voltage) or low voltage levels (under-voltage), the main impacts identified are loss of life of equipment, additional equipment energy usage and possible device maloperation. Device maloperation, i.e. failure to operate correctly or destruction due to extreme voltage levels, is the most evident impact of inappropriate voltage levels. Damage to equipment has obvious economics impact as does failure of equipment to operate correctly or at all. The impact of steady state voltage magnitude is not adequately addressed in the published literature. This may be due to the fact that in many countries, voltage levels are kept close to the nominal operating voltage. However, this is not the case in Australia. Results from the LTNPQS indicate that voltage levels on Australian electricity distribution networks are generally at the higher end of the nominal voltage range [7]. That being the case, the most significant economic impact associated with steady state voltage magnitude for

Australia is likely to be related to loss of equipment life caused by premature aging and failure of equipment due to over-voltage. It is important to note that depending on the design, impact on equipment, (i.e. loss of life), may occur for voltage levels that are maintained within the allowable range. That is, voltages do not need to exceed the nominal range for equipment deterioration to occur.

The most obvious example of equipment loss of life is the premature failure of incandescent light globes. In the case of these lights, for voltages near to the rated voltage, a 5% over-voltage will approximately halve the lamp life [8] making the premature failure obvious. However, for other equipment, the premature aging and failure may not be immediately obvious or may not even be identified by the equipment owner at all. However, whether detected or not, premature failure of equipment requires investment before it would otherwise be required and as such can be considered as a cost.

Based on studies performed by the Australian government such as [9] and data from the Australian Bureau of Statistics, e.g. [10] and [11], it is relatively easy to show that an average domestic household contains nearly $14,000 worth of electrical appliances. The vast majority of these appliances are now supplied using electronic switch mode power supplies (SMPS). These power supplies are directly exposed to the incoming supply voltage. The electrolytic DC filter capacitor in the SMPS is often cited as the weakest link and the one of the most likely component to fail in electronic equipment [12]. These capacitors are generally very sensitive to the input voltage level. Most equipment is designed for optimum operation at or near the 230 V nominal AC voltage. Movement above nominal voltage levels has an impact on equipment operation. For high steady state voltage, loss of equipment life occurs due to a combination of thermal degradation and voltage stress leading to premature insulation breakdown. At the voltage levels likely to be seen on most distribution networks, thermal degradation and voltage stress as opposed to catastrophic failure are considered to be the main contributors to equipment loss of life. Given the large number of households even if a small amount of depreciation per year is caused due to over-voltage, the economic impact across the entire network can accumulate to a very large value.

Determination of the rate of depreciation of equipment due to sustained over-voltage is an area still requiring significant research. While there is a well understood relationship between supply voltage and lifespan for devices such as incandescent lamps, the relationship between supply voltage and electronic equipment is still an area of conjecture. The actual thermal lifetime of an appliance is a function of its standard (rated) lifetime, the ambient conditions and the voltage profile. The relationship which links the equipment lifetime to applied voltage could be described the relationship:

$$\text{Life}\,(V) = \text{Life(Standard)} \times \exp\left(-DF\left(\frac{V_{\text{rated}}^{\alpha}}{V_{\text{applied}}^{\beta}} - 1\right)\right) \qquad (1)$$

In (1), V_{rated} refers to the rated voltage of the equipment, V_{applied} refers to the voltage applied to the terminals of the equipment and DF refers to a Decay Factor, which is yet to be determined, linking equipment lifetime to supply voltage. The exponents α and β are yet to be determined. The sign and magnitude of the decay factor and exponents will be dependent on the difference between the rated and applied voltages. The validity or otherwise of this proposed model would need to be verified and improved through experimental work. Figure 1 illustrates the shape of curve described by (1) for two different decay factors.

