APPLICATION NOTE

THE COST OF POOR POWER QUALITY

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October 2015

ECI Publication No Cu0145

Available from www.leonardo-energy.org

Document Issue Control Sheet

Document Title:	Application Note – The Costs of Poor Power Quality
Publication No:	Cu0145
Issue:	03
Release:	October 2015
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Reviewer(s):	David Chapman, Roman Targosz

Document History

Issue	Date	Purpose
1	March 2012	Initial publication on Leonardo Energy
2	May 2012	Reworked version for publication in the Good Practice Guide
3	October 2015	Review

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SUMMARY

Power quality is important when market liberalization focuses on electricity price and regulators are focused only on energy efficiency. Lack of power quality may cause damage and the total cost of using electrical energy can be thus doubled.

Interruptions are costly to the whole society while some industrial sectors like continuous manufacturing or IT are particularly sensitive to voltage dips. Regardless of whether the origin is a short or long interruption, a voltage dip, a transient or other voltage disturbance, the consequence is an outage. Interruption duration is important but much more so is the frequency of PQ problems and the serious impact they may have on industrial productivity.

PQ costs may, in extreme cases, reach values of millions of dollars, as was reported by EPRI for brokerage operations. Although the costs are lower in most cases, they are still significant and are characterized by very large variations between apparently similar cases. The decisive factors are the equipment immunity and level of supply disturbance.

PQ costs should be investigated and understood; the quantification is needed for many reasons such as contract negotiation, building the case for investment to improve PQ and building the awareness of all important market actors, including regulators.

INTRODUCTION

Dependency on electrical energy is steadily increasing. Electrical energy has been traditionally used for motive power and lighting and, for the last few decades, it has powered electronics and power electronics for which there is no competition. Recently, it has increasingly become an alternative energy carrier for heating and transport applications.

The energy sector is undergoing market transformation. Liberalization of the electricity market has introduced a risk that quality of electricity supply may deteriorate and consequently regulators need to safeguard the quality of such an important product as electrical energy.

Modern lifestyles and economies rely on a continuous supply of electricity. In the future, smart grids, with energy storage, may help to decrease dependency on the supply from centralized power generation, although the increased reliance on highly volatile renewables, together with the future risk of more severe weather, increases the risk to continuous supply in the form of power blackout.

Once a continuous supply is in place, voltage quality must be considered. Supply voltage quality is affected by events on the distribution network (such as faults, harmonic disturbances and lightning strikes, etc.) so no supply is ever perfect. On the other hand, end-user equipment has limited immunity to these voltage disturbances; excessive disturbance will result in a degree of malfunction or equipment damage. The balance between maintaining a suitably low level of system disturbance and a practical degree of equipment immunity is called ‘compatibility’ and is the concept behind most standardization efforts. The performance of the supply system is controlled by the setting of planning levels and equipment emission limits while equipment immunity is maintained by product performance standards together with installation standards and practice. This is illustrated in Figure 1.

