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Survey on demand side sensitivity to power quality in Ireland

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ABSTRACT

Power systems require a reliable supply and good power quality. The impact of power supply interruptions is well acknowledged and well quantified. However, a system may perform reliably without any interruptions but may have poor power quality. Although poor power quality has cost implications for all actors in the electrical power systems, only some users are aware of its impact. Power system operators are much attuned to the impact of low power quality on their equipment and have the appropriate monitoring systems in place. However, over recent years certain industries have come increasingly vulnerable to negative cost implications of poor power quality arising from changes in their load characteristics and load sensitivities, and therefore increasingly implement power quality monitoring and mitigation solutions. This paper reviews several historical studies which investigate the cost implications of poor power quality on industry. These surveys are largely focused on outages, whilst the impact of poor power quality such as harmonics, short interruptions, voltage dips and swells, and transients is less well studied and understood. This paper examines the difficulties in quantifying the costs of poor power quality, and uses the chi-squared method to determine the consequences for industry of power quality phenomenon using a case study of over 40 manufacturing and data centres in Ireland.

Introduction

Power quality (PQ) may be defined as a set of parameters describing the properties of a power supply delivered to the user in terms of continuity of supply and the characteristic of voltage [1]. Good power quality is essentially the provision of voltages and design of the system so that the electric power user can successfully obtain electric energy from the distribution system without interference or interruption [2]. The sensitivity to high power quality is growing, the reasons for which are twofold. Firstly, the ever increasing presence of non-linear loads on the distribution system is resulting in new disturbances and poorer power quality. Non-linear loads are usually electronic devices that draw a distorted current [3]. These loads include switched mode power converters, electronic equipment, variable speed drives, adjustable speed drives, industrial equipment (such as arc furnaces), fluorescent lighting and compact fluorescent lamps (CFLs) [2,4–6]. Secondly, the use of electronic devices such as microprocessors, telecommunications equipment and computerised equipment has increased significantly [4]. Electronically controlled and automated processes are extremely sensitive and require high quality power with little variation in frequency and voltage, and therefore their performance are susceptibility to power quality disturbances [7–9]. This is due to the interconnectedness of their components where the failure of one component (the weakest link) can lead to the failure of an entire system.

The cost of poor power quality is high and rising. The annual cost of wastage to industry (in EU-25 countries) caused by poor power quality exceeds €150 billion, occurring as a direct result of electrical power installations not being sufficiently reliable and resilient for today's and future's operating demands [10]. These losses can account for as much as 4% of industry revenue in Europe [10]. It is important for companies to know the economic impacts of power quality issues and the costs of avoiding these issues, hence highlighting the importance of power quality surveys.

Both high and low tech industries are extremely sensitive to the supply quality resulting in potentially serious financial losses [4,9]. The most common economic loss incurred is due to nuisance tripping of sensitive equipment [11]. Costs associated with these stoppages include materials and labour wasted, idle staff, equipment damage, costs of process restart, penalties or fines, among others [10–12]. Other economic losses include reduction of equipment lifetime (e.g. overheating of transformers), poor long term productivity or product quality and additional energy losses (thermal) [8,10,13].

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Evidently, electrical maintenance and reliability teams should be aware of these power quality issues to prevent these economic losses. One way of evaluating the impact of poor power quality and reliability is to carry out a power quality survey. In this paper, a power quality survey was carried out for over 40 manufacturing plants and data-centres in Ireland in 2013. This survey assessed this awareness, and the methods that the industrial, commercial and IT enterprises used to mitigate power system reliability issues. Survey questions relating to electrical problems were broken into a number of different sections including power quality, systems design, maintenance practices, system knowledge and documentation.

The remainder of this paper is organised as follows; in section 'Power quality definitions, effects, mitigation and costs' the power quality phenomenon discussed in this paper are defined, and their effects, associated costs and methods of mitigation are described. Many other power quality surveys have been carried out which assess the costs of poor power quality and reliability; section 'Difficulties in quantifying costs of poor power quality' reviews these methodologies and findings of these surveys and summarises the difficulties and challenges in determining the cost of poor power quality as reported in these surveys. In section 'Survey methodology & results', the survey methodology and results of a PQ and electrical reliability survey undertaken in Ireland are presented which uses the chi-squared approach to investigate the occurrence of PQ events and the associated effects. Further analysis of the results is given in section 'Analysis of results', with outcomes and recommendations presented in section 'Outcomes and recommendations'. Finally, conclusions are given in section 'Conclusions'.

It will become apparent from the PQ survey review, that the majority of these power quality surveys are focused on outages, and the effects of poor power quality such as harmonics and voltage dips are less well studied and understood. Consequently, the focus of this paper is to investigate the occurrence of specific PQ phenomena and to use the chi-squared method to determine the consequences of these specific PQ issues for the industry customer. This will serve to increase their awareness on what PQ monitoring should be carried out, and what mitigation solutions should be implemented.

Power quality definitions, effects, mitigation and costs

PQ phenomena definitions

The IEEE standard on Monitoring Power Quality groups PQ phenomena into seven broad categories; (1) transients, (2) short-duration rms, (3) long duration rms, (4) imbalance, (5) waveform distortion, (6) voltage fluctuations and (7) power frequency variations [1]. The power quality phenomena (1)–(3) and their subcategories, as defined in [1], are graphically displayed in Fig. 1, whilst categories (4)–(7) are presented in Table 1. From an economic point of view, voltage oscillation, harmonics and interruptions are considered the most important power quality issues; dips and short interruptions account for almost 60% of the overall cost of poor PQ to industry in EU-25 [14].

