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# Power Quality Monitoring and Classification

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## 1. Introduction

Experts generally agree on the need for standardized power quality indices allowing to monitor and to report power quality on a common basis. Values for the quality indices represent a few numbers that are the result of characterizing, reducing or extracting from a large volume of power quality measurement data. The systems for power quality data acquisition, storing and reporting are mostly separated stand alone applications, which have its drawbacks. However, distribution automation reveals new possibilities for continuous power quality monitoring. Advanced computer systems with open architecture make it possible to integrate power quality data with the normal network operation data.

In this chapter an overview of power quality monitoring is given. The power quality indices will be discussed and the compatibility levels as stated in the European standards and as example the National Dutch grid code will be described. Then possible methods for normalizing indices for power quality phenomena are introduced. An example of how power quality phenomena can be classified and translated into easy to understand and to analyze data is described. The end of this chapter gives details of some applications.

## 2. Power Quality indexes, levels and limits

For several reasons, there is a need for common power quality indices. With indices it is possible to report quality in a consistent and harmonised manner, either to customers, regulators or within the grid operator. The values for these indices have to be compared to the limits described by the national regulator. Because there is still a lot of discussion about the acceptable levels and the corresponding time limits (95% or 99% or 100%), converting power quality data into indices has to be done in a flexible way, so changing the limits must be possible without a lot of consequences. A number of international standard documents define the limits and the measurement process, including EN 50160 (Cenelec 2009) and IEC 61000-4-30 (IEC 2009). The last one is a standard that explains exactly how power quality instruments should work.

### 2.1 Power Quality indexes

In general the responsibility for Power Quality is a shared responsibility between grid operator, manufacturer and customers, as shown in Fig. 1.

The grid operator is responsible for the quality of the supply voltage. The manufacturers are responsible for the immunity and emission of the equipment and devices. The customer is responsible for the installation connected to the installation. The current at the point of

connection (POC) shall influence the quality of the supply voltage. That means that there should be good limits and indexes, not only for the supply voltage but also for the current at the POC. In table #.1 some of the existing power quality indices are given. Also is indicated where indices are still not available or which indices are subject of discussion in international committees. The table has indices for the quality of voltage (grid operator's responsibility) and quality of current which is (mostly) the responsibility of the customer.

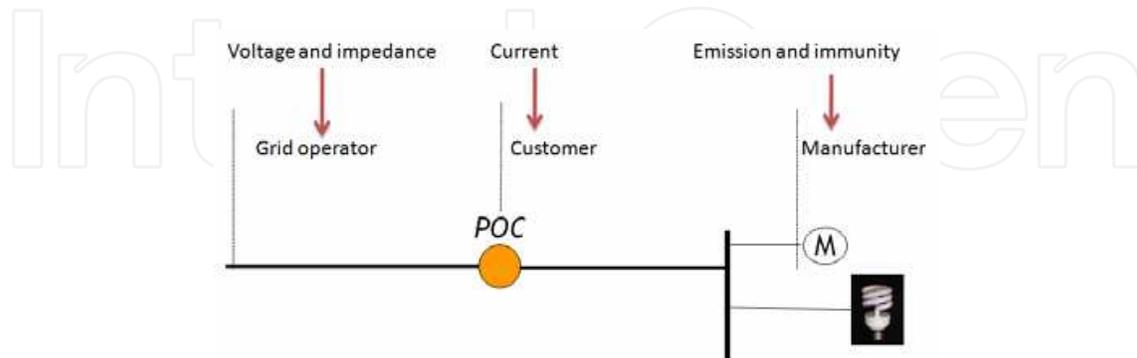


Fig. 1. Shared "Power Quality" responsibility along several parties

The current capacity of the point of connection is limited by the protection device at the POC. Certainly this is more an economic limit, because the grid operator includes a certain diversity factor for the grid design. There is only a weak relation with the voltage indices. Harmonic current limits are defined for devices, but at the point where there is a contract between customer and grid operator no harmonic current limits exist in European standards or grid codes. For the grid operator, limits at the point of connection are needed. The IEEE 519 (IEEE, 1992) aims to state harmonics for a whole installation. For flicker there is an additional requirement for flicker severity variation implemented in the Dutch National grid code. In most European countries this is not the case.

Power Quality phenomena	Indices grid operator	Indices customer
Magnitude of voltage	$U_{nom}, U_c$	current capacity at the point of connection 2)
Voltage level	$\Delta U_{nom}, \Delta U_c$ 1)	-
Harmonic voltage	$THD_U, U_h$	$THD_I, I_h$ 3)
Flicker severity	$P_{lt}, \Delta U$	$\Delta P_{st}, \Delta P_{lt}, \Delta U$ 4)
Voltage dips	- 5)	-
1) Discussion about the acceptable levels 2) Only as indication, no time restrictions 3) Harmonic currents are only regulated for devices and not yet at the POC 4) Regulated in the Dutch grid code, in most countries no indices at the POC 5) No regulation yet, discussion about acceptable number of dips is ongoing. Some restrictions in National grid codes General remark: All power quality indices are defined for a certain percentile within a measuring period of one week. Measured are the 10-minutes average values. There is discussion in international committees concerning power quality about this measuring period of 10 minutes.		

Table 1. Indices for power quality phenomena

Phenomenon	Criteria
Frequency	50 Hz +/-1% during 99.5% of each year 50 Hz +4%/-6% during 100% of the time
Magnitude of voltage (Voltage level)	Low voltage : $U_{nom}=230V$ $U_{nom} +/-10%$ for 99% of all 10 min. average measured values during 1 week $U_{nom} +15/-15%$ for all 10 min. average values Medium voltage $U_n < 35 kV$ $U_c$ =nominal voltage as stated in contract with client $U_c +/-10%$ for 99% of all 10 min. average measured values during 1 week $U_c +15/-15%$ for all 10 min. average values *+15% is still under consideration on time of printing this book
Flicker	Low voltage and medium voltage $U_n < 35kV$ $P_{lt} \leq 1$ during 95% of the time  In the Dutch grid code for example is stated: $P_{lt} \leq 1$ during 99.5% of the time $P_{lt} \leq 5$ during 100% of the time
Unbalance	Low voltage and medium voltage $U_c < 35kV$ The negative sequence voltage is smaller then 2% of the positive sequence voltage during 99.5% of the time.  In the Dutch grid code is stated: The negative sequence voltage is smaller then 2% of the positive sequence voltage during 99.5% of the time. The negative sequence voltage is smaller then 3% of the positive sequence voltage during 100% of the time.
Harmonic distortion	Low voltage and medium voltage $U_{nom} < 35 kV$ Under normal operating conditions, during each period of one week, 95 % of the 10 min mean r.m.s. values of each individual harmonic voltage shall be less than or equal to the values given in Table 3. $THD \leq 8%$ for all harmonics up to the 40 <sup>th</sup> during 95% of the time  In the Dutch grid code is additional stated: For harmonics that are not mentioned the smallest value referred to in the standard counts. $THD \leq 12%$ for all harmonics up to the 40 <sup>th</sup> during 99.9% of the time The relative voltage per harmonic is smaller than the percentage stated in EN-50160 multiplied by 1.5 for 99.9% of the ten-minute values.

Table 2. Requirements for supply voltage, EN50160

## 2.2 Voltage quality levels

The limits set by the national Regulator are used as the starting point for defining the quality of the supply voltage. As a minimum requirement, these limits have to be fulfilled at each POC (the point of connection of a customer). The European Standard EN50160 is always used in European countries as a basis for the quality of the supply voltage, so as basis for the different national grid codes. The quality of the voltage is characterised by the following aspects:

- Magnitude of voltage
- Voltage changes (Dips and flicker)
- Harmonic distortion
- Unbalance
- Frequency

Table 2. gives an overview of the power quality levels as stated in the EN50160 on June 2009.

Odd harmonics				Even harmonics	
Not multiples of 3		Multiples of 3		Order h	Relative voltage $U_n$
Order h	Relative voltage $U_n$	Order h	Relative voltage $U_n$	Order h	Relative voltage $U_n$
5	6,0 %	3	5,0 %	2	2,0 %
7	5,0 %	9	1,5 %	4	1,0 %
11	3,5 %	15	0,5 %	6 ... 24	0,5 %
13	3,0 %	21	0,5 %		
17	2,0 %				
19	1,5 %				
23	1,5 %				
25	1,5 %				

NOTE: No values are given for harmonics of order higher than 25, as they are usually small, but largely unpredictable due to resonance effects.

Table 3. Limits for harmonic voltages

At the time of printing there were no requirements in the EN50160 for the amount, depth and duration of voltage dips. Because a dip is an event and not a continuous appearing phenomenon a different classification method is necessary. In section 5 this classification method for dips is described

## 3. Power Quality monitoring

The need for monitoring the Power Quality (voltage and current) is growing. Industrial processes in installations are more and more depending on a sufficient quality of the voltage. The (over)loading of equipment as transformers, motors, conductors is depending on the quality of the current. Due to the shared responsibility of power quality it is important to monitor the voltage and currents at the POC and in the low-, medium and high voltage grid.