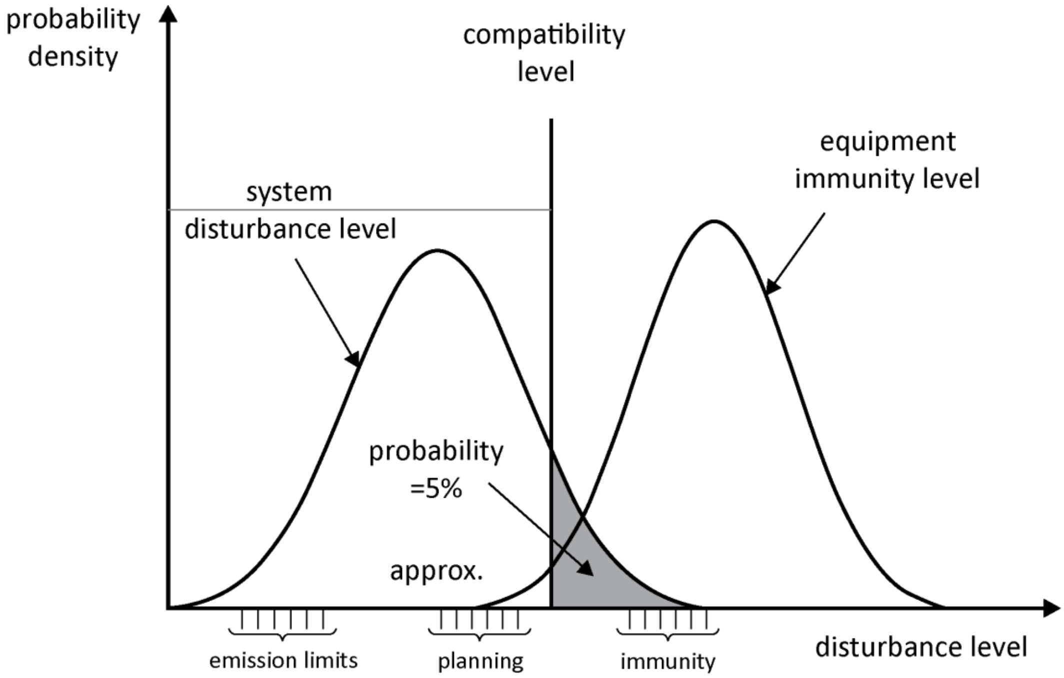

Figure 1 – Relation between compatibility, immunity, planning and emission levels according to IEC 61000-2-12.

The efforts of the Standardization bodies in developing the increasingly detailed IEC 61000 series and EN 50160 standard is vital in maintaining compatibility between the supply network and the equipment used by consumers. There is a shared responsibility; the supply industry is responsible for maintaining a certain level of performance while the consumer is responsible for ensuring that his equipment and plant have the appropriate functionality to work well on the supply. The crucial role here would be to define precisely the level of quality which will separate the responsibility, a concept known as ‘responsibility sharing’.

When the responsibility for power quality problems of users lays a charge on suppliers, the crucial thing will be to quantify the investment which is needed to compensate PQ cost for the whole society (see Figure 2). Technical measures are known and investment costs can be easily estimated, while knowledge on PQ cost is not necessarily straightforward.

In the last decade multiple studies have tried to analyze the causes of PQ problems and assess associated costs. This publication will briefly summarize them.

Regional and country level

The financial impact of poor power quality should be analyzed locally because the difference in costs incurred by different sites is very large (in the LPQI survey the mean value exceeds median by a factor of 3 while the standard deviation exceeds the mean value by a factor of 5). This is quite common and, for example, in an Italian survey on the costs of voltage dips to industrial customers the mean and median values differ by a factor of 6; at one extreme some customers experience tremendous costs while at the same time other customers report no costs at all, all within a relatively small geographical area and the same time frame. However the overall picture can be very important and may provide good conclusions if results are properly aggregated and extrapolated. There have been a number of studies having the ambition to do such aggregation and extrapolation of costs to national level.

In 2001 the Consortium for Electric Infrastructure to Support Digital Society under the leadership of EPRI presented a report of the Primen survey in the US. This report (later on referred to as EPRI's report) estimated the losses due to outages and other PQ phenomena at between 119 billion USD and 188 billion USD with other PQ phenomena having less than a 13% share.

In 2006 the Leonardo Power Quality Initiative presented the results of a pan European survey. The survey covered larger customers particularly from industry. It showed that power quality events can be very harmful for industry, particularly continuous manufacturing sectors. The survey reports that around 30% of the most sensitive industry sectors may incur a PQ cost of about 4% of their turnover with about 60% of the cost contribution from voltage dips and short interruptions. When extrapolating the survey to European level, the total PQ costs to European economy exceeds 150 billion €.

Analysis of the impact of interruptions and voltage dips in Norway indicates annual customer costs between 805 and 1125 million NOK (1€ ≈ 8 NOK) with 430 million NOK as a consequence of long interruptions, 255 million NOK for short interruptions and between 120 to 440 million NOK for voltage dips.

DETAILED CONSIDERATIONS

CIGRE/CIRED Joint Working Group C4.107 has developed a report summarizing the current knowledge on economics of PQ. One of the main conclusions was that, regardless of the type of phenomena, the main PQ impact arises when a process is stopped as a consequence. Such stoppages, further referred to as outages, create financial losses. Of course, the root cause of an outage may be different but still the main direct consequences are similar – a financial loss dependent on the duration of the stoppage and the scope of the processes affected. The categorization of costs can be standardized. Cost categories could be the following:

- Lost production; materials and labour which are wasted
- Labour costs of idle personnel during the outage
- Process restart cost
- Equipment damage
- Other indirect costs, such as penalties or compensation.

