Need of Voltage Quality Regulation in the Future Electricity Infrastructure

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Abstract—Electricity as a commodity should satisfy strict quality requirements. In the last two decades, the customer’s urge for good quality of power supply has increased due to the use of more sensitive electronic devices which on the other hand might influence the electricity network too. At present, no definite responsibility with respect to power quality (PQ) aspects at the point of connection (POC) is defined in the European standard EN50160 or other standard. Also, the limiting values for various power quality parameters differ in different standards available in different countries of the world. For implementing power quality regulation in the future electricity infrastructure, it is required to evaluate the actual performance level of the electricity network. In this paper, various PQ related problems in different countries of the world are highlighted. A brief overview is presented on the present PQ status of the Dutch network and other PQ related activities.

Keywords- power quality; regulation; point of connection; EN50160; PQ monitoring.

I. INTRODUCTION

Modern customers use large number of sophisticated, high sensitive equipments: for example computers, electronic ballasts, variable speed drives and other power electronic devices for their regular activities. These devices require reliable power supply which should possess a high level of power quality (PQ). However, due to their non-linear characteristics most of these devices often cause distortions in the supply voltage which might lead to poor PQ at the POC. From worldwide customer surveys, it is noticed that the complaints due to poor PQ are increasing every year among different types of customers. To identify the sources of problems, number of PQ monitoring programs have been implemented or are in progress in different countries all over the world. Voltage quality, one of the important attributes of PQ, is a multi-dimensional issue which comprises several parameters. In the international communities both IEEE and IEC (International Electro-technical Committee) have created a group of standards that addresses various PQ parameters from a variety of perspectives. In most of the European countries, the CENELEC standard EN50160 is used as a basis for the ‘National Grid Code’ for low and medium voltage networks. Various voltage quality parameters are defined in EN50160. The values of voltage quality parameters indicated in EN50160 are often found too loose for most of the European networks [1]. In South Africa the national standard NRS 048-2 is used to define the power quality of the electric supply. Therefore, a harmonization among various standards is required to judge the actual performance of a network while comparing it with the other. In this paper, the requirement of power quality regulation is emphasized and a brief comparison is done on various PQ related standards available for different countries. An overview of PQ problems experienced by the customers throughout the world is highlighted. In the last part of this paper, the ‘state of art’ of the PQ activities for the Dutch network are discussed and the project called ‘Voltage quality in the future infrastructures’ - (‘Kwaliteit van de spanning in toekomstige infrastructuren (KTI)’ in Dutch), is described. In this project, a long-term continuous PQ monitoring program has been started at different locations in the low and medium voltage networks of the Dutch grid.

II. POWER QUALITY AT POINT OF CONNECTION

A. Defining Power Quality

Regulators are more and more interested in all aspects of the power supply that have an impact on the customer’s devices from the view point of voltage quality and supply reliability [1]. Besides this, in the changing electricity market
due to liberalization and deregulations, the customers have become more aware of the ‘quality of service’ (QOS) of the electricity that is provided by the network operator. The Council of European Energy Regulators defines the quality of service as a combination of reliability and power quality of the electric supply, and the relational aspects between the utility and customers (commercial quality) and is shown in Figure 1.

Power quality is often considered as a combination of voltage and current quality. In most of the cases, it is considered that the network operator is responsible for voltage quality (VQ) at the point of connection (POC) while the customer’s load often influences the current quality (CQ) at the POC. These two characteristics VQ and CQ affect each other by mutual interaction that might lead to the distortion of the power supply at the POC. Therefore, it becomes difficult to identify the actual cause of poor power quality. [4].

Various PQ disturbances can be classified into two main categories: 1) ‘continuous’ or ‘variation type’ and 2) ‘discrete’ or ‘event type’. Continuous type disturbances are present in every cycle and typically include voltage variations, unbalance, flicker and harmonics. Discrete type disturbances appear as isolated and independent events and mainly include voltage dips, voltage swells and oscillatory or impulsive transients. [5]

B. Defining Point of Connection

The point of connection (POC) is the physical point of connection of the customer with the utility grid. Another term often used by utility is the so called point of common coupling (PCC). PCC is defined as the closest electrical point at which more than one customer may be commonly connected to the network. PCC may or may not be the same physical point as POC, depending on the network configuration [3]. In Figure 2, PCC and POC are explained.