### 3.1 Monitoring in installations

There can be several reasons to monitor the power quality in installations. Measuring at the point of connection can be useful to check the quality of the supply voltage. Power quality

monitoring can also be used for analyzing a problem. The time scale of the measurement is totally different in both cases. The quality of the supply voltage has to be measured during at least one week. Analysing a problem for example with inrush currents and voltage deviations could be done during the moments of switching on and off the equipment involved. Also the data needed for doing these analyses is different. In the first case we need average values; in the second case even waveforms could be needed.

Fig.3 shows an example of voltages measured at a low voltage POC. Measured are according the EN 50160, 10 minutes averages during a week. The voltages are within the given limits, so no problem with voltage level is measured.

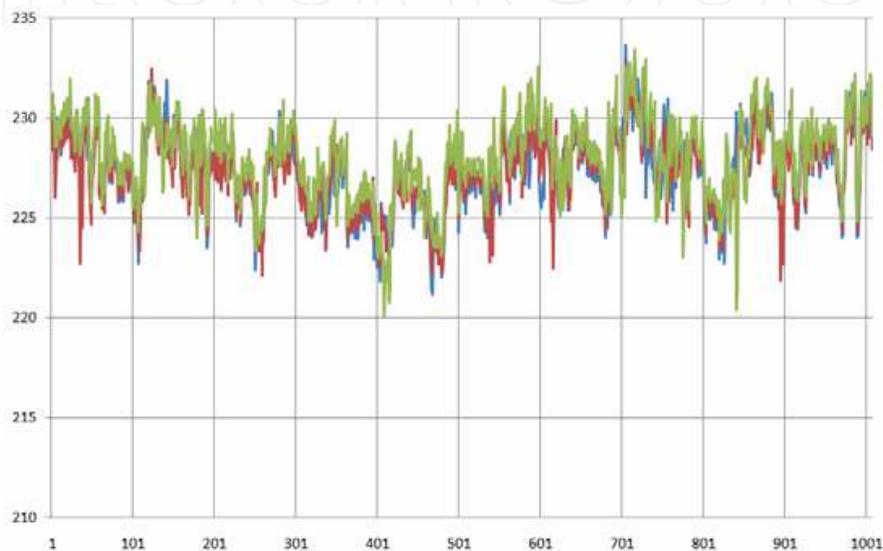


Fig. 2. Voltages measured on LV-POC (1008 measured 10-minutes averages)

Another example of a measured power quality phenomena is the flicker index  $Plt$  as shown in fig.3. The 95% limit of this index should be below 1. A serious problem is measured on this POC.

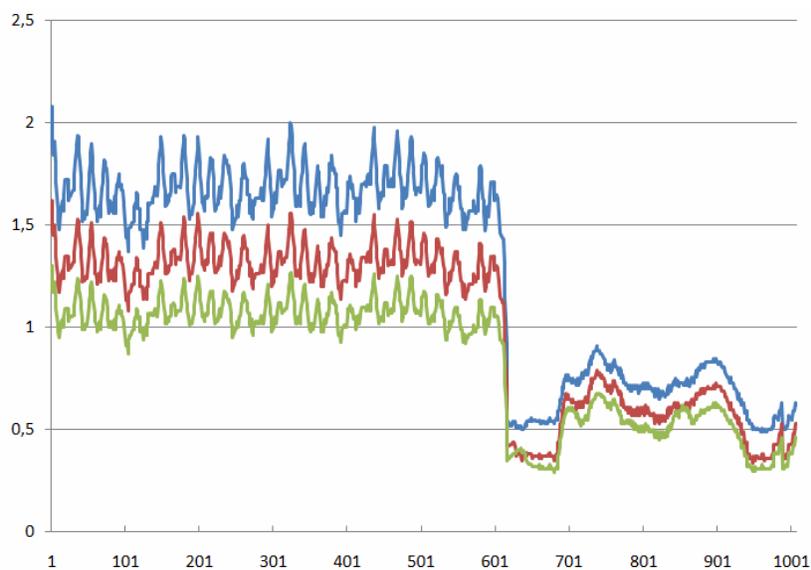


Fig. 3. Flicker index  $Plt$  measured at LV-POC

Most PQ-measurement devices will give a quick overview of several power quality phenomena to check if all phenomena are within the given limits. In fig.4 is a picture given of a possible overview screen.

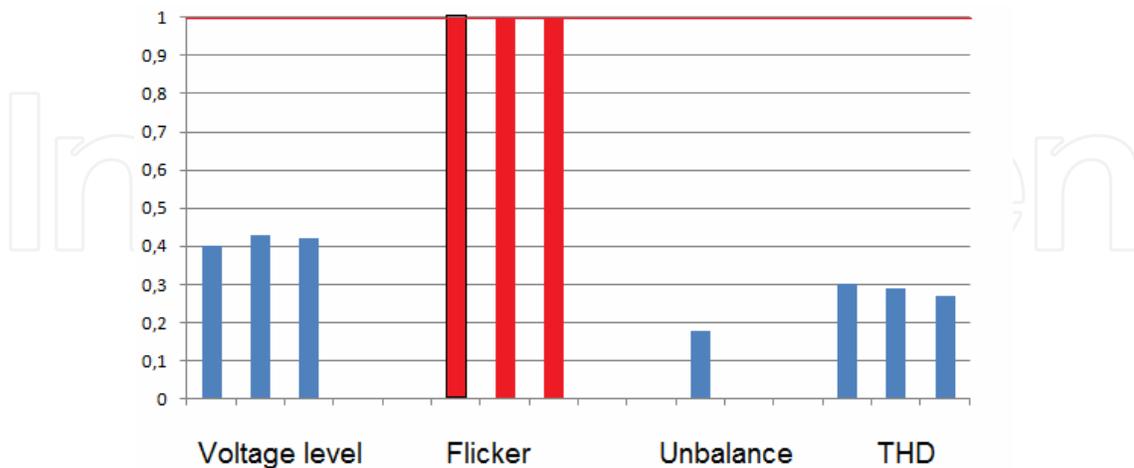


Fig. 4. Overview screen of PQ-measurement device

For a single installation it could be important to measure all power quality phenomena in voltage and current for the following reasons:

- Checking the quality of the supply voltage.
- Analyzing the harmonics in the current (overloading most of the components).
- Analysing the power flow (contract with the grid operator, overloading transformer, cables, switchgear, ...).
- Controlling trends in the power quality phenomena.
- Analyzing problems within the installation.

For most of the measurements a fixed installed measurement device is needed. For analyzing problems a portable device could be used. Measuring with portable devices could give a need for additional safety measures (see fig. 5)



Fig. 5. Measuring in an installation requires several safety measures (Source: Fluke).

### 3.2 Monitoring in grids

Monitoring in grids could be done for the same reasons as for monitoring in installations. Nevertheless, there are more reasons to measure in (more) points in the grid.

First of all is it important for analyzing the quality of the grid (supply voltage) and the operation of the grid. Also, more and more information about the quality of supply voltage is required, for individual customers but also for the National regulator.

The interest of the regulator is not only on the quality of one POC but the general level of voltage quality. This could be given by measuring the quality at a random chosen number of POC's and report about it. In Fig. 6 an example of the result of measuring the THD-level in the low voltage grid in the Netherlands is given.