For the purposes of this paper (and associated survey) the IEEE defined sub-categories (shown in Fig. 1 and Table 1) are grouped into six broad headings. Fig. 2 illustrates how four of these overlap with the IEEE definitions. The authors believed that these terms and broader definitions would be easily interpreted and understood by the survey respondents. These six PQ phenomenon are.

Surges and transients (S&T)

Surges and transients are impulsive transients without oscillatory behaviour. They correspond to IEEE definition of transients and instantiations sags and swells, lasting no longer than 30 cycles. Surges or transients can arise from the effects of lightning strikes or switching of heavy or reactive loads. Usually protective devices in the network ensure that they are kept to a safe level, when problems due to surges and transients occur the source is usually physically close to the installation.

Voltage dips and swells (VD)

Voltage dips are short term reductions in rms value (between 10% and 90% of nominal voltage) of voltage supply lasting from a 30 cycles to 60 s. Swells are rms excursions beyond 110% of rated value over the same time window. Thus this definition combines the momentary, temporary and long duration time windows of the IEEE definitions.

Short interruptions (SI)

A short interruption is equivalent to the IEEE defined momentary interruption, i.e. a short but complete loss of supply, where the supply voltage decreases to less than 10% of its original value for a period of time greater than 30 cycles not exceeding 1 min.

Harmonics (H)

A harmonic is a sinusoidal component of a periodic waveform that is an integral multiple of the fundamental system frequency. Harmonic distortion is usually caused by non-linear characteristics of loads, often using power electronics.

Unbalance (U)

Voltage unbalance can include unequal voltage magnitudes, phase angle deviation or unequal levels of harmonic distortion in three-phase power systems. Causes and effects of unbalance along with a discussion on standards is comprehensively presented in [16].

Long interruptions (LI)

In accordance with IEEE definition, a long interruption is a complete loss of supply lasting longer than 1 min. It is important to note that this paper will focus on the previous phenomena (1–5) and long interruptions will be regarded more as power reliability (PR) rather than power quality (PQ) issue.

Symptoms and PQ correction

Symptoms of poor power quality in a plant include equipment mis-operation, computer lockups [17], circuit breakers tripping, equipment failing, automated systems stopping, thermal effects and life expectancy reduction [18]. Often, unexplained production losses are a sign of poor power quality, where a component failure occurs and the focus is on restarting the process quickly to meet customer demand rather than finding the cause of the issue [6].

The methods of power quality correction and/or mitigation depend largely on the offending parameter. Common solutions include proper design of the load equipment [5] (addresses S&T, VD, H and U), the application of active or passive filters (addresses S&T and H), voltage compensators (addresses S&T, VD and U), UPS devices (addresses SI and LI), standby power (addresses SI and LI) and attempts to isolate the process from the disruptive event [19,11]. Although power quality improvement is a shared responsibility among utilities, customers and equipment manufacturers [12], this power quality survey focuses on the PQ concerns of customers.

Previous power quality surveys

A number of power quality surveys have been carried out in [7,10,13,20,21] which investigate the impact of poor power quality and estimate its cost implications on industry. Due to the stochas-

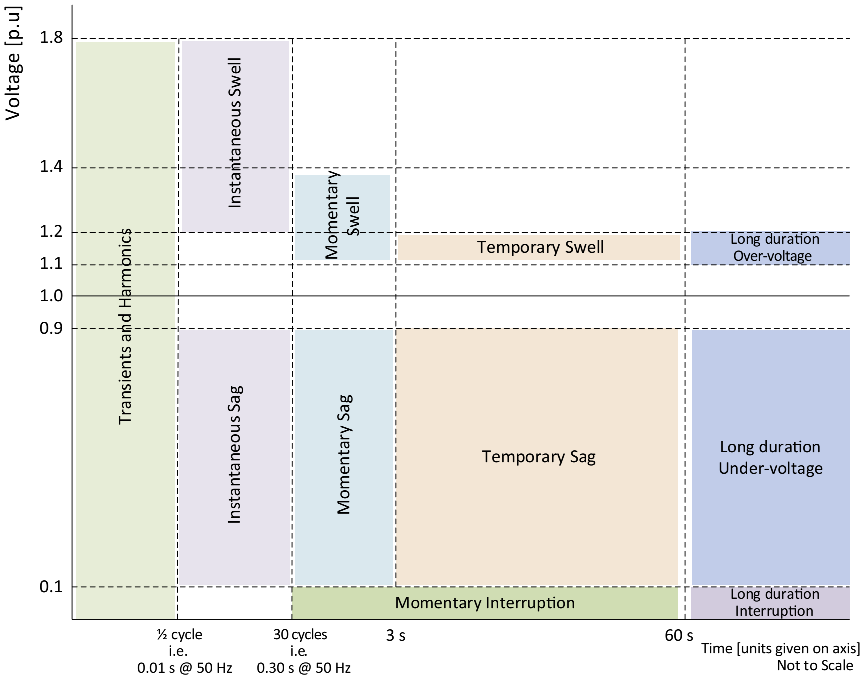

Fig. 1. Graphic summarising IEEE PQ phenomena (1)–(3).

Table 1
Summary of IEEE PQ phenomena (4)–(7).