III. OVERVIEW OF POWER QUALITY PROBLEMS

In the last two decades, PQ related problems have increased largely in almost every country. Modern society is highly dependent on digital technology and electronic devices. The uses of computers, data processing equipments, variable speed drives, electronic ballasts, etc. have increased enormously. These devices are very sensitive to voltage variations. On the other hand, these devices produce distortions in the voltage waveform due to their non-linear characteristics and therefore influence the quality of power supply. Typical PQ complaints arise from the customer side when the operation of those sensitive devices are affected leading to data loss, corruption or damage of data, physical damage of sensitive devices, flickering of computer screens, or complete loss of the power supply. It is noticed that the sensitivity to a PQ disturbance varies among the different types of customers as the financial loss associated with the poor PQ might differ appreciably.

A. Power Quality Complaints Worldwide- Brief Summary

From various surveys it is found that the complaints related to PQ disturbances are growing all over the world. The frequency of PQ disturbances and associated problems depend on many factors: such as type of customer and the equipment involved, the topology and the length of the electric lines supplying the customers and the geographical area. From various studies, it is observed that almost 70% of the PQ disturbances are originated at the customer’s premises while 30% are developed at the utility side [7].

Electric Power Research Institute (EPRI) conducted a five year (1990-1995) monitoring program for distribution power quality (DPQ-I) among 24 utilities throughout the United States of America. Another program DPQ-II was conducted in 2001-2002. From these study results, it was found that voltage sags (dips), transient over-voltages, voltage swells and momentary interruptions are common PQ problems in the American network. In 1998, a PQ survey was done by Florida Power Corporation among different electricity customers of the United States of America and the result is shown in Figure 3.
In 2001, European Copper Institute has done a PQ survey covering 1,400 sites in 8 countries of Europe. It is found that harmonic distortions, power supply reliability, voltage dips and electromagnetic compatibility are the most important issues for the European countries [8]. In the United Kingdom the complaints are due to supply standards which include fault interruptions and supply quality issues relating to voltage dips, harmonics and flicker [9].

In Tasmania, PQ survey has been conducted by Hydro-Electric Corporation in the year of late ‘90s. It is found that there are no severe problems with quality of electricity supply in Tasmania. However some PQ problems do exist that include under-voltages and over-voltages, voltage dips, interruptions and harmonics [10]. In South Africa, voltage dips and transients have been identified as major PQ problems as large part of the electricity infrastructure consists of overhead lines [11].

In the year 2004-2005, Laborelec and KEMA have jointly conducted a PQ survey among different types of customers in the Netherlands. It was found that the majority of the complaints are registered by the domestic customers (56%) followed by the commercial (12%), agricultural (11%) and small-scale industrial customers (10%). Various PQ problems as reported by the customers are shown in Figure 4.

**B. Identifying PQ Problems and their Consequences**

Different PQ problems have varying importance for different types of customers.

- It is generally noticed that the residential customers suffer inconveniences due to under voltage and light flicker. These problems generally do not have major direct financial impacts.
- Agricultural customer’s complaints are due to under voltage and stray voltage problems which affect the behavior of the domestic animals and the production.
- Commercial customers face problems for damaged equipment and business down time, data loss etc. due to sudden voltage dips. Also, there are complaints on neutral currents due to harmonics that cause additional heating of the equipments. This group of customer is also vulnerable to sudden transient surges which can cause unwanted tripping of the protective devices.
- For large industries (for example semiconductor industry, paper plants, glass and steel industries etc.) suffer large financial losses when voltage dips occur at their plant sites. Therefore, voltage dips are considered as main problem for continuous process operation. The industrial customers complain against harmonics and resonances that cause fast ageing and early failure of the equipments. Flickering of light are also considered as irritating problems.

From the survey of European Copper Institute in 8 countries of Europe (2001), it was found that poor PQ has large technical consequences and is shown in Figure 5.

**Figure 5. Consequences of poor PQ in Europe [8]**

Poor PQ in different business sectors can cause large financial losses annually [13]. Various financial impacts because of poor PQ can be categorized as follows:

- **Direct costs**: Lost production, damaged product, damaged equipment, loss of raw material, salary costs during non-productive hours, extra maintenance etc. [14].
- **Indirect / Hidden costs**: Costs of lost sales, cost of premature equipment failure, costs of out-of-specification product or services [14], costs associated with poor reputation for non-delivery etc.
- **Non-material inconveniences**: Some inconveniences due to PQ disturbances can not be expressed in terms of money (for example: loss of entertainment).