Additionally to this, other non-process outage related costs may appear:

- Energy losses (due to harmonics, reduced voltage value which has to be compensated by larger current or unbalance)
- Premature aging of equipment, mainly because of overheating or unstable operation
- Mis-operation costs when process is continued but cannot reach its full capacity and thus productivity is decreased

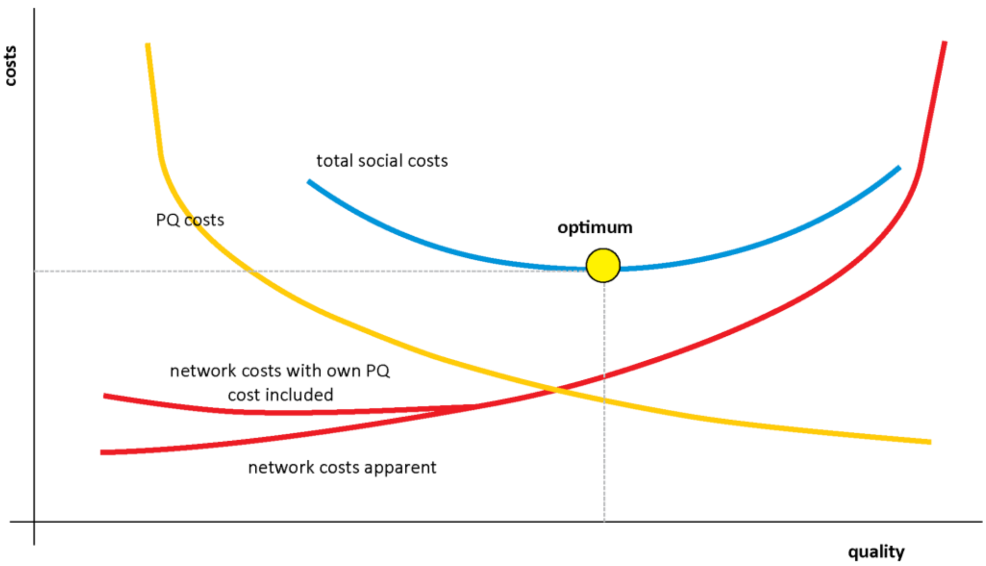

Figure 2 – The trade-off between network costs and PQ costs.

When considering consequences of poor power quality it is important to note that utilities (in Europe called Distribution System Operators or DSOs) also bear PQ costs. These costs can be divided in following way:

- Costs incurred to mitigate PQ issues (the whole variety of technical measures in distribution networks; sectionalizing, undergrounding, insulating, animal guards, lightning protection, fast switching)
- Costs of improving reliability but not PQ; reclosing schemes, redundant feeders, loops
- Costs for responding to PQ issues; call centers, responding crew, inspection, monitoring, consultations, mitigation
- Maintenance; for example tree trimming, equipment maintenance

CHARACTERISTICS OF DISTURBANCES

INTERRUPTIONS

Long interruptions are caused when a supply interruption, caused either by external factors (such as damage to cables, etc.) or by internal equipment failure, cannot be quickly restored by clearing a non-permanent fault or by switching to an alternative supply or route. There are some differences in the characterization of this phenomenon by IEEE and Cenelec in terms of the voltage thresholds and the duration that is used to differentiate between long and short interruptions. However, these differences are not so critical because most non-permanent short interruptions are much shorter than 1, 2 or 3 minutes and the residual voltage of an interruption is either zero or very close to zero rather than 1%, 5% or 10%. Long interruptions are sometimes referred to as blackouts although this second term is usually applied to interruptions of long duration and wide area coverage which can be extremely damaging. In private life the consequences can be range from inconvenience, such as limiting leisure activities, such as watching TV, or basic functionalities such as lighting. Sometimes the consequences can be much more serious. If a blackout is long and if there is no energy storage in the home, the food in the freezer and refrigerator will be wasted, space heating will not function (as even non electric heating equipment uses electricity for control and hot water circulation) so people will need to leave their homes. In extremely low temperatures water may freeze in pipes and cause serious damage. As electricity is required to power home automation systems such as alarms, fire or burglary may not be detected (the back-up supplies in such systems have a limited maximum duration).