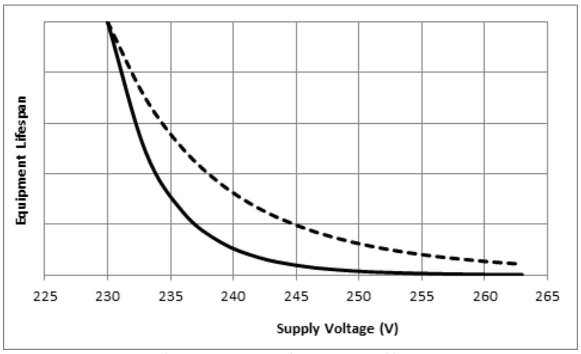

Figure 1. Example Lifetime Curves for Two Different Decay Factors

A less well understood and difficult to identify economic impact associated with sustained over-voltages is the cost related to the additional energy which is consumed by equipment. Equipment is designed to operate most efficiently at a given voltage level. Operating equipment at voltage levels above this will reduce efficiency and result in wasted energy. There is considerable evidence [13], [14] which indicates that a reduction in voltage levels will result in reduced electricity demand and hence reduced energy bills for customers. Once again, given that Australian voltage survey results shows that voltage levels on Australian electricity distribution networks are generally at the upper end of the nominal voltage range [7], sustained over-voltage may be having a significant impact on consumer electricity bills. For purely resistive loads, the relationship between supply voltage and additional energy usage is described by (2) and is illustrated in Figure 2. The relationship between supply voltage and additional energy usage for more complex devices is an area which requires additional research.

$$P = \frac{V^2}{R} \qquad (2)$$

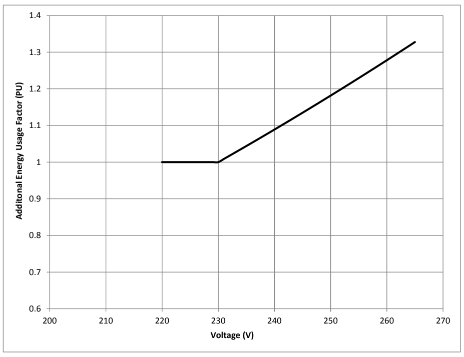

Figure 2. Relationship between Supply Voltage and Additional Energy Usage for Resistive Loads

For motor equipment, the main impact of over-voltage is additional energy losses. The added heating effect of over-voltage causes loss of insulation life in fully loaded single phase motors. Most single-phase motors are sized to almost perfectly suit their load, there is little scope for additional heating in motor windings before loss of life occurs due to thermal degradation of insulation. This is not generally the case for three-phase motors which tend to be oversized compared to their load. Additional heating in the motor is due to the fact that the current in the motor windings increases as the voltages increases. There are two mechanisms which lead to additional current in single-phase motors under over-voltage conditions. The first is that the motor will turn slightly faster thus increasing the load. The second is that many motors will begin to saturate magnetically when exposed to over-voltage conditions. This leads to a significant increase in the reactive current draw.

B. Voltage Unbalance

Economic impacts associated with voltage unbalance are generally related to additional losses, particularly in induction motors where the negative sequence voltage will establish a counter-rotating magnetic field leading to additional heating. In [2] the problems associated with unbalanced supply to three-phase motors have been identified as:

- Inverse torque. This will impact on bearings.
- Additional heating in the stator and rotor which may necessitate oversizing the motor to accommodate the unbalance levels.

The relationship between voltage unbalance and motor losses is described in [15] and reproduced in Figure 3.

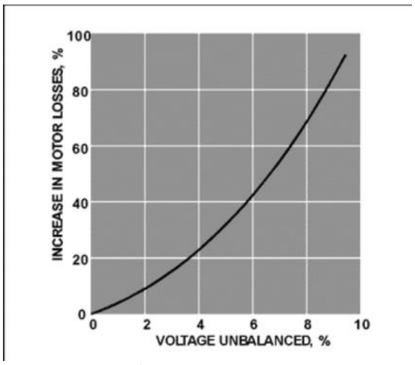

Figure 3. Impact of Voltage Unbalance on Induction Motor Losses [15]

The authors of [15] also claim that the costs for unbalance are related to additional losses and ineffective use of parts of the installation. Specifically these are:

- Reduction of current capacity of the installation cables
- Additional losses in the neutral conductor
- Additional energy losses in cables

Voltage unbalance is considered to be of secondary economic importance. This is due to the following:

- Surveys such as [5] shows that unbalance levels on Australian distribution networks are modest and generally below 2%
- There are very few three-phase motors used as a domestic load
- Many new three-phase motors are connected using variable speed drives which mitigate and/or protect against unbalance (or trip if unbalance levels are too high). In addition, direct-on-line motors are often oversized compared to the load. In this case, the additional load due to the unbalance still means that the load on the motor is below rated and hence there will not be loss of life caused by the unbalance.