Imbalance (4)	
Current	0.5–2%
Voltage	1–30%
Waveform distortion (5)	
DC offset	0–0.1%
Harmonics (0–9 kHz)	0–20%
Interharmonics (0–9 kHz)	0–2%
Notching	
Noise (broadband)	0–1%
Voltage fluctuations (6)	
Voltage fluctuation (<25 Hz)	0.1–7%
Flicker	0.2–2 P_{st} see [15]
Power frequency variations (7)	
Power frequency variations (<10 s)	±0.1 Hz

tic nature of the cost calculations, these studies either generalise the results or use simplified techniques relating GDP to power quality costs.

The objective of these surveys was to evaluate the costs due to poor PQ which resulted from many factors including repair costs, spoiled products, damage to raw material and finished products, rebooting, and salaries to employees who cannot work due to the interruptions. Interruptions of varying duration and frequency were evaluated, whilst in [26] interruptions were further separated into planned and unplanned occurrences.

The methods used to analyse and evaluate costs associated with poor PQ and long interruptions to customers include case studies, indirect analytical evaluations and surveys of customers and utility companies, where the latter is the most commonly used. The main advantage of the survey method lies in its flexibility, as it may be tailored to address the desired issues. A sample questionnaire is given in [22]. Typically, the information addresses the customer details (sector, power demand, etc.), interruption details (frequency, duration, effects and related costs, etc.), equipment used to mitigate PQ issues, and customer satisfaction with the transmission system. Disadvantages of the surveys lie in the reliance on the competence of the interviewee.

In this section a number of international surveys are reviewed and compared. Table 2 summarises details about the survey (geographical region, year of study and sample size). For each survey, cost information was extracted for the PQ phenomenon where possible. An "*x*" symbol signifies that the paper has studied the phenomenon but not placed a cost figure on it and a blank cell indicates that no studies were done on the phenomenon.

Evidently, from Table 2, the majority of surveys studied [7,10,13,20–23] focus mainly on long interruption costs rather than the costs incurred due to PQ phenomena such as harmonics. This may be explained by the difficulty customers can face in quantifying such costs and an emphasis on mitigation for the more costly long interruptions over other PQ events. In [10], it is recommended to use the figure of 4% of revenue. However, this can prove unfeasible as many surveys completed were of single plants which were part of a larger company, meaning that the company wide revenue figures would not be unsuitable. There are methods which can be used to determine the potential downtime of the components of an electrical distribution system. Once this is calculated it can be compared to the potential cost of loss of a particular processes relying on the electrical system.

$$\begin{aligned}\text{Cost of power loss} = {} & (\text{potential for equipment failure due to poor power quality issues}) * (\text{potential of running a particular process}) \\ & * (\text{cost of loss of this process}).\end{aligned}$$

The potential failure of electrical equipment may be determined using methods such as the IEEE 493 standard for electrical reliabil-

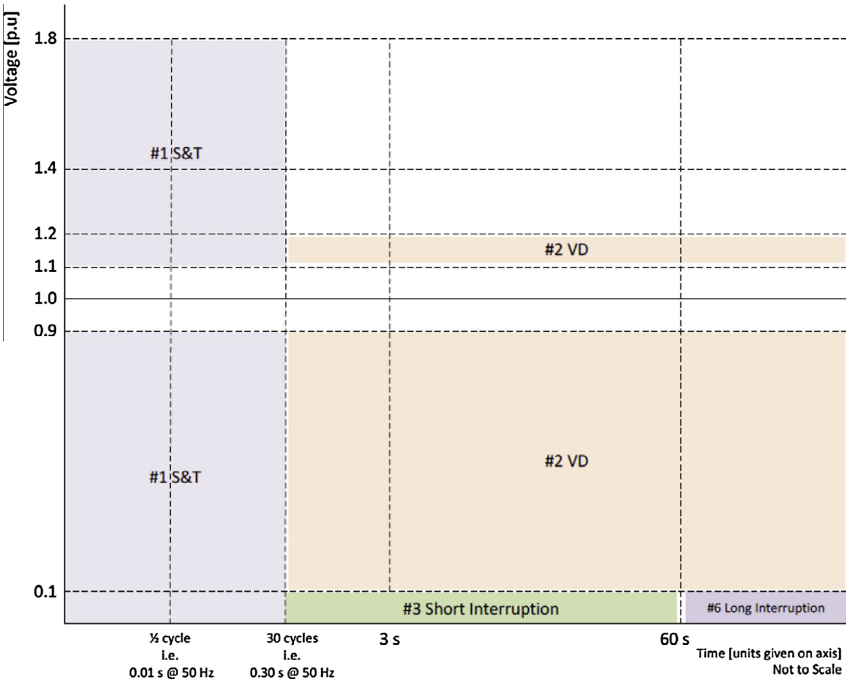

Fig. 2. Simplified PQ phenomena definitions – used in survey in this paper.

Table 2

Complied cost data from multiple surveys, costs per company per event by disturbance type.