The method most often used to quantify inconvenience and exposure to the risks described above is to determine the users' willingness to pay (WTP) more for reliable supply and their willingness to accept (WTA) compensation in case of lack of reliability. These amounts are related to consumption – most often in kWh. Since respondents prefer compensation over a higher price, the mean value of WTA and WTP is treated as a weighted user value of energy not supplied. According to Italian surveys, which resulted in regulation of continuity of supply, this value exceeds price of electricity by a factor of nearly 100 for residential customers.

For industry and commerce, the values are much higher with WTP in the order of a factor of 100 but WTA reaching a factor of 400 to 600. The reason for this is because of the heavy dependence of the economy on electrical energy and high cost of disruption when energy is not available. Furthermore, industrial facilities may experience damage to equipment, waste of raw materials and loss of work in progress during an outage. In extreme cases lack of electricity may seriously endanger safety; the damage at the Fukushima reactors may have been less extensive if the cooling water pumps had been driven by electric motors with an adequately resilient supply. When comparing WTA/WTP interviews with surveys of interruption costs, the direct costs are slightly lower but results and the proportions between different user groups are quite similar. In 2007 KEMA Consulting prepared a report, 'Quality of Supply and market regulation; survey within Europe', for ECI.

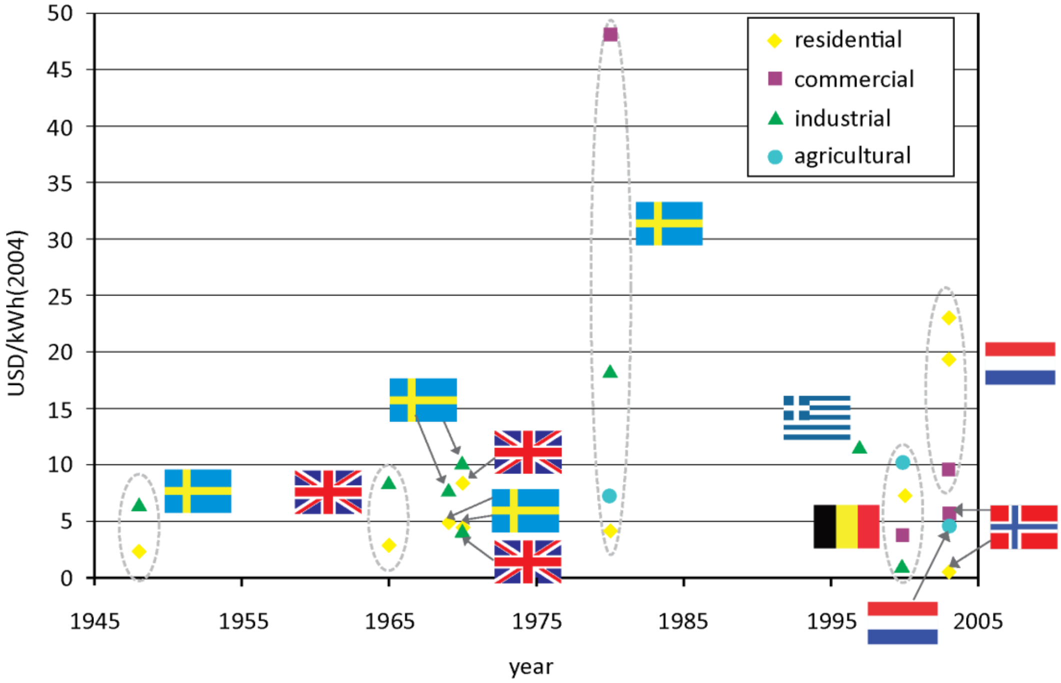

Figure 3 – Outage costs from European surveys, KEMA 2007.

The report suggests that the average value is a factor of 50 for residential customers and a factor of 200 for non-residential customers.

Sometimes damage due to interruptions is expressed as the monetary value of loss against the lost load (€ or $ per kW). This is quite reasonable and is more accurate, particularly if the damage has a different intensity over time. Typically (but it varies from one sector to another) customer damage functions are not characteristically linear but may have an “S” shape with damage per kW remaining flat until some critical moment when the function rises steeply to a higher plateau when the costs level off. In such cases, loss per kW may have very different values depending on the duration of the interruption. Some examples are illustrated by a Dutch survey undertaken by KEMA.