C. Voltage Harmonics

Economic impacts for voltage harmonics are generally divided into costs due to additional losses and costs due to equipment maloperation due to supply waveform distortion. In [2], the costs have been divided into direct and indirect costs as follows:

Direct Costs

- Damaged components (e.g. capacitor banks)
- Damage to parts of the installation (e.g. cables)
- Costs due to loss of production
- Loss of staff productivity
- Costs of repairs

Indirect Costs

- Additional loading of components
- Additional energy losses
- Ineffective use of the current carrying capacity of the installation
- Reduced lifetime of components
- Less effective functioning of protection components

One of the main challenges in determining the economic impact of voltage harmonics is that there are many harmonic orders to consider. Different orders will impact different equipment in different ways. For electronic equipment, the high frequency components of voltage harmonics will lead to loss of life in the capacitors installed in electronic equipment due to low impedances, higher capacitive currents and higher heating losses.

For motors, the main impact of voltage harmonics has been identified as additional losses in single- and three-phase motors and loss of life in single-phase motors. In simple terms, these motors present an inductive impedance to the network. When supplied by a voltage with harmonic content, this impedance will draw an inductive harmonic current in addition to the fundamental current. Low frequency harmonics are the most important in this process. These harmonic currents do not assist motor operation and manifest as a loss by inducing additional heating in the motor. The additional heating associated with the harmonic current is generally small and tends to have little impact on three-phase motor insulation due to the fact that the motors are generally oversized. This may not be the case for single-phase motors which are generally designed to closely match the load. As such, the additional heating caused by harmonic currents in single-phase motors is more likely to lead to degradation of insulation and associated loss of life.

One method of assessing the economic impact of harmonics which alleviates the problem of having many harmonic orders to consider is to calculate indices which aggregate the high and low frequency harmonics. An example of such indices are given in [16]. In this study, two indices are calculated; one which combines the low order harmonics and another which combines the higher order harmonic. These indices can then be used in equipment impact model as appropriate.

Harmonics receive a lot of exposure as a major PQ problem. However, harmonic levels are generally well within planning levels or other limits at the majority of sites. Sites with high harmonic levels are generally low in likelihood but the distortion can have a high impact. The impact of harmonics on equipment lifespan is generally not well understood and is an area which requires more research.

D. Flicker

Flicker is a modulation of the voltage waveform envelope. It leads to rhythmic changes in light output from incandescent lighting sources. For some individuals, this rhythmic change in light output can result in health problems ranging from annoyance and lost productivity through to headaches through to seizures in extreme cases. As such, the cost impact of flicker is difficult to quantify as it does not generally lead to obvious equipment problems. Rather, the costs tend to be societal and apply to employee health and safety. This is supported by [17] which states that the consequences of voltage flicker are not highly financial, rather it impacts the health of employees (with associated downtime) who may experience health problems due to light flicker, and by [2] which states that the main costs due to flicker are due to loss of productivity due to the irritation to personnel caused by the disturbance.

With the phase out of incandescent lights in many countries, there was an expectation that flicker limits may be able to be increased as the societal issues would be reduced due to new lighting technology. However, flicker also has an undesirable impact on equipment [18] and there are concerns that excessive flicker levels may lead to equipment problems including loss of life.

In Australia the LTNPQS has shown that there are some sites with flicker levels which exceed AS/NZS 61000.3.7 [19] planning and compatibility levels. These sites are generally those which are electrically close to fluctuating loads such as arc furnaces or mesh welders. There is very little data which assesses the quantitative impacts of flicker whether that be the societal impact or the impact on equipment. Accordingly, this is an area requiring additional investigation.

E. Voltage Sags and Interruptions

The costs due to voltage sags and interruptions are wide and varied. Generally, equipment is not damaged; however, interruptions of almost any length often lead to some loss of productivity due to equipment tripping. Long interruptions are dealt with in considerable detail in [3]. The authors state that long interruptions have been the subject of many international studies. One generic finding is that the relationship between the cost of a long interruption and its duration is not proportional; rather it can be expressed as a logarithmic curve. The cost of a long interruption is stated to depend heavily on the following:

- The type of industry, e.g. for continuous manufacturing, the cost difference between a 1 s, 1 minute and 1 hour interruption is stated to be negligible
- The day and time of day and at which it occurs (e.g. weekday, weekend, day time, night time)

In [17], the actual financial losses are customer specific and depend mainly on:

- Customer category
- Type and nature of activities interrupted
- Customer size

It is also claimed that losses are event specific and different event severity leads to different economic loss.