Region	Year	Method	Sample size	Survey results						
				Power reliability	Power quality					
				LI	SI	VD	H	U	E&EMC	S&T
Libya [20]	2012	Survey	400 (via the DSO)	x	x	x	x	x		x
Southeast Asia [26]	2012	Survey and bottom up direct costs analysis	124	$313,284	$28,203	$345 k	$14410	$1873	$12,853	x
Northeast Brazil [7]	2012	Survey and direct costs analysis	17	$250,000 for 1 h (22.5 $/MW h)	$45,000 for 1 s (0.75 $/MW h)					
Portugal [13]	2011	Survey	20	€15,746 (18.98% of monthly bill) (1 h)	4888 €/event (5.89% of monthly electricity bill) (1 s)					
Europe [10]	2008	Survey, regression analysis to relate to annual turnover	68	91,021€/event	16,539 €/event	4177€/ event	x	x	x	€ 175,871
Korea [28]	2006	Survey	302	€1.89[a] to €166.4/kW (1 h)	€1.19 to €58.25/kW (<3 s)					
Italy [27]	2005	Survey	512	x	x	x				
Norway [29]	2003	Survey	2351	€3.89[b]/kWh (>3 m)	€0.84/kW (<3 m)	€ 0.6/ kW				
Nepal [30]	2003	Survey with statistical sampling	200	x						
Sri Lanka [22]	2003	Survey with statistical sampling	150	x		x				
USA [25]	2001	Survey with statistical sampling	985	$7795 (1 h)	$1477 (1 s)	x	x			x
Taiwan [31]	2001	Survey	284	$117.70/kW	$88/kW					
Finland [32]	2001	Bottom up direct costs analysis	5			€ 1060				
Sweden [33]	2000	Survey	100		x	x				x
Greece [34]	1998	Survey	494	$8010 or 10.95 $/ kW (1 h)	$1645, or 1.92 $/kW (1 s)					
Australia [23]	1997	Survey	26	x	x	x	x			
Canada [21]	1996	Monitoring PQ	550			x				x

[a] An exchange rate of €1 = 1378.93 won was used.
[b] An exchange rate of €1 = 8.32 NOK was used.

ity (“IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems”) [24], data from equipment manufacturers or on-site maintenance data. Reliability statistical analysis may be supported with recent maintenance and manufacturer’s data together with the use of State Enumeration or Monte Carlo methods to provide a more accurate source of evaluation.

Generally, losses due to PQ phenomena are significantly smaller than those due to longer interruptions. For example, industrial and digital economy companies in the USA are collectively losing $45.7 billion annually to outages and $6.7 billion to PQ phenomena [25]. The cost of long interruptions varies from about 1.5 times to 22.5 times greater than the cost of PQ phenomena. Despite the fact that the costs of PQ phenomena are smaller than interruption costs and much more difficult to quantify, they are by no means insignificant.

Difficulties in quantifying costs of poor power quality

The main point to note from the previous surveys summarised in section 'Power quality definitions, effects, mitigation and costs' (and Table 2) is the obvious difficulties in quantifying costs due to PQ phenomena as opposed to interruptions. It is easy to calculate the cost of interruptions post event. Very few studies (only [26,10]) placed a cost figure on PQ phenomena such as harmonics, surges or transients, whereas costs of long and short interruptions were generally well evaluated. The difficulty in ascertaining the costs of power loss or equipment failure due to poor power quality, electrical design, low system resilience, poor maintenance or a combination of all of these have has acknowledged in [27]. The calculation of financial damages related to PQ issues varies, and is dependent on many factors. These include the diversity of electrical equipment used by customers, time of day, week and year [14], and customer type (whether industrial, residential or public customers), although losses resulting from PQ events can vary widely, even for the same customer type.

Survey methodology & results

Given the challenges associated with cost estimations of poor power quality, this PQ and electrical reliability survey undertaken focuses on the occurrence of power quality events and the causes of equipment malfunction in cost sensitive sites in Ireland. However, anecdotal evidence of PQ costs in Ireland has been gathered some of which is presented here to indicate the scale of potential losses.

1. A large pharmaceutical plant incurred reported losses in the order of €2 million due to abnormal voltage harmonic distortion caused by a failure of a capacitor, c-filter on the secondary side of UPS, which supplies mission critical freeze drying process.
2. A pharmaceutical plant which experienced failure of a UPS system narrowly avoided potential losses between €1 million and €3 million as the fault was spotted in time.
3. Stray voltage and current in an intensifier bar inside a mixing vessel in a pharmaceutical plant almost cost the company between €1 million and €2 million.
4. Earthing issues and EMC interference lead to vital processes stopping in sterilizing vessels in a pharmaceutical plant, resulting in losses of €11,000 in up to 5 vessels per day.
5. Variable speed drive (VSD) failures relating to sags on the network supplying a baby nutrition plant resulted in losses of product worth up to 200 k multiple times.

Survey methodology

In 2013, 40 Irish companies were surveyed. The questionnaire was designed to gather information on a broad range of issues related to power quality including presence of PQ phenomena, consequences experienced, monitoring, solutions employed and technical site details. Care was taken to identify a suitably qualified person in each company. In all cases, the survey was completed by interview, either face-to-face or by phone.

A breakdown of the survey sample set by sector, number of employees, maximum import capacity (MIC), and voltage rating of supply is shown in Fig. 3. The companies were mainly pharmaceutical (PH) or medical device (MD) plants, the majority having a MIC of below 6 MVA with a supply voltage of 10 kV.