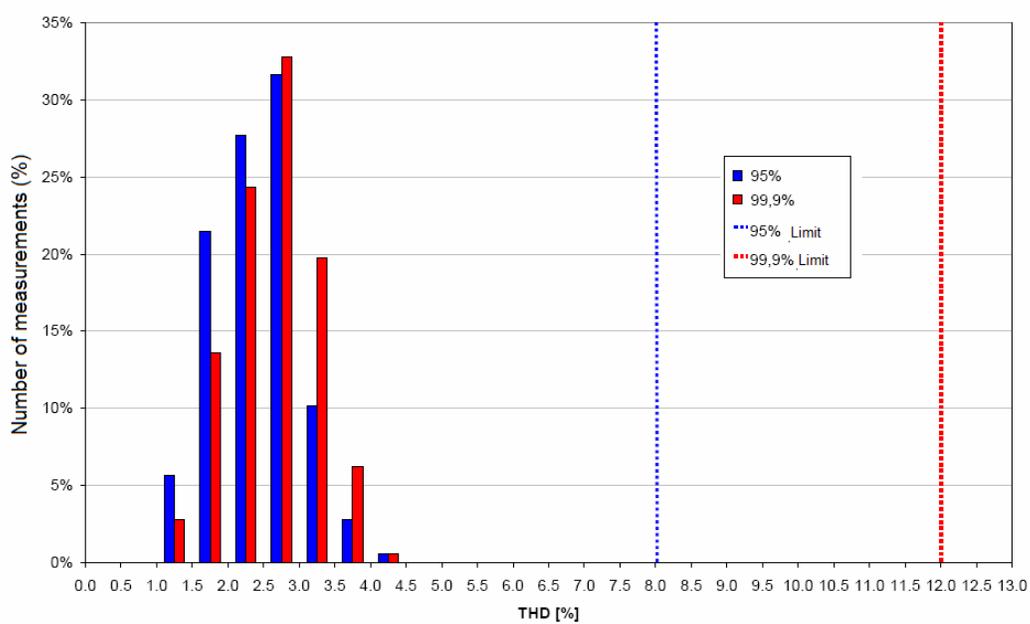


Fig. 6. Measured level of THD on random chosen POC's in the LV-grid

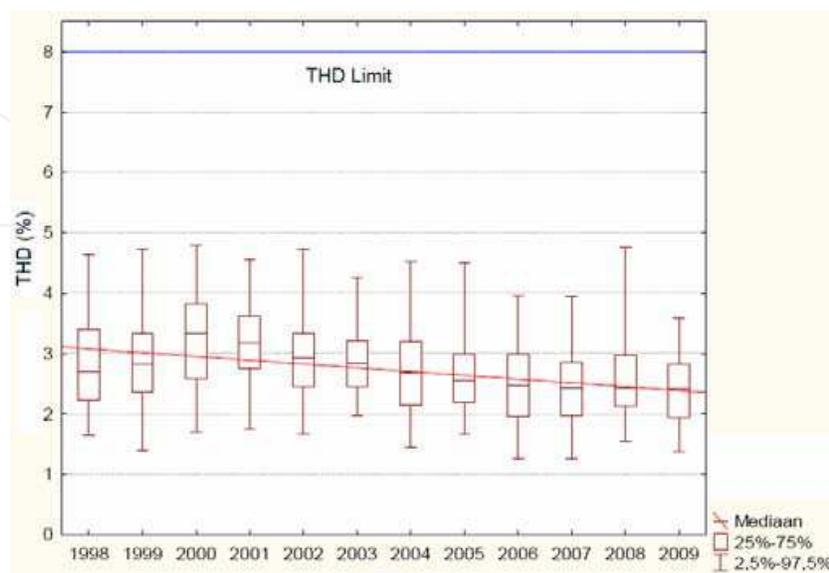


Fig. 7. Trend over the years 1998-2009, LV-grid in the Netherlands

When this is done for several years the trend over the measured years can be given. In Fig. 7 this is done for the measurements over the years 1998-2009. In spite of the connection of more non linear loads we can conclude that the level of the THD in the low voltage grid is decreasing.

In the future there will be more PQ-measurements in the grids, installed as PQ-devices in the substations (see Fig. 8) or as sensors measuring voltage and current which will also be used for analyzing the PQ-level.



Fig. 8. PQ measurement devices installed in a substation (Source: Metrum)

The advantage of having more information is more control and knowledge of the grid. The measured data can be combined with other data for fault localisation, protection, control of loads or dispersed generation and lot of other applications. The disadvantage is a lot of data what has to be analysed. So, automatic processing of data and application of data is needed. Also, for the grid operator, the customer and the regulator an easy to understand classification is needed. In the next chapter a possible method is described.

#### 4. Normalizing and classifying PQ-data

Making a classification we have to realise that most people that will use this classification are not familiar in detail with power quality and all the different limits of each phenomenon. This classification can be used for several purposes as:

- Customer's information, important for the image of the grid operator but also for industrial customers.
- To report about the quality of the voltage to the management of the grid operator, the grid owner or the regulator
- To use the data in network operation and planning

Monitoring the quality of the voltage will lead to an enormous amount of data which has to be reduced to a format that can be analysed quickly and easily. An important element in the communication with the customer is that the results should be easy to interpret. The first step in reaching a suitable classification is to normalise all power quality aspects (Meyer, J., Schegner, 2005). The second step is to make the appropriate classification (Cobben, J.F.G. 2007). Choices made here by realizing a classification are proven to be practical but can be discussed. Other choices can be made depending on purpose, planning levels, etc.

Nevertheless, the handling of data into such visual classification is a promising development.

#### 4.1 Normalising

For each continuous phenomenon we can calculate the normalised power quality level using the formula:

$$r_{(v,q,p)} = 1 - \frac{m_{(v,q,p)}}{l_{(q)}} \quad (1)$$

$r_{(v,q,p)}$  = the normalised power quality aspect  $q$ , on location  $v$ , for phase  $p$

$m_{(v,q,p)}$  = the actual level of phenomenon  $q$ , on location  $v$ , for phase  $p$

$l_{(q)}$  = the compatibility level of phenomenon  $q$

When there is no disturbance the normalised value will be 1 ( $m=0$ ). If the disturbance level is equal to the accepted compatibility level, the normalised value will be zero. If the disturbance level exceeds the specified limit, the performance index  $r$  becomes negative.

The plane from “no disturbance” to a level of “twice the acceptable disturbance level” is divided into six areas ranging from very high quality (A) to extremely poor quality (F), as shown in Fig. 9. Although the number of areas is disputable, there are good arguments for choosing six. These arguments are:

- For each voltage disturbing phenomenon a compatibility level and a planning level can be recognised. So three areas could be defined by these levels (the levels of 0.33 and 0.66 could be fitted to these levels).
- More areas will define more levels of quality than necessary but also will lead to more switching results week by week to a different quality level.
- By analysing complaints it is of interest to have some differentiation in not acceptable quality, which makes it easier to make trends visible. But in the “not acceptable quality” part it is not helpful to have more areas than three for the same reason as mentioned before.

Voltage level	Dips	Flicker	Harmonic distortion	Unbalance
1	A	Very high quality		
0.66	B	High quality		
0.33	C	Acceptable quality		
0	D	Poor quality		
-0.33	E	Very poor quality		
-0.66	F	Extremely poor quality		
-1				

Fig. 9. Classification of power quality phenomena

The classification from very high quality to extremely poor quality is made on basis of a technical judgement of the voltage. Of course, for some customers poor quality can be acceptable quality too, certainly when they can pay less for their energy. These economic aspects are not introduced into this classification.

#### 4.2 The percentile method

The most accurate method for classifying a certain power quality aspect is the so-called "Percentile Method". For each continuous existing characteristic the EN 50160 uses a certain percentile and level as a limit for the measured average values. For example, the flicker level ( $P_{fl}$ ) has to be below 1 for 95% of all measured average ten-minute values.

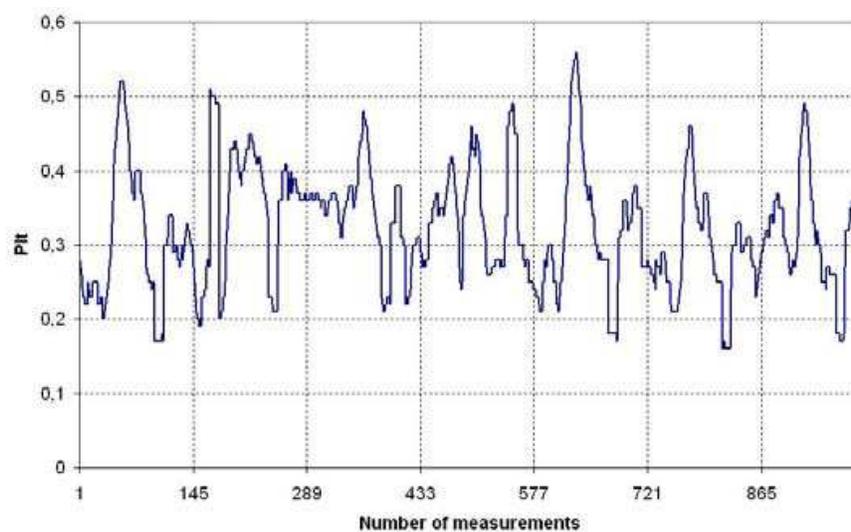


Fig. 10. Flicker level at a random chosen POC

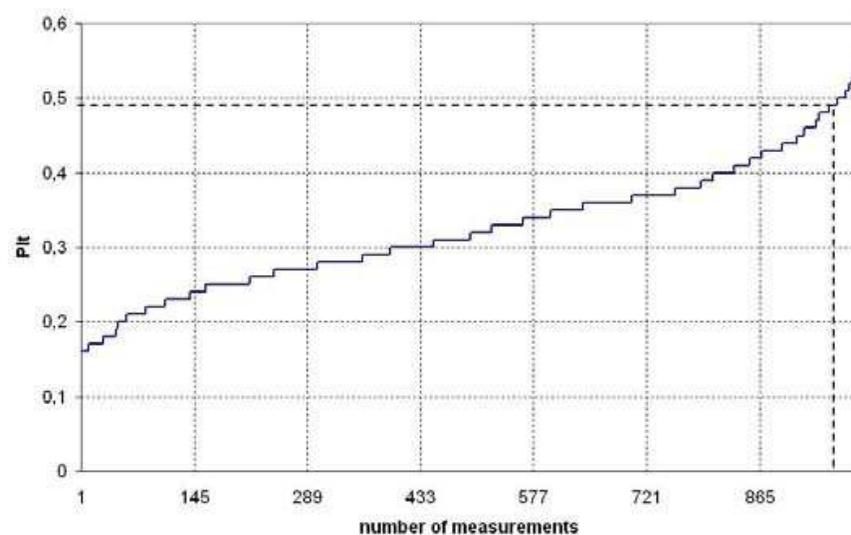


Fig. 11. Sorted data flicker level

The measured flicker level for a point of connection of a customer (POC) chosen at random is shown in Fig. 10. By sorting the data the 95% percentile value can be established, which in the given example is 0.48 (see Fig. 11). Classification of the POC with respect to flicker can be done by normalising the flicker level, the result being:

$$r_{(v,q,p)} = 1 - \frac{0.48}{1} = 0.52$$

This corresponds to a high quality classification (B) for this POC with respect to flicker. The disadvantage of this method is that the end result does not give a lot of information about

the actual flicker level. Fig. 12 shows two extreme distributions with the same 95% percentile result, nevertheless the distribution in a) presents a better performance with respect to flicker than situation b).

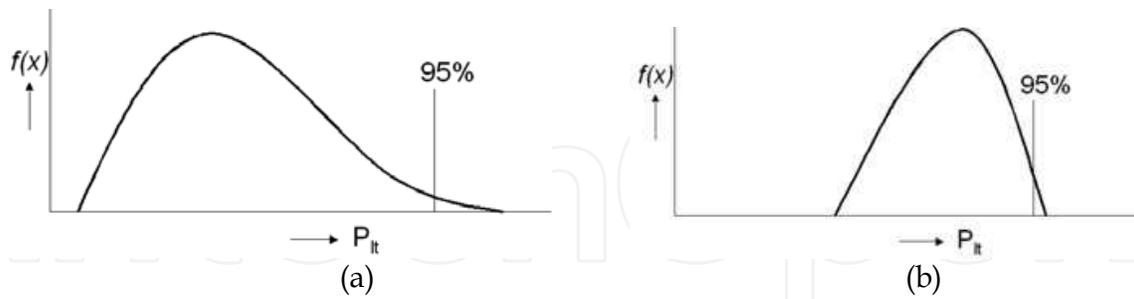


Fig. 12. Two different distributions of flicker levels

Grid operators also need good general information about the power quality level, so the 95% percentile value alone does not satisfy their needs. However, for checking the quality in relation to the standard (usually set by the regulator), this method is the most accurate.

#### 4.3 The STAV method

Classification according the “STAV (standard deviation, average value) Method” explores more information about the distribution of the aspect involved. Take for example the flicker level measured over the course of a week, as shown in Fig. 10. Calculating the average value and the standard deviation of this distribution results in:

$$P_{lt,av} = \frac{\sum_{i=1}^n P_{lt,i}}{n} = 0,323 \quad \text{and} \quad \sigma = \sqrt{\frac{\sum_{i=1}^n (P_{lt,i} - P_{lt,av})^2}{n-1}} = 0,082$$

Fig. 13. Shows how the data, as shown in Fig. 10, is distributed. Fig. 13 also includes the best fitted normal distribution.

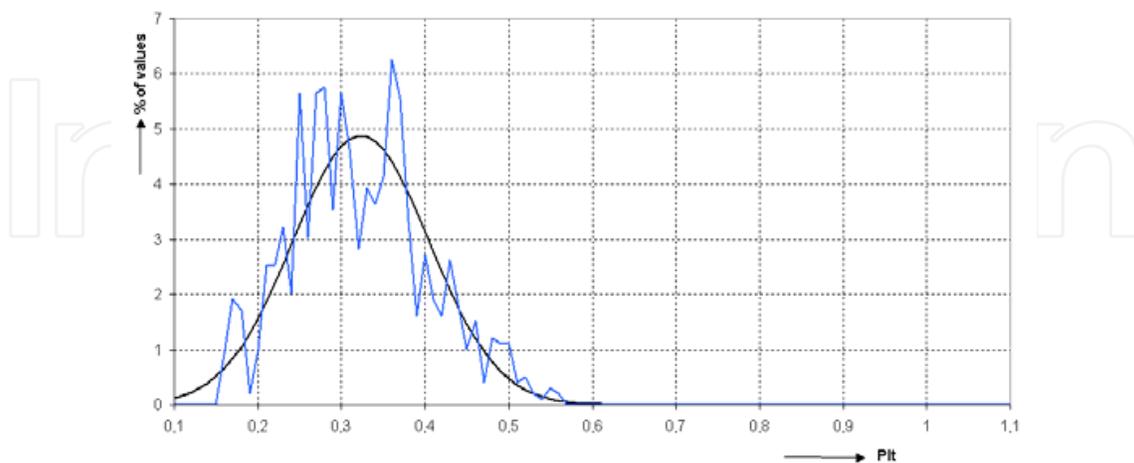


Fig. 13. Distribution of flicker level and best fitted normal distribution

Assuming that the flicker level is normally distributed, a classification method based on the same basic principles as used for the percentile method can be made. The most important requirements for the flicker level according to the national grid code are:

- 95% of all ten-minute average values of  $P_{lt}$  within a period of 1 week have to be  $\leq 1$ .
- All ten-minute average values of  $P_{lt}$  within a period of 1 week have to be  $\leq 5$ .

The relation between the standard deviation and the average value of all ten-minute values can be calculated using the following formula (#.2).

$$P_r \{X \leq x\} = P \left\{ Y \leq \frac{x - P_{lt,av}}{\sigma} \right\} = P \left\{ Y \leq \frac{1 - P_{lt,av}}{\sigma} \right\} = 0.95 \quad (2)$$

$P_r$  = chance of occurrence

$X$  = normal distribution variable

$x$  = normal distribution value

$Y$  = standard normal distribution variable

$P_{lt,av}$  = average value of  $P_{lt}$  within given distribution

$\sigma$  = standard deviation of  $P_{lt}$  within given distribution

This is the case where  $(1 - P_{lt,av}) / \sigma = 1.65$ , based on the table for a standard normal distribution. According to formula (2.1) and the borders 0, 0.33, 0.66, 1, 1.33, 1.66 and 2 as explained before, six planes can be made with the classification A through F, as shown in Fig. 14. Advantages of the STAV method are the quick overview of the quality of the considered aspect, a simplified result that is easy to communicate and less influence of some of the extreme measuring points on the weekly data. A disadvantage is that it does not answer the question of whether the measured value was within the limits required by the regulator in a certain week.

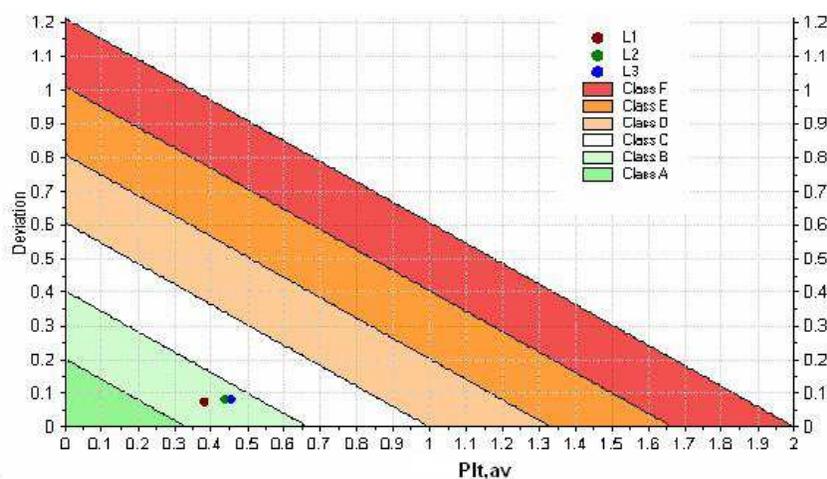


Fig. 14. Classification according STAV method (flicker)

All other continuous power quality phenomena can be classified in the same way as for the flicker phenomenon.

A particular point in relation to voltage level is that there are two limits. Take as an example the voltage measured during a week, as shown in Fig. 15.