For voltage sags specifically, if the sag is long or deep enough, the impact will be similar to an interruption. Even sags which are not particularly severe may result in the tripping of a sensitive piece of equipment. If this piece of equipment is part of a primary control system the trip may result in the loss of a whole production facility. In [4] it is stated that a 1 sec power failure or very deep sags leads to a 1- 30 min process interruption for 56% of customers. For industrial customers it is stated that the average process outage time after a 1 s power failure is 21 minutes. Figure 4 shows outage durations for a 1 s power failure.

When quantifying the economic impact of sags and interruptions the result is highly dependent on the industry sector and individual circumstances. There are many resources such as [3], [15] and [4] which give widely conflicting costs. In many cases, case studies are cited which may not be applicable to most consumers. The value of customer reliability (VCR) figures compiled by AEMO [20] provide some indication of the economic impact of interruptions to all customers. While these figures effectively represent the willingness of consumers to pay to avoid an interruption, it is expected that this willingness to pay has a strong relationship with actual cost. Table I shows the VCR values given in [20]. These VCR values may be used in conjunction with system reliability figures to begin to place a quantitative cost on interruptions.

TABLE I: CUSTOMER VCR VALUES

Customer Class	**VCR ($/kWh)**
Residential	25.95
Agriculture	47.67
Commercial	44.72
Industrial	44.06
Aggregate NEM Wide Value	33.46

When evaluating the cost sags, a key factor that needs to be taken into account is whether or not cost begins at $0 and increases linearly with time. In [4], it is stated that the cost of a 1 second outage is given as $1477 while the cost of a 1 hour outage is given as $7795. From these figures it can be seen that the 1 second outage incurs approximately 20% of the cost of a 1 hour outage. The data given in [21] has a remarkably similar ratio. For this study, the cost of a momentary outage is given as $1696 while the cost for a one hour outage is given as $8513. Once again, the ratio of momentary-outage cost to one-hour outage cost is approximately 20%. Using this relationship, the cost of sags compared to duration has a relationship similar to that given in Figure 4 which has an initial offset followed by a linear relationship between cost and duration.

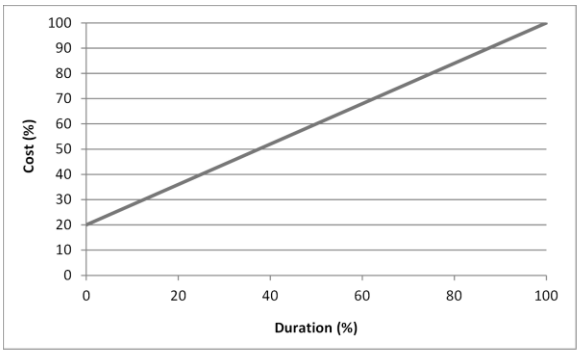

Figure 4. Example Relationship between Sag Duration and Cost

For voltage sags, it may be possible to determine a quantitative cost by relating the impact of sags to that of interruptions. If a voltage sag is deep enough or long enough or a combination of both, the impact on equipment might be equivalent to that of a short interruption. Based on this concept, it is possible to evaluate the cost of voltage sags using VCR data. The key question is what is the relationship between voltage sags and an outage? Using the relationship between short and long outages described previously, if it is accepted that the cost of a voltage sag which is equivalent to a momentary outage is 20% of the cost of a 1 hour outage, it is possible to calculate the ‘value of customer sags (VCS) values shown in Table II. Once these values have been determined, evaluating the cost of sags requires the use of an index which equates sag activity to interruptions. Such an index is the Sag SAIFI index fully described in [22]. This index uses equipment performance to assign sags an equivalent interruption value. An index of 1 mean that the sag has had the same impact as a short interruption.

TABLE II: VCS Values

Customer Class	**VCS ($/kWh)**
Residential	5.19
Agriculture	9.53
Commercial	8.944
Industrial	8.812
NEM Wide Aggregate	6.692

CONCLUSIONS

In general, the power quality disturbances that receive significant attention with regard to economic impact are harmonics and sags. In the case of sags, this attention may be warranted as the costs associated with loss of production and loss of raw material due to sags are significant. However, for Australian networks, a strong case can be made to suggest that economic impacts due to sustained over-voltages may be the most significant economic concern and worthy of further research.

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