Presentation of results

Once the surveys were completed, the data was compiled, quality checked and analysed. Results are presented in four data-dense

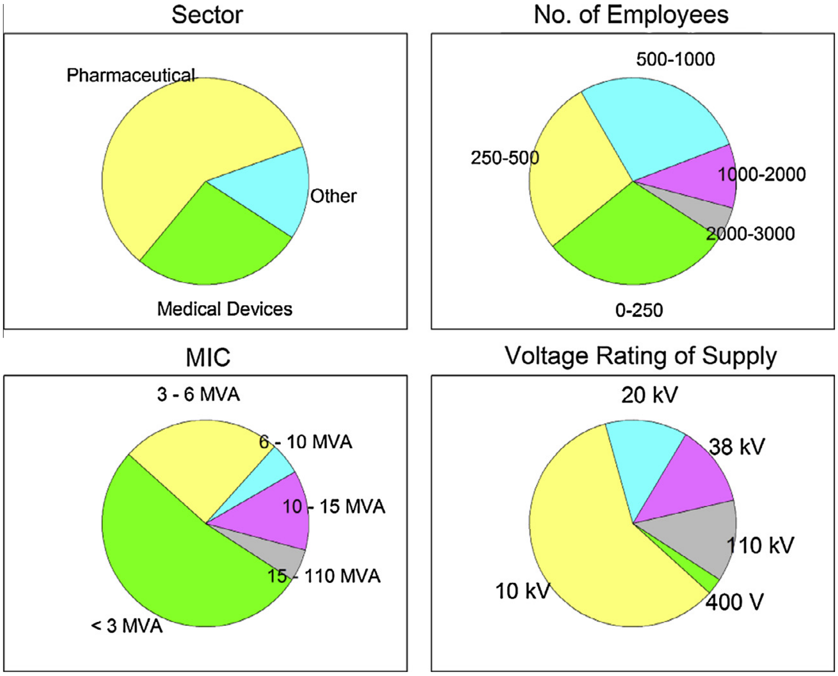

Fig. 3. Information on survey sample set: companies.

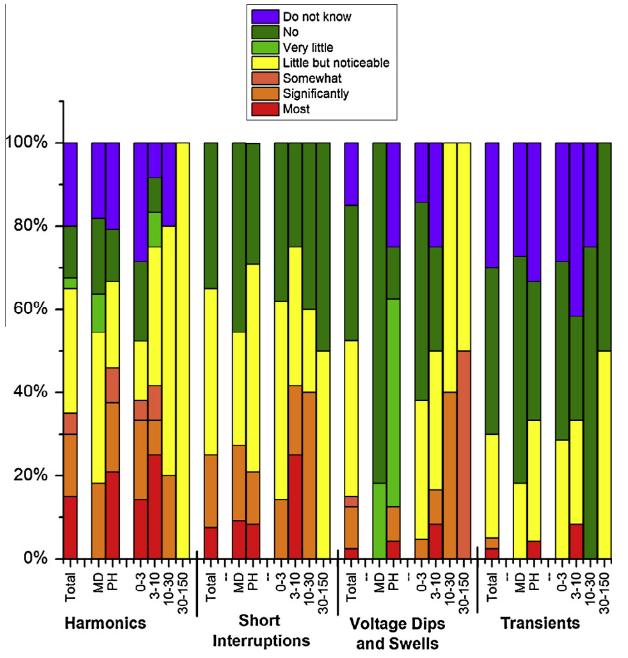

Fig. 4. Presence of PQ phenomena by sector and MIC.

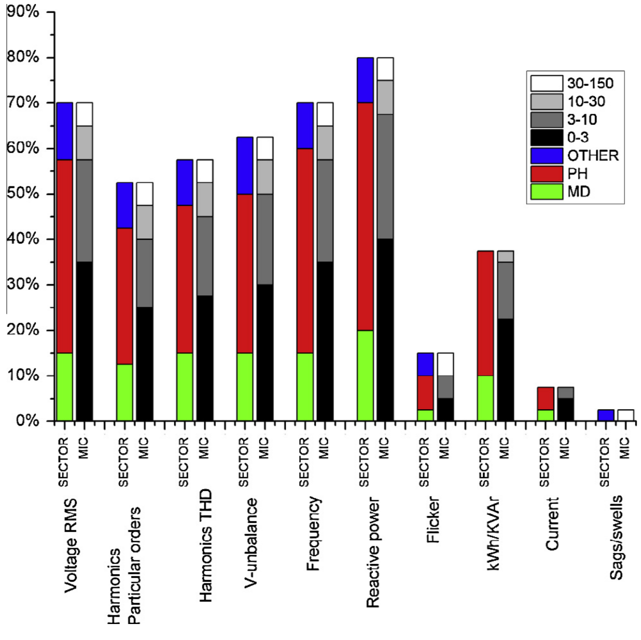

Fig. 5. Monitoring of PQ phenomena by sector and MIC (MVA).

figures which aim to provide comprehensive information on reported of PQ phenomena, monitoring of PQ, consequences of poor PQ and finally the solutions used to mitigate poor PQ.

The presence of PQ phenomena as noticed by the companies broken down by sector and MIC rating may be seen in Fig. 4. The data is grouped by PQ parameter and broken down by sector and MIC and ranked on a scale of the severity of the presence. Information on the types of monitoring carried out may be seen in Fig. 5. Reported consequences of poor PQ may be seen in Fig. 6. In Fig. 7 solutions implemented by the surveyed companies to mitigate the effects of poor PQ are displayed. These are also broken down by sector and MIC.