Calculating the average value and the standard deviation of this distribution results in:

$$U_{av} = \frac{\sum_{i=1}^n v_i}{n} = 225.3 \text{ V} \quad \text{and} \quad \sigma = \sqrt{\frac{\sum_{i=1}^n (v_i - U_{av})^2}{n-1}} = 2.43 \text{ V}$$

Assuming that the voltage is normally distributed, a classification method based on the same basic principles as before can be used. Fig. 16 shows how the data, as shown in Fig. 15,

is distributed. Fig. 15 also includes the best fitted normal distribution. The normally distributed fitting curve in Fig. 15 shows that the measured voltage is indeed close to a normal distribution. The limits given by the national Dutch regulator (as still valued during the printing of this book) are taken to create the border between classification C and D. The requirements for the low voltage level are:

- The nominal voltage is 230 V.
- 95% of all measured average ten-minute values of the voltage within a period of 1 week have to be within  $\pm 10\%$  of the nominal voltage.
- All average ten-minute values of the voltage within a period of 1 week have to be between  $-15\%$  and  $+10\%$  of the nominal voltage.

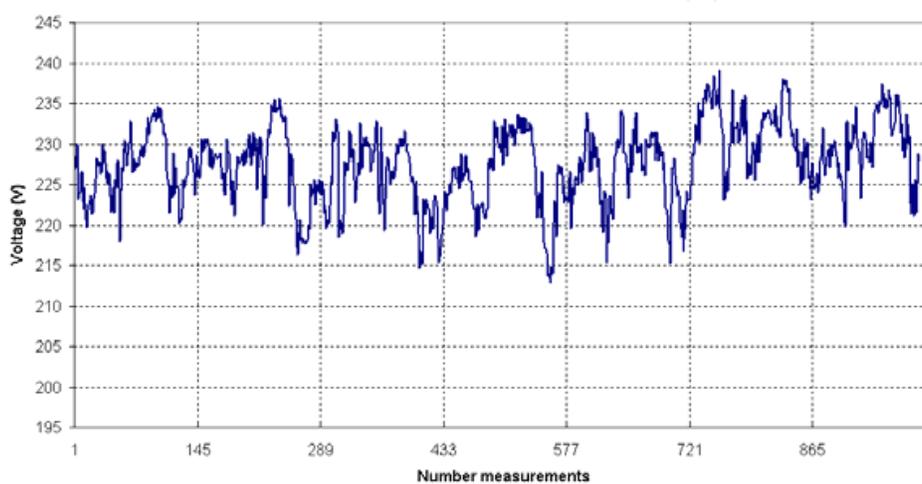


Fig. 15. Voltage measured at random POC

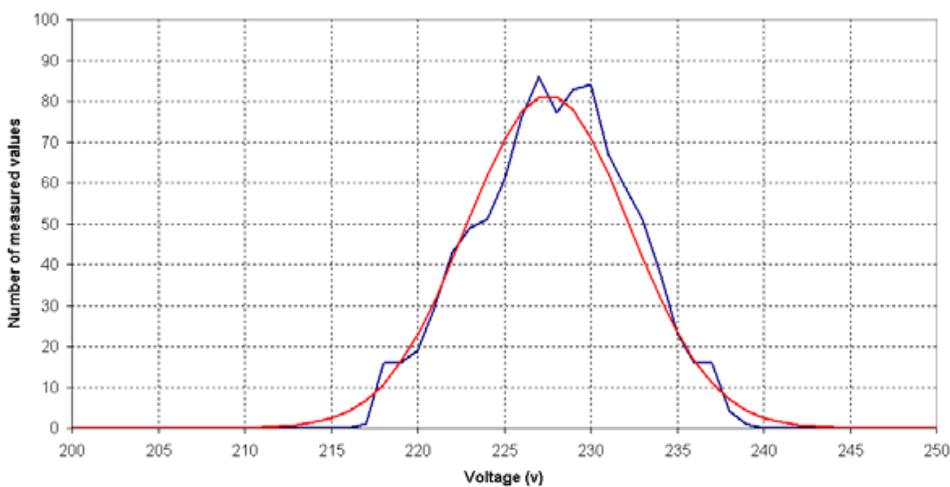


Fig. 15. Comparing measured distribution with normal distribution

For the voltage level the two theoretical extreme distributions, which just fulfil the requirements of the national Dutch grid code, are shown in fig.16. This figure plots the  $\pm 10\%$  limits of the voltage. The upper limit may not be exceeded. Here we suppose that 99.9% is acceptable. The limit on the left (lowest voltage) may be exceeded for 5% of all measured values.

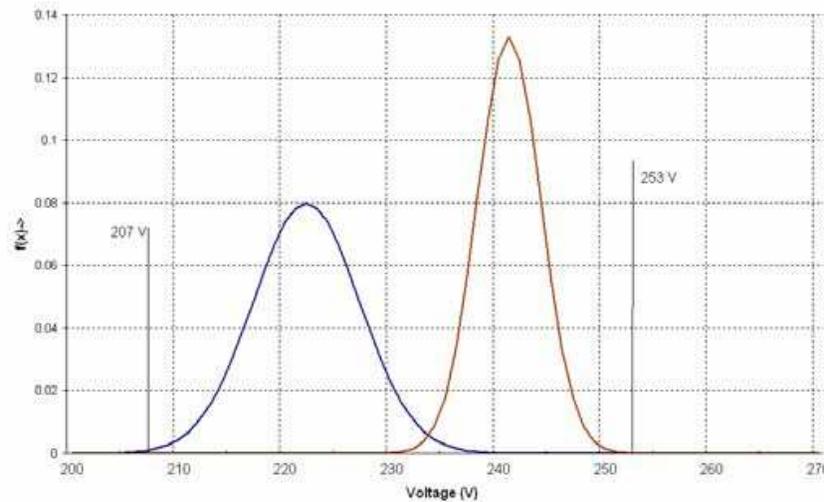


Fig. 16. Extreme distributions of low voltage level

For the upper limit the relation between the deviation and the average of all measured values is represented by:

$$P\{X \leq x\} = P\left\{Y \leq \frac{x - U_{av}}{\sigma}\right\} = P\left\{Y \leq \frac{253 - U_{av}}{\sigma}\right\} = 99,9\% \quad (3)$$

Looking at the statistical table of the normal distribution (see appendix A), this is the case where:

$$\frac{253 - U_{av}}{\sigma} < 3.1.$$

For the lower limit the following formula has to be used:

$$P\{X \leq x\} = P\left\{Y \leq \frac{x - U}{\sigma}\right\} = P\left\{Y \leq \frac{207 - U_m}{\sigma}\right\} = 5\% \quad (4)$$

This is the case where  $(207 - U_{av})/\sigma = -1.65$ . The relation between the deviation and the average voltage for both extreme distributions are shown in Fig. 17.

The lines drawn in fig.17 are the borders of the normal quality C.

Again formula (#.3) and the borders from 0 to 2 as described before are used for normalising (in this case) the voltage level. The following borders can be defined for classification A, B, D, E and F.

$$\text{Border A / B : } r = \frac{1}{3} = 1 - \frac{\left|\frac{253 - U_{A/B}}{230}\right| \cdot 100}{10} \rightarrow U_{A/B} = 253 - \frac{2}{3} \cdot \frac{230}{10} = 237.66 \text{ V}$$

$$\text{Border B / C : } r = \frac{2}{3} = 1 - \frac{\left|\frac{253 - U_{B/C}}{230}\right| \cdot 100}{10} \rightarrow U_{B/C} = 253 - \frac{1}{3} \cdot \frac{230}{10} = 245.33 \text{ V}$$

<sup>1</sup> For practical use, the 99.9% value is used instead of the 100% value

A normalised border on the minimum voltage level side is calculated as follows:

$$\text{Border B/C} : r = \frac{2}{3} = 1 - \frac{\left| \frac{U_{B/C} - 207}{230} \right| \cdot 100}{10} \rightarrow U_{B/C} = 207 + \frac{1}{3} \cdot \frac{230}{10} = 214.66 \text{ V}$$

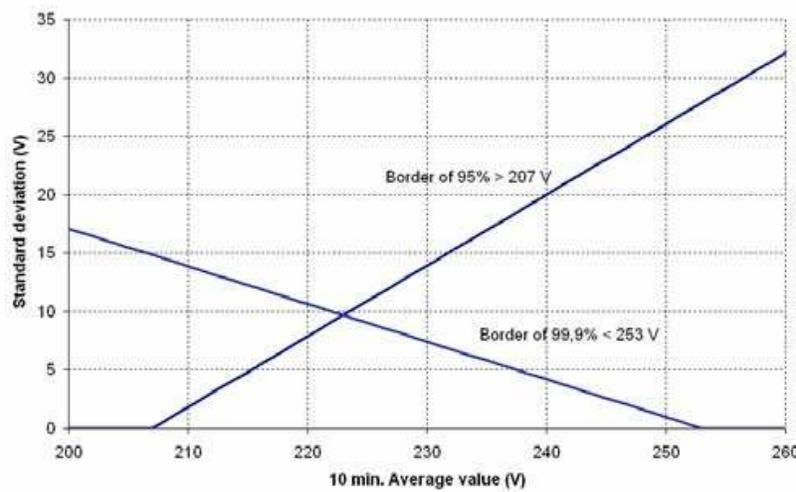


Fig. 17. Border of normal classification, low voltage level

Similarly, all other borders can be calculated, resulting in the classification areas as shown in Fig. 18.