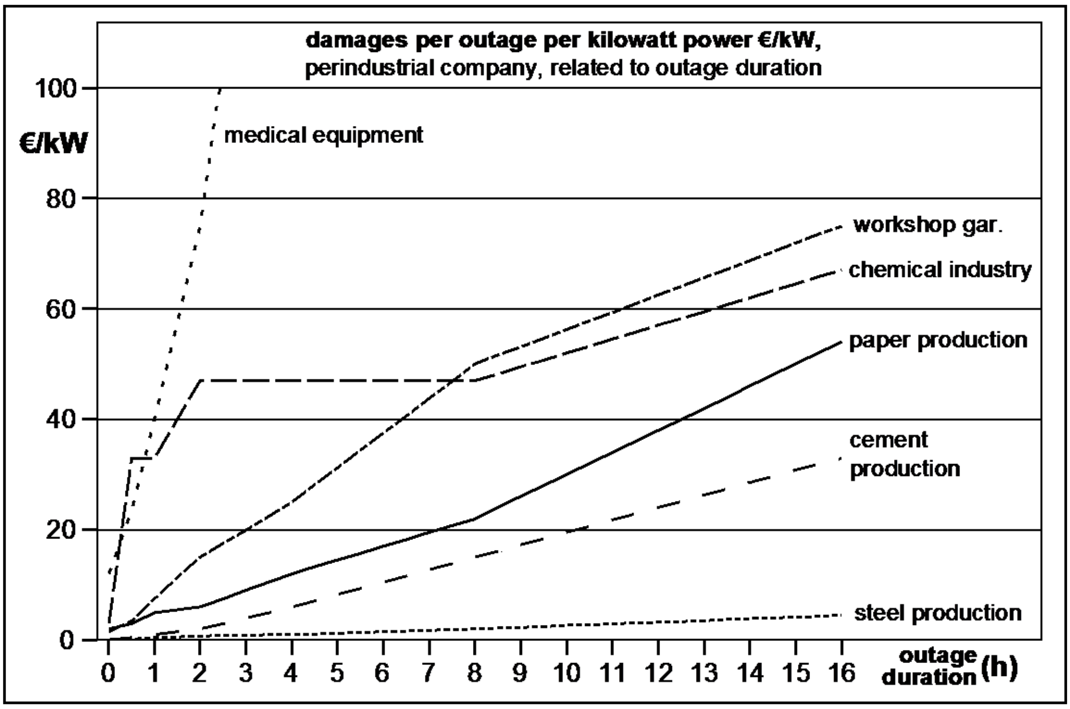

Figure 4 – Interruption costs as a function of outage duration, KEMA 2005.

There is an additional benefit of expressing customer damage functions in relation to kW of lost load; backup supply solutions are usually priced in relation to kVA of load so the investment can easily be compared to consequences of lost load.

VOLTAGE DIPS AND SHORT INTERRUPTIONS

There have been attempts, particularly of energy suppliers, to treat short interruptions in a similar way to long interruptions i.e. in terms of energy not supplied. This approach will not compensate for the real loss because the consequences, as explained above, are usually two orders of magnitude higher but what is most important in this context is that the financial losses resulting from short interruptions are not directly proportional to interruption durations. For example, the losses resulting from a 1 hour interruption will typically be an order of 2 to 4 greater than that of a 1 minute interruption while the ratio of the process restoration time will be even lower.

Short interruptions are, in fact, more of a voltage quality issue. The most common cause of a short interruption is a short-circuit fault; in such a case the fault is cleared by the high fault current – e.g. a tree branch is blown away - and is followed by a successful auto-recloser operation. Downstream of the fault, a short interruption is evident while upstream of the fault a voltage dip would be observed.

A second common cause of dips, especially of shallow dips is the starting of (or switching between) large loads (e.g. motors without soft starting), particularly if the short circuit power is low.

If the system immunity is insufficient to ride through a voltage dip or short interruption the consequence will be a production outage. Electric motors are, to some extent, protected by their inertia. However, if the voltage dip is more severe, the motor torque and speed will be seriously reduced and may face problems in returning to normal. Motors equipped with variable speed drives are even more sensitive to voltage dips as the controls will also malfunction. Other sensitive elements which may not have sufficient immunity are relays, contactors and motor starters and all electronic equipment such as computers or controllers. The light flux of incandescent lamps strongly depends on the voltage value and they are also subject to flicker. Discharge lights, for example the very popular high pressure sodium lamps, are sensitive to dips – if the discharge is interrupted it cannot be restarted until the lamp has cooled.