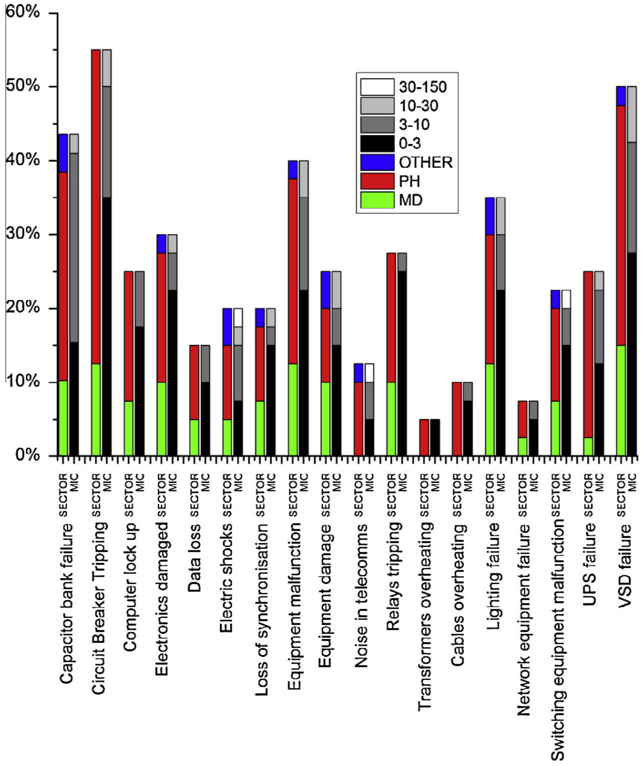

Fig. 6. Consequences of poor PQ by sector and MIC.

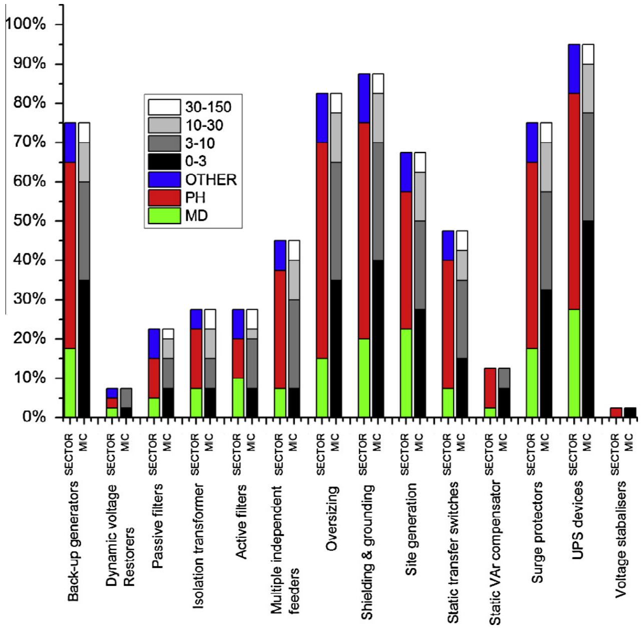

Fig. 7. Solutions implemented by sector and MIC.

The results figures contain a lot of information and can be used to extract interesting observations. For example, in Fig. 5 illustrates that 28% of companies reported experience 'relay tripping' as a result of poor PQ. From the bar-chart, it is observed that both medical and pharmaceutical companies report this, only those with MIC less than 10 MVA are affected.

Analysis of results

Pearson's chi-squared test (χ^2) is a statistical test used to determine how likely it is that any observed difference or similarities between the sets arose by chance. The χ^2 test was used to find correlations between the presence of PQ parameters, consequences, monitoring and solutions. Following a worked example of the χ^2 test, the results are discussed below, where the values supplied with each correlation percentage likelihood that there is a real link between the data. The analysis of results is broken into sections by PQ parameter.

Example of Pearson's χ^2 test

As an example, consider two sets of data from the survey. Each of the 40 companies gave details response to the following two questions; "Are you aware of the presence of harmonics in your plant?" and "Have you experienced UPS failure". Their survey responses and individually assessed. Based on knowledge of the responder, their level of expertise, and the nature of their response (e.g. "Observed rarely") and cross checking with other questions in the survey, a binary conclusion was drawn and a 'yes' or 'no' result was concluded. Following this quality assurance step, observed responses were that 7 companies answered 'yes' to both questions, 23 companies answered 'no' to both, 3 responded that they experienced UPS Failure but hadn't noticed harmonics and 7 reported harmonics but no UPS failure (Table 3(a)).

If there was no correlation between the data, and the responses were completely unrelated, of the 10 respondents who reported UPS failure, random distribution would expect 3.5 of those to see harmonics and 6.5 not to see any harmonics.

$$\begin{aligned}&\mathit{Expected\ Yes\ Yes} = \mathit{Harmonics\ Total\ Yes} \cdot \mathit{UPS\ Total\ Yes}\\&\qquad\qquad\qquad\quad /\mathit{Number\ of\ Companies}\\&3.5 = (14 \times 10)/40\end{aligned}$$

The result is added to Table 3(b) and is marked with an asterisk. The calculation is repeated for the other combinations and to complete the table. Table 3(b) contains the expected values for a pair of *uncorrelated* binary data sets. The chi-squared (χ^2) test compares the observed data in Table 3(a) with the expected data for uncorrelated data sets in Table 3(b). As detailed in Appendix A, χ^2 values are computed for each case (Yes–Yes, Yes–No, No–Yes, No–No) and their sum is evaluated (Table 3(c)). The χ^2 value (7.0132) is compared to the χ-distribution for a single degree of freedom case and a χ distance (χ_{dist}) is calculated, 0.81% in this example. (This is analogous to the classical statistic approach of using the sigma value, σ, of a normal distribution to determine that the probability of a data point occurring within a $\pm 1\sigma$ distance is 68.23%.) The χ_{dist} is of measure of non-correlation is (χ), so a low χ_{dist} implies a high probability of correlation, in this example 99.19%.

Harmonics

Harmonics are reportedly the most prevalent PQ phenomenon, as can be seen in Fig. 4, with 30% of companies describing a significant or greater presence. They are more common in pharmaceutical companies than in medical devices and mainly present in smaller companies, with MIC less than 10 MVA.