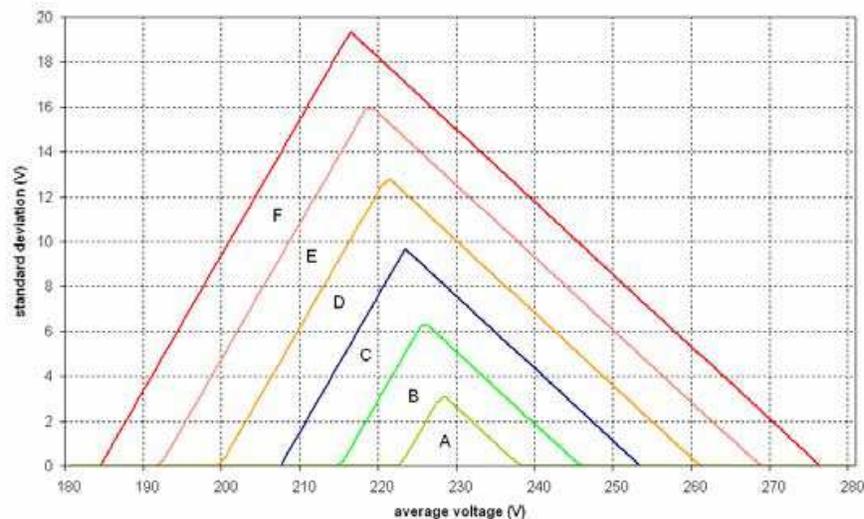


Fig. 18. Classification low voltage level

Implementation of a power quality monitoring system using this classification can help a grid operator to have a general overview of the quality of the grid without an additional need for analysing a lot of data.

## 5. Classification of dips

There are several causes for dips. The most important are faults in the MV or HV grid. Three-phase faults will have the greatest impact on the installation or processes of

customers if they are sensitive to voltage dips. Mitigation of dips will be very difficult or expensive if a lot of active and/or reactive energy is required to keep the voltage on an acceptable level. If the remaining voltage falls below 50% of the nominal voltage, a critical border is reached.

The reasons for classifying dips are:

- To make it easy to inform customers about the expected dip profile, without details which are irrelevant or even unjustified.
- To make it easy to inform the national regulator about the quality of the grid, in relation to this power quality phenomenon.
- To make it easy to gather information about dips in the grid and to draw some conclusions about the quality of the grid, taking into consideration trends over a period of several years.

Converting the dip table into a system indices or the presented “ABCDEF” classification makes it very suitable as a management tool to control the overall quality of the grid and to communicate about this power quality phenomenon in the same way as for other phenomena.

It is also possible to make the general classification more tailor-made for a specific customer with a sensitive process or installation. A good insight is then needed into the cost arising from a dip and the possible cost of mitigating a dip.

By developing a classification for dips there are some general applications where this classification can be used:

- Giving information about the background (sources) of the dips.
- Giving some guidance about the way to solve possible dip problems.
- Giving information about the quality of the grid.
- Showing responsibilities (manufacturer, grid operator, customer).

A distinction can be made between the following sources of the dip problem:

- Faults in the HV grid.
- Faults in the MV grid (primary section).
- Faults in the MV grid (secondary section, own feeder).
- Low voltage problems.

Faults in the HV grid are mostly of short duration, so the duration of the dip is rather short too. Faults in the MV grid are disconnected in times varying from 0.3 seconds to a few seconds. The depth of the dip is mostly not very big, but sometimes the depth can be large if it is a fault in the same feeder after a secondary protection device.

Low voltage problems leading temporarily to a voltage below 90% of the nominal voltage can last a longer time but these dips are never deep. In fact it should not be counted as a real dip.

Another way of looking to the problem is through the “how to solve the problem” debate. Most severe dip problems are the three-phase dips, with a remaining voltage less than 50% (Didden M., 2003). Customers can protect their installation against these kinds of dips, only with high costs. This can be a reason to divide the table into dips with remaining voltages below and above 50% of the nominal voltage. Seen from the manufacturer’s point of view the ITIC curve is an important curve. All dips that occur with a remaining voltage above this curve should not give any problem in the installation. Furthermore, we can conclude that dips with a remaining voltage below 70%, in combination with duration of longer than five seconds, seldom occur.

All these considerations make it advisable to divide the table in six parts, as shown in Table 4. The green part lies above the ITIC curve and is the responsibility of the manufacturer. All

devices have to work properly within this area. Furthermore the following parts can be recognised:

- S1: Short duration 1, mostly having its origin in the HV grid, but with a remaining voltage above 50% of the nominal voltage. Easy to solve in customer’s own installation.
- S2: Short duration 2, mostly having its origin in the HV grid, but with a remaining voltage below 50% of the nominal voltage. Difficult to solve in customer’s own installation.
- M1: Short duration 1, mostly having its origin in the MV grid, but with a remaining voltage above 50% of the nominal voltage. Easy to solve in customer’s own installation.
- M2: Short duration 2, mostly having its origin in the MV grid without coils or with secondary protection, but with a remaining voltage below 50% of the nominal voltage. Difficult to solve in customer’s own installation.
- L1: Long duration 1, occurs due to low voltage problems, mostly with high remaining voltage which makes it easy for the customer to solve in customer’s own installation.
- L2: Long duration 2, will lead to severe problems but will in practice only occur in very extreme situations.

$\Delta U$ $t_d$	0.01-0.02	0.02-0.1	0.1-0.5	0.5-1	1-2	2-5	5-10	10-20	20-60s
80-90		ITIC-curve							
70-80									
60-70		S1		M1				L1	
50-60									
40-50		S2		M2				L2	
30-40									
20-30									
10-20									
1-10									

Table 4. Classification of dips

This is a similar classification of dips as is described in the South African standard NRS 048 [Nrs01]. The areas chosen in this standard are given in Table 5.

Retained voltage U	Duration t		
	20=t<150 (msec)	150=t<600 (msec)	0,6 = t < 3 (s)
90 > U = 85	Y		
85 > U = 80			
80 > U = 70			
70 > U = 60	X <sub>1</sub>	Z <sub>2</sub>	
60 > U = 40	X <sub>2</sub>		
40 > U = 0	T		

Table 5. Dip-classification according South African standard

Although it is also a dip depth and time presentation, it is a little bit more complex and not completely according to the EN50160 dip definition. Furthermore it defines some small dips areas, what increases the problem of unstable values. Also the important border of 50% is not used.

The way to develop an "ABCDE" classification in the same sense as done in this research for other Power Quality phenomena is shown in Fig. 19.

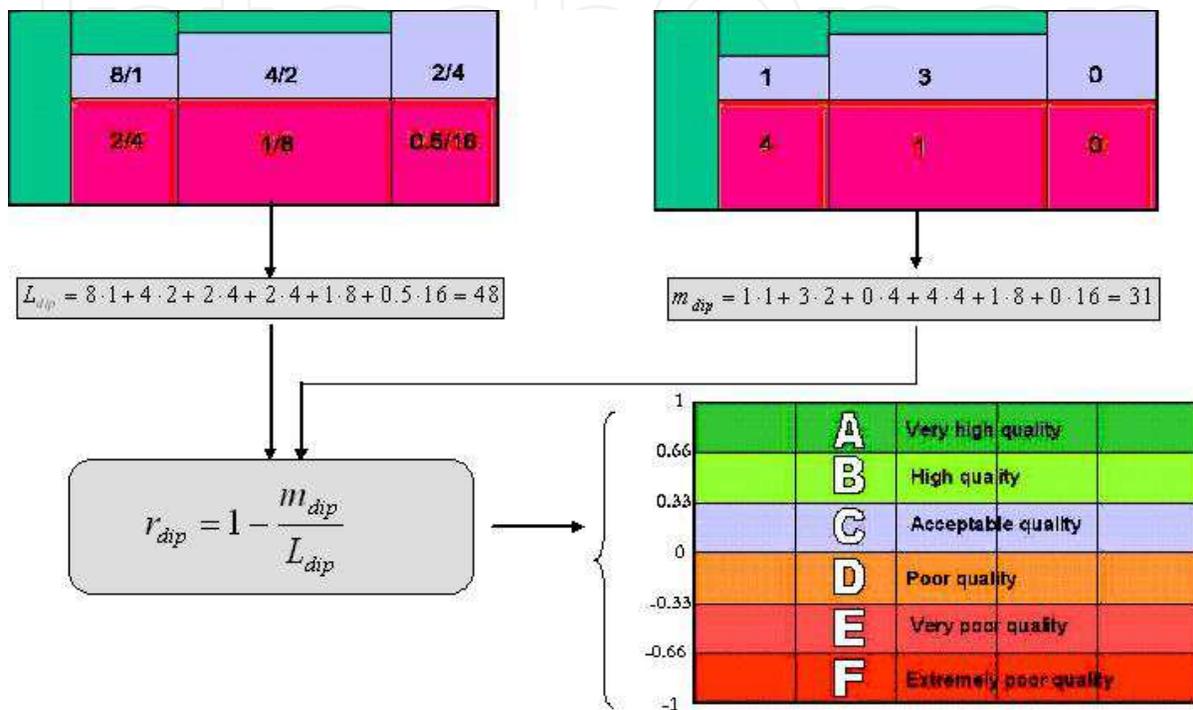


Fig. 19. Converting measured dips to "ABCDE" classification

First we have to define  $L_{dip}$ , being the limit for dips, as for example a  $P_{lt}$  value of 1 was the limit for the flicker phenomena. In each defined dip zone two parameters has to be given. These parameters are:

- The amount of dips, which normally should not be exceeded. This value could be determined by taken the 95% value of measured dips in a substation. In this example it is taken as 8 for the dip zone in the upper left corner of the table.
- The weighting factor. A certain weighting factor must be given to each defined dip zone. A deep dip with long duration will have a much higher impact on the installation than a shallow dip with short duration. These weighting factors should have a relation with the costs of mitigation of the corresponding dip. Research as described in (Wang, J., Chen, 2007) or (Driesen, J., Belmans, R., 2006) could be helpful to determine these weighting factors. In fig.19 this relation is not yet made, but the values of 1 (zone S1), 2 (zone M1) 4 (zone L1 and S2), 8 (zone M2) and 16 (zone L2) are given as example.

The maximum limit value for dips  $L_{dip}$  can be calculated using the given limits for the number of dips and the weighting of each dip zone (see fig.19). When on a POC or a substation the amount of dips are measured as is displayed in the right table, the dip value  $m_{dip}$  can be calculated. In this case it is 31, resulting in classification B, high quality but near to acceptable quality. Due to the different distribution of dips each year, the measured value

to be used should be an average value over a period of five years. A gliding window of five years could be used, giving a more stable and reliable classification of the grid.

More research has to be made after the optimal level for voltage dips objectives. The total costs for network and customer has to be considered, for determine the weighting factors. Measurements have to be performed and published to estimate the existing performance level and to determine the maximum amount of dips for each zone. This can be done for several type of grids (cables, lines, urban grids, rural grids). These measurements also see the "hidden dips" which are not included in the calculating or prediction process. With "hidden dips" is mend the dips due to faults in the grid, lasting a very short time and do not lead to interruptions

## 6. Application of Power Quality data

Power Quality monitoring can be defined as the process of gathering data about voltages and currents including time, transporting that data and converting it into useful information. The ideal power quality monitoring system should have the following characteristics:

- It gathers all of the data that is required.
- It moves the data to a certain location where it can be saved and processed.
- It converts the data into information that can be used to take action or to inform people involved.
- It combines the power quality data with other sources of data.

Power quality monitoring as stand-alone function on certain points in the network has its drawbacks because:

- It will not give a total overview of the voltage quality in the grid.
- An additional communication system is needed.

Monitoring these devices is difficult to integrate in normal operation. Therefore, power quality monitoring will in future be integrated in substation automation systems. Two examples of integrated systems which are under development within Liander (Dutch grid operator) are described in the following sections.

### 6.1 PQ-monitoring in HV/MV substations

Fig. 20 shows the integration of a power quality monitoring system in a substation, as already is implemented in several substations end 2006, beginning 2007 (Riet van, M. J., Baldinger, F. L. 2005).

The several components in the systems are:

- VIM (Voltage Interface Module); measuring the voltage.
- CIM (Current Interface Module); measuring the current.
- BIM (Breaker Interface Module); for status information about the breaker or giving commands to the breaker.

In every incoming and outgoing feeder the currents are measured with a high sampling frequency to gather information about the current waveform. This information can be used for several purposes such as:

- Power quality issues (for example harmonic distortion).
- Short circuit currents for calculating the location of the fault in combination with measured voltage.

- Remaining capacity of the feeder.

All the measured data can be stored on a local computer. Transmitting all data to a central operating room of the network operator is not efficient. Only in faulted situations it will be needed to get on line detailed information. For power quality phenomena, the data can be processed locally to determine power quality indices. These indices can be further analysed centrally. When needed, for instance in case of complaints, detailed information can be sorted out and examined centrally. The system is able to measure harmonics up to the 50<sup>th</sup> and all other Power Quality aspects stated in EN 50160, such as voltage dips, sags, swells, flicker, etc.

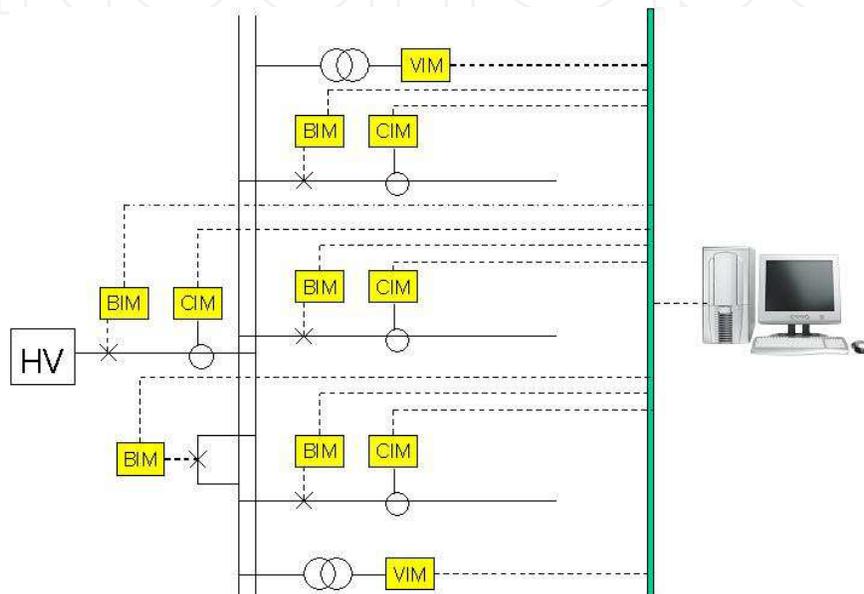


Fig. 20. Distribution automation system, implemented in a HV/MV substation

Gathering a lot of power quality data with this system is possible but analyzing all the data will take an enormous amount of time. For this reason the percentile or STAV method is used.

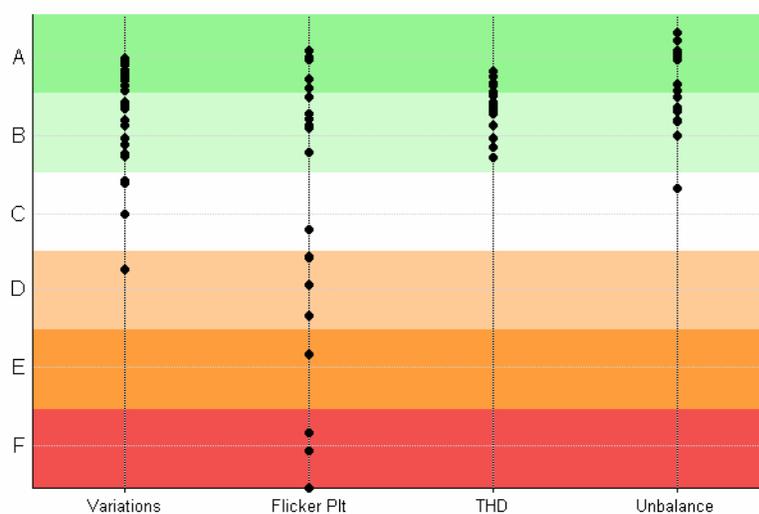


Fig. 21. Classification of supply voltage in substations (example, not based on real data)

First of all there is the advantage of sending only three values of a weekly measured power quality phenomenon: the average, the standard deviation and the 95% percentile value, whatever is important for the regulator. Using this method makes it possible to analyse the data quickly. All weekly data from the substations and transforming substations measured is plotted on a screen, as shown in Fig. 21. This gives an overview of the quality of the supply voltage for each measured busbar in the different substations and for the different power quality phenomena.

Studying Fig. 21., we can conclude that there is one location with a voltage level problem and several locations with a flicker problem. To get more information about the grid situation a more detailed screen relating to voltage level can be selected. Fig. 22 shows this screen, made using the STAV method. There is indeed one bullet across the border of plane C, placed in plane D. This means that the limit of the grid code (border between plane C and D) is exceeded.