Immunization against dips is a very complex issue. Protecting a whole plant by UPS, which will guarantee immunity, may be very costly. The correct approach is to find those components that are critical to the maintenance of the process, such as power supplies of programmable logic controllers and contactors which are sensitive to dips.

The cost of a voltage dip is usually lower than that of a short or long interruption but dips are much more frequent. An interruption will affect all (unprotected) processes but a dip may affect only those that are most sensitive. Those not affected may, if organized in parallel paths, continue to operate without problems.

Voltage dips are mainly a problem in industry. Different surveys studied sensitivity of voltage dips in industry showing that the continuous manufacturing and IT sectors are the most sensitive. In a Swedish study from 2002, the authors presented sensitivity of different industries to voltage dips in terms of the estimated cost per industry. The highest position in this ranking is occupied by the semiconductor industry which, according to some other sources, experiences the highest cost of voltage dips compared to their electricity bill or company turnover of any sector.

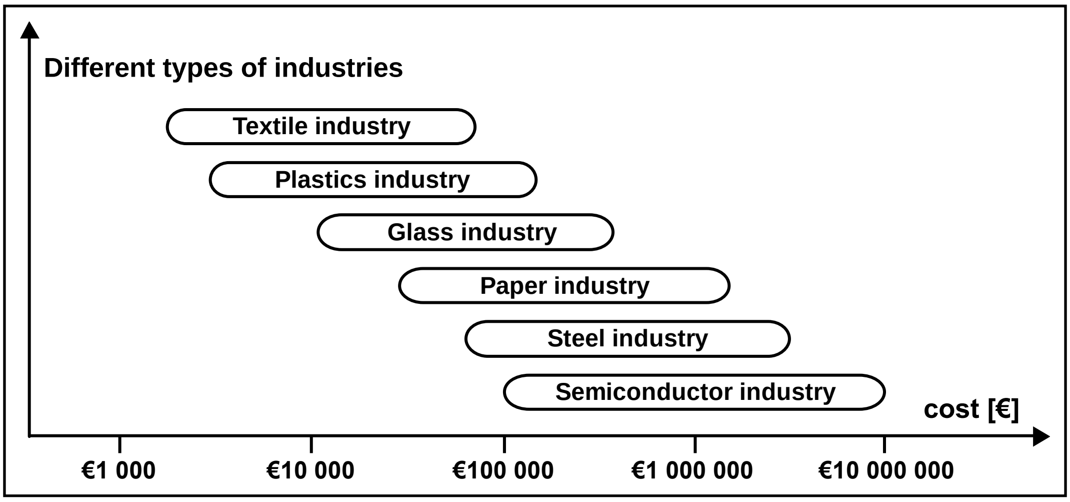

Figure 5 – Sensitivity of voltage dips to different industries, STRI AB and Vatenfall, 2002.

The conclusion of the Leonardo Power Quality Survey was that the most sensitive industries, representing 20% of European turnover and around 30% of industry, experience power quality costs equivalent to about 4% of their turnover. 24% of this cost is due to the effects of voltage dips while 19% is due to short interruptions. The cost per voltage dip event is between 2.120 and 4.682€. Short interruptions are, on average, 3 times more costly for industry and over 9 times more costly for services. All users reported, on average, 13 voltage dip events and 6 short interruptions per year.

Based on an Italian survey from 2007, those industrial sites that reported losses, incurred an average loss of 74,6€/kW while the median value (considered to be more practical for impact analysis) is 21.3 €/ kW. The most sensitive industries were metal processing and manufacturing of electrical machines. When considering the loss due to a single event the median value is 1.1€/kW, which suggests around 20 disturbing dips in a year.

Another comparison of costs of different disturbances is presented in *Table 1* showing the financial losses of large commercial and industrial customers for various disturbances adapted from this US example.

Scenario	Financial Losses ($)
4 hour outage without notice	74,835
1 hour outage without notice	39,459
1 hour outage with notice	22,973
Voltage dip	7,694
Momentary outage	11,027

Table 1 – Power interruption costs to industrial and commercial consumers of electricity, M.J. Sullivan et al IEEE, 1997

So far, the consequences of interruptions and voltage dips, which are relatively well studied and quantified, have been described. According to EPRI's investigations voltage dips were responsible for 48% of PQ problems excluding interruptions.