For the purposes of the χ^2-test companies were split into those who reported significant or extreme levels of harmonics and those who didn't.

From the χ^2-test it is observed that the presence of harmonics is linked to capacitor bank failure in companies (97.76%). Power factor corrector (PFC) units are prone to failure when non detuned units amplify the existing harmonic content due to resonance

Table 3
Example of χ^2 calculation.

(a) Observed values

		Harmonics?		
		Yes	No	*Total*
UPS failure?	Yes	7	3	*10*
	No	7	23	*30*
	Total	*14*	*26*	*40*

(b) Expected values (for *uncorrelated* data)

		Harmonics?		
		Yes	No	*Total*
UPS failure?	Yes	3.5*	6.5	*10*
	No	10.5	19.5	*30*
	Total	*14*	*26*	*40*

(c) χ^2 values

		Harmonics?		
		Yes	No	Total
UPS failure?	Yes	2.57143	2.46154	5.03297
	No	1.52381	0.46154	1.98535
			$\chi^2 = 7.01832$	

caused by capacitive elements. These overload the capacitor banks and cause them to overheat and fail [35]. Aging detuned banks and passive filters can be a cause of similar issues. Shifting the tuning frequency of the PFC unit, due to failure of the capacitive components, may result in amplification of harmonic orders.

The presence of harmonic distortion results in lighting equipment failure (99.2%). This may include flickering of incandescent or fluorescent lights due to transformer saturation.

The use of UPS systems is a cause of harmonics. The χ^2-test proved a correlation between the use of UPS systems which cover at least 10% of the load and harmonic distortion (99.09%). This echoes the results in [16] which determined the UPS resulted in increased harmonics due to suboptimal use of the equipment.

Harmonics may lead to motor or process equipment malfunction due to misfiring from incorrect triggering due to multiple zero crossings causing failure of electronic equipment which relies on zero crossing threshold detection devices. Multiple zero crossings can also affect the performance of UPS units relying on the zero crossing of the waveform when calculating the frequency. This results in undesired switching of the UPS into by-pass mode and exposing the system to increased risk of failure. Additionally, the presence of these multiple crossings can cause problems in any device using timing signals, such as rectifiers, inverters, and thyristors. The monitoring of particular orders of harmonics is strongly linked with the absence of equipment malfunction in surveyed companies (97.2%).

Passive and active filters are linked to the successful operation of residual current devices (RCDs) and circuit breakers (97.01%). The reduction of harmonics in the system can reduce the total current in the switchboard, preventing nuisance trips, and prevent overheating in transformers and cables.

Short interruptions

As shown in Fig. 4 the presence of short interruptions is reported as being significant or greater in 26% of the surveyed companies.

Short interruptions are linked to motor and process equipment malfunction (99.7%) and damage (95.9%). Even a short loss of power can lead to complete shutdown and damage, as many industrial processes rely on constant motion.

Loss of synchronisation of process equipment is also related to the presence of short interruptions (99.01%). Similarly to voltage dips, VSD and static converter failure are linked to short interruptions (97.3%). This may be due to bridge rectifier circuits failing with multiple zero crossings. Computer lock up is another common fault which is related to short interruptions in the companies surveyed (99.6%), as well as employees receiving electric shocks (98.93%) from equipment.

Voltage dips

As can be seen in Fig. 4 and 13% of companies reported at least a significant presence of voltage dips in their systems.

Voltage dips and swells in industry are linked to motor or process equipment damage (97.47%). Mechanical damage to equipment may be sustained when equipment resets or shuts down due to a decrease in voltage. Voltage swells cause damage due to overheating or motor stalling. Voltage dips and swells are also attributed to network and telecommunication failures (97.26%).

VSD and static converter failures are linked to voltage dips and swells (95.04%). This is typically due to the incorrect setup of the VSD or converter, and is in many cases preventable, if correct control parameters are adjusted.

Monitoring of flicker (97.72%) and oversizing of equipment (99.82%) are both linked to the prevention of equipment damage in the surveyed companies.

Surges and transients

Transients and surges are the phenomenon about which surveyed companies have the least information, with 30% stating that they did not know whether they are present in the system. Of those who did report transients and surges, smaller pharmaceutical plants were the more affected. Only 6% of the companies reported significant or greater presence.

Transients and surges are responsible for nuisance tripping of switching equipment such as relays and contactors (95.99%) and circuit breakers and RCDs (99.16%). Oversizing of equipment (99.58%) is related to the absence of failures in relays and contactors. Network and telecommunication failures (99.99%) and VSD/static converter failures (96.25%) are also linked to transients and surges. Potentially, put the mitigation solutions in one section, and recommendations for further activities.

Systems design

A vast amount of reliability issues can be associated with poor industrial network design. The under sizing of equipment, insufficient spare capacity, inadequate protection discrimination, lack of redundancy paths and single points of failure on the network are common sources of problems related to system resilience.

A single point of failure is a potential risk posed by a flaw in the design, implementation or configuration of a power system in which one fault or malfunction causes an entire system to stop operating. Adding alternative power routes at the planning stage can result in increased returns on investment, through the reduced downtime.

Ineffective design is a big obstacle, delaying or even preventing any process expansion, upgrades or implementation of mitigation solutions, once the PQ issue has been diagnosed. Costs associated with the installation of filters, generators, UPS units and PFC banks can be largely multiplied if the initial design didn't allow for further growth and implementation of new solutions.