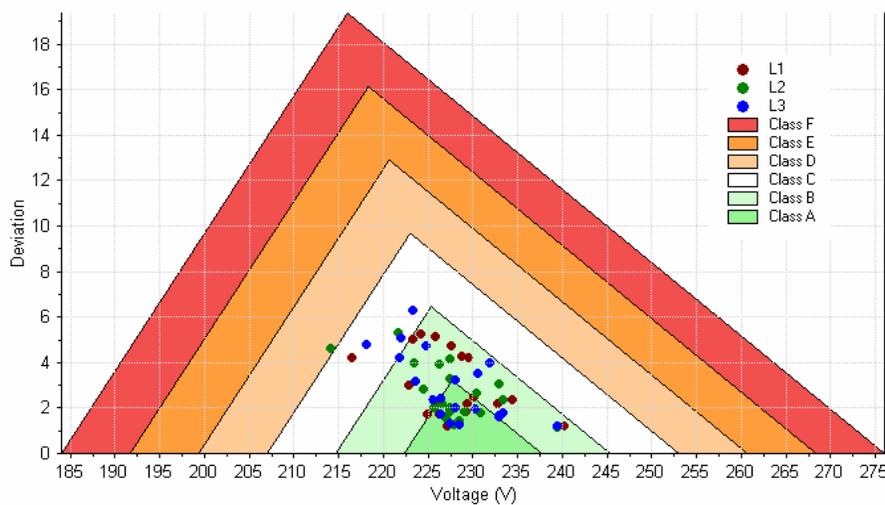


Fig. 22. Measured voltage in transforming substations (LV side), using STAV method  
The flicker problem can be analysed using the screen shown in Fig. 23.

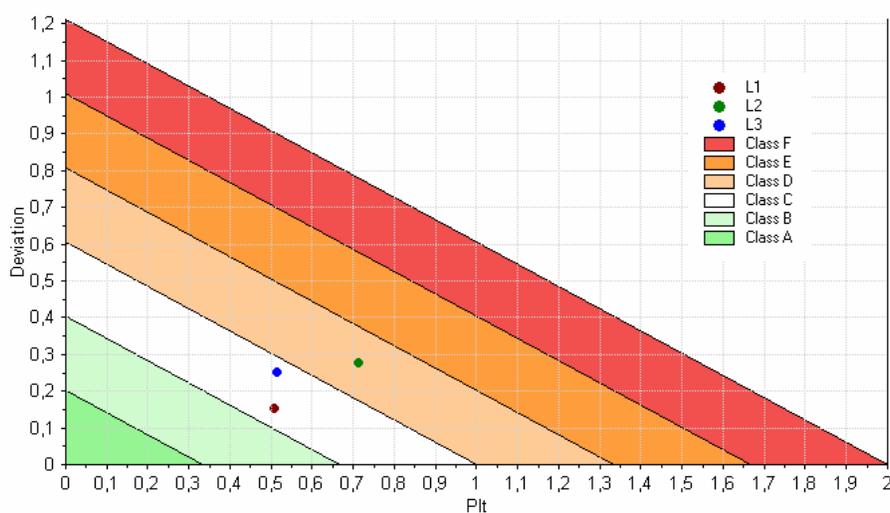


Fig. 23. Flicker data for one selected point in the grid (one phase is exceeding the limit)

Only when more detailed information is needed can all the data of this measurement be downloaded and a graph of the measured values of  $P_{it}$  made according to fig.10. In most cases this will not be necessary because the supply voltage will generally be well within the limits. Presenting the data in the way described above makes it possible to implement data of several weeks, months or even years in the same plot. Trends in the different power quality phenomena can, with all selected data in one graph very easily be analysed.

## 6.2 PQ monitoring in MV/LV substation

A second example of integrated distribution automation is the MV/LV transforming substation as shown in fig.24. With increasing DG there is a need to have more control on the low voltage network. Therefore more information about the voltage and the currents in the low voltage network must be gathered. This automation will be developed and realised in the coming years.

In the coming 5 to 10 years at all Dutch consumers premises an energy meter with additional functionality will be installed. The energy meter can be remotely managed and read. This could be based on power line communication using the existing low voltage electricity network.

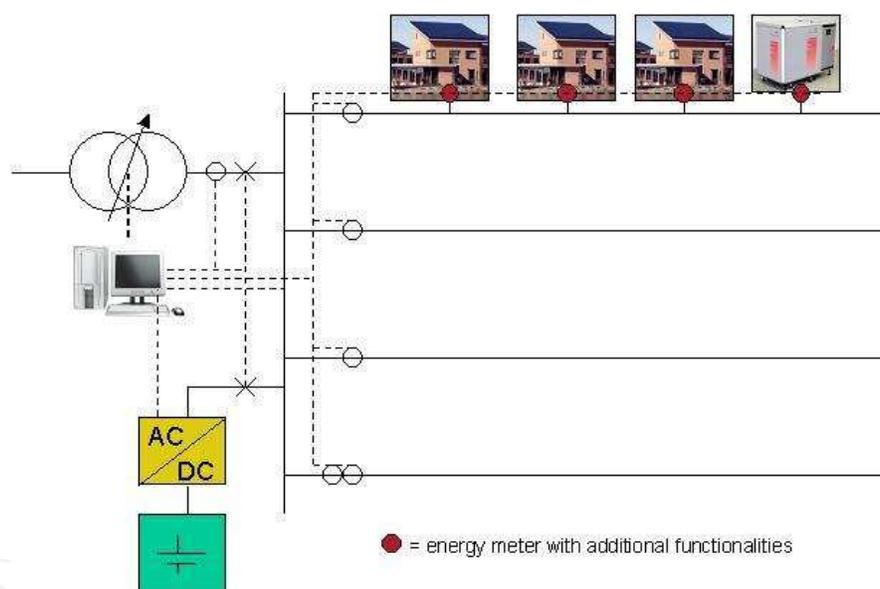


Fig. 24. Development of advanced MS/LS substation with additional functionalities

In the MV/LV transforming substation possibilities for energy storage could be present. This approach enables the grid operator to control the low voltage level, to improve power quality (harmonics flicker) and to optimise the loading of the network. Again, concentrating on power quality phenomena, the amount of data available will be enormous, so it has to be converted locally and in normal situations only indices has to be communicated to a central location.

## 7. Conclusions

For several reasons there is a need for common power quality indices. With indices it is possible to report quality in a consistent and harmonised manner, either for customers,

regulators or for use within the grid company. However, due to the growing importance of power quality, monitoring the present power quality is needed and more monitoring programs are done in the last years and will be done in the coming years. A new development is integrating power quality measurements into substation automation. However, this will lead to enormous amounts of data, even using indices. Therefore an additional classification will be helpful.

In this chapter a promising and already implemented classification is explained. The first step in reaching this classification is to normalise all power quality aspects. The second step is to make the appropriate classification. The most accurate method for classifying a certain power quality aspect is the so-called "Percentile Method". This method can be used for controlling the power quality on a single connection point of a customer. The disadvantage of this method is that the end-result does not give a lot of information about the actual power quality level. To overcome this disadvantage the "STAV Method" is introduced. Advantages of the "STAV Method" are the quick overview of the considered quality aspect, a simplified result that is easy to communicate and with less influence of some of the extreme measuring points on the weekly data. A disadvantage is that it does not answer the question of whether the measured voltage was within the limits required by the regulator in a certain week. Nevertheless, for the grid operator it is a very useful tool for controlling the performance of the grid and to inform customers and regulators about the general voltage quality in the network.

Measuring events as voltage dips and transient are even more complex. Nevertheless for each power quality phenomena an easy to use classification can be made. The data available and the need for detailed information is depending on the application. For analyzing a problem detailed information as waveforms could be needed. For monitoring the quality of the grid more average and general information can be used.

In the coming years, the need of monitoring the quality of voltage and current will rise and depending on the application data handling will become more important.

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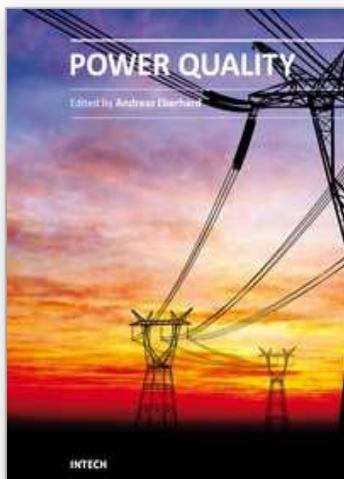
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Almost all experts are in agreement - although we will see an improvement in metering and control of the power flow, Power Quality will suffer. This book will give an overview of how power quality might impact our lives today and tomorrow, introduce new ways to monitor power quality and inform us about interesting possibilities to mitigate power quality problems.

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