In the following sections the consequences of other PQ problems are briefly described.

Harmonics

Harmonics is a PQ disturbance directly related to the increasing use of non-linear loads, especially associated with the increasing penetration of power electronics. Permitted equipment emission levels are now limited by standards and manufacturers have responded by, for example, increasing the number of pulses in three phase equipment and by using power factor compensation in single phase power supplies.. Also mitigation techniques have become cheaper and more efficient. However, the number of electronic items in use means that the problem remains. Voltage distortion and, to a greater extent, current distortion may cause immediate loss by initiating a power interruption. If a transformer or power cable fails due to excessive heating caused by harmonics, the consequence will be an interruption and the root cause is harmonics. Non-outage related effects include the following:

- Current effects:
  - Erroneous tripping of circuit breakers due to higher crest factor
  - Overheating of neutrals in 4-wire circuits feeding single-phase loads
  - Overheating of transformers due to excess eddy current loss
  - Failure of capacitors due to high harmonic current
- Voltage effects:
  - Increased losses in directly connected induction motors
  - Over stressing of PFC capacitors due to resonance effects
  - Erroneous operation of controls based on zero-crossing.

Overheating of equipment leads to a serious shortening of irq service lifetime.

In the LPQI survey harmonics were found to be responsible for 5.4% of all power quality costs. However, respondents very rarely specified harmonics as the trigger of an outage with the majority of costs being allocated to process slow down i.e. small errors, minor nuisance tripping or loss of synchronization and increased error rate. 25% of the harmonic costs were related to equipment, either in the form of damage or the need for additional maintenance. Although harmonics are known to generate extra losses in equipment, respondents were unable to provide information about the scale of these losses. This is an essential observation; a potentially significant cost element remains difficult to quantify.

EPRI's survey indicated harmonics as the root cause of 22% of all power quality problems (excluding interruptions).

Recently the adverse effect of supra-harmonics (>2 kHz and < 150 kHz) came under scrutiny. These harmonics are generated by different types of electronic devices and can – among other effects – affect power line communication signals, on which automated power distribution grids are heavily relying.

Transients

Transients are voltage disturbances of very short duration (up to a few milliseconds) but high magnitude (up to several thousand volts) with a very fast rise time. Because of the high frequencies involved they are considerably attenuated as they propagate through the network so that those occurring close to the point of interest will be much larger than those originating further away.

Causes include switching or lightning strikes on the network and switching of reactive loads on the consumer's site or on sites on the same circuit. Transients can have magnitudes of several thousand volts and so can cause serious damage to both the installation and the equipment connected to it.

Electricity suppliers and telecommunications companies go to some effort to ensure that their incoming connections do not allow damaging transients to propagate into the customers' premises. Nevertheless, non-damaging transients can still cause severe disruption due to data corruption.

A little surprisingly, transients have been quite noticeable by respondents in LPQI survey. Although they do not occur very often, once they do happen very close to a site, the consequences are severe. Also EPRI identified transients as the second most visible event reported by users.

Other phenomena

Voltage swells are less frequent than dips but may also cause damage, particularly if voltage rise is relatively high. The consequence is usually equipment damage which is rather rare in case of dips. Load unbalance may overheat lines and transformers, generate extra losses and shorten equipment life. Flicker may cause so called sick building syndrome. Although the use of incandescent lamps (which are most sensitive to flicker) is now rare, recent experience shows that switching jitter in electronic converters may lead to similar issues with CFL and LED lamps. All these disturbances are however perceived as less costly. In the LPQI survey the whole group accounts for less than 5% of all PQ costs and the main consequences are process slowdown i.e. malfunction.

CONCLUSION

Different surveys worldwide show that the cost of poor power quality is significant and is comparable with the cost of the electricity bill. In sensitive sectors the magnitude of PQ costs may greatly affect the productivity of the company. The LPQI survey showed a high correlation between the amount of load covered by PQ mitigation solutions and the mitigated PQ cost. However, there is large difference in scale between the amount spent on solutions and the unmitigated PQ cost - according to the LPQI survey, this ratio is approximately 10%.

While statistics and indicatory values are helpful, no two companies, even when operating in the same sector, will be equally vulnerable to PQ disturbances. Individual checks are therefore needed.

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