Outcomes and recommendations

The in-depth nature of the interview process used during the survey has resulted in several conclusions about the general awareness and attitude of the surveyed companies. These outcomes (along with recommendations) are detailed in this section.

General awareness of PQ issues

This power quality study showed that there is a diverse range of awareness on the part of the companies when it comes to PQ phenomena meaning that these companies are not aware of the negative economic impact these PQ issues are having on their plant. Aside from long interruptions, 20% of companies do not know whether harmonics are in their system, 15% are unaware of whether dips and swells are present and 30% of companies do not know whether transients and surges are an issue. All companies surveyed provided a response on the various levels of interruptions experienced. This shows why it may be easier to place a cost on these as opposed to other PQ phenomena, as observed in other surveys. With this survey, their awareness of power reliability problems and their effects on electrical infrastructure is raised.

Quantify the cost of poor PQ

A business case based on the costs of interruptions and poor PQ is required to illustrate to decision makers the advantages of investing in PQ mitigation. However, IEEE493 and statistical reliability analysis was utilised only by one of the interviewed companies. The engineering department of the plant was very successful in obtaining funds for reliability related projects and system upgrades.

System level and equipment level considerations

The majority of interviewed companies have a number of reliability solutions in place. Predominantly they are implemented at the main distribution level: generators, backup feeds, UPS units and oversizing of network components. There is however very little emphasis put on reliability solutions and PQ mitigation at the equipment level. Solutions such as: active and passive harmonic filters, cascaded surge protection, tracking filters, EMC filters and sag-ride-through devices, are implemented infrequently. System power quality monitoring and alarming which is crucial for investigating and correctly diagnosing problems, is utilised only by 30% of the participants.

Unforeseen impact of energy efficiency improvements

In recent years, rising costs of energy and a challenging economic climate have forced many companies to initiate significant energy reductions. Easy energy conservation measures allowing for justifiable savings were VSD's for process/utilities motors and smart lighting solutions. Typically these upgrades introduce a considerable amount of non-linear loads to the system and PQ issues associated with them – predominantly harmonics. The most efficient way to tackle harmonic problems is at the source. New installations should be designed with harmonic mitigation in mind, preferably at equipment level. The expansion of power quality metering systems to downstream locations can improve traceability of existing harmonic & PQ sources allowing the implementation of suitable mitigation solutions.

Traditionally there has been a ratio of 80/20 between the client/utility in relation to the source of power quality problems. The introduction of renewables and the changing structure of power generation on the utility side will give rise to a new source of power issues in the future.

System knowledge and documentation

Site documentation and system data availability is crucial when diagnosing power quality and reliability issues. Up to date electrical drawings, schematics, schedules and equipment inventory lists allow for tracing the problems in an efficient manner.

An electrical knowledge base, in the form of a power system software model, offers an excellent system overview, along with the ability to design, predict and prevent. Certain software modelling tools provide the ability to perform IEEE493 reliability type analysis, which allows the user to identify weak points on the network through State Enumeration or Monte Carlo probability simulations.

The correct and successful tracing and diagnosing of power quality events predominantly depends on the availability and scale of metering available throughout the industrial network. The size of the metering grid, the quantity of recorded parameters as well as the accessibility of historical data and alarming capabilities determine how effective the power quality metering system is. Portable power quality metering can enhance the trouble shooting process, however cannot fully replace a fixed system, as it doesn't provide historical data. Quick identification of the problem through power monitoring is vital for the reliability improvement process and the reduction of losses.

Conclusions

Power quality surveys are typically focused on the implications of interruptions, and the impact of poor power quality is less well studied. This paper examined the difficulties in quantifying the costs of poor power quality, and determines the consequences of poor power quality to industry using a case study of over 40 cost sensitive manufacturing and data centres in Ireland. The χ^2 method was used to determine the dependence between power quality and equipment malfunction and failure. The power quality phenomena studied include harmonics, short interruptions, voltage dips and swells, and transients. The survey also highlighted the diverse range of awareness on the part of the companies in relation to PQ phenomena meaning that these companies are not aware of the unnecessary negative economic impact these PQ issues on their plant. Finally, recommendations are made to improve reliability and reduce financial losses due to poor power quality.

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Appendix A. *c*-squared test methodology

Pearson's χ^2 test is used to determine whether relationships between variables in a number of samples are due to chance or if they are systematic, i.e. whether or not there are correlations between data sets [36].

The null hypothesis of the χ^2 test is that the sets of data are independent. The methodology of the test includes allocating each observation to a contingency table and deriving a table of expected variables which can be compared to the observed variables. The closer the observed values are to the expected values the larger the chance of independence between them is.

The value of Pearson's cumulative test statistic is:

$$\chi^2 = \sum_{i=1}^{r}\sum_{j=1}^{c}\frac{(O_{i,j} - E_{i,j})^2}{E_{i,j}} \tag{1}$$

where O_{ij} is the number of observations of type *ij* and E_{ij} is the number of expected observations as predicted by the null hypothesis and r and c, are the number of discrete values in each data set.

The test value may then be used to calculate a *p*-value by means of comparison with a χ^2 distribution. The number of degrees of freedom, *dof*, is calculated by:

$$dof = (r - 1)(c - 1) \tag{2}$$

A *p*-value may be calculated by comparing the test value to a χ^2 distribution using the calculated degrees of freedom. If the *p*-value is less than 0.05 the null hypothesis may be rejected and the alternative hypothesis assumed, where the variables are correlated in some way.

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