From the above discussion a brief summary on some consequences of poor PQ is obtained. It is important to identify the actual sources of problems and mitigate them. Presently, there is a dilemma for the network operators, customers and the equipment manufacturers, who should take the responsibility...
for PQ problems encountered as no standard regulation is currently available for POC.

IV. TOWARDS POWER QUALITY REGULATION

In the deregulated market, the network operators are under pressure to provide good quality power at low price. Price and quality are complementary terms but together they define the value of the service that the customers obtain from the electricity network. To reduce the price, the network operator may try to compromise the quality of power supply. To prevent this undesired reduction of quality, the need of quality regulation is considered important and is adopted by the energy regulators within Europe and elsewhere. [15]

Due to the multi-dimensional nature and inherent difficulties in the measurements, the power quality regulation is rather complicated. To make it more structured and effective, the main issues have been identified as follows:

- Develop a good understanding of PQ aspects and its measurement processes. It can be done by monitoring the performance of the existing system, quantify and compare them in light with the international best practice available.
- Define an optimal desired quality level that the customer ideally would like to achieve.
- Choose appropriate quality control in order to achieve the defined objectives.

In Figure 6, three types of quality control are distinguished.

The indirect method of quality control covers performance monitoring of the network and making the information available to the public. Secondly, it is required to develop the minimum standard for the power supply. It can be achieved by comparing various national and international standards and define clearly the limiting values for each PQ parameter. The network under consideration has to meet the minimum standard requirements that might be defined by the regulators. Under the third quality control method, incentive schemes are proposed. It is a bridge between the actual performance and the financial incentives (as penalty or a reward). This method is considered quite effective but complicated as it requires large numbers of performance monitoring at every part of the network. From the monitored data, the actual power quality of the network can be obtained in comparison to the minimum standard requirements.

A. Requirement of Performance Monitoring

Performance monitoring of an electricity network is the first step towards the development of power quality regulation and is considered as an ‘indirect’ method, as shown in Figure 6. PQ problems encompass a wide range of different phenomena with time scales between tens of nanoseconds to steady state. Many PQ problems arise from the incompatibility in the electrical environment between the utility supply system and the equipment it serves. By continuous monitoring of PQ data, the sources causing poor power quality might be identified. A majority of PQ problems can be characterized through the measurement of voltage and current[17]. As PQ events are relatively infrequent, continuous PQ monitoring of the system is required for an extended period (for example: three to five years) and all the related data have to be recorded. From the monitored data, the system operator would be able to identify any abnormal conditions of the network that might have occurred during the monitored period. If the problem is identified accurately, it might be possible to prevent it. Also, the accurateness of analysis of the monitored data and their correct interpretations are required to judge the actual performance level of the network. Six scale classification methodology, containing ‘A’ for the best quality, ‘C’ for the normal quality up to ‘F’ for the extremely poor quality, was proposed to quantify the quality of a grid [4]. To maintain a better customer relationship, all the information related to the system performance has to be available to the customers. From the measurement it is possible to find out if the customer’s device is the cause of the problem. It is the responsibility of the equipment manufacturers to ensure that their devices do not pollute the customers’ premises by emitting harmful electromagnetic emissions and the connected devices are able to function appropriately in the network. Thus, continuous PQ monitoring would indicate the network’s overall electromagnetic environment and the system’s performance.

B. Harmonization of PQ Standards

Standards are needed to achieve coordination between the characteristics of the network’s power supply and the requirements of the end use equipment. In the international community, both IEEE and IEC have created a group of standards that defines different PQ parameters. The Australian standard AS/NZS 61000 is mainly based on IEC standard. The South African PQ standard NRS048 is comparable to the IEC standard with some exceptions on the PQ measurement uncertainty criteria (such as 95% criteria) [11]. The South African standard is new in the area of voltage dip classification. The European standard EN50160 [18] describes the voltage characteristics of the electricity which is supplied to the public distribution systems. A frequent criticism of this standard is that it gives limits related to conditions that exist for 95% of the time [1]. Different voltage parameters described in EN50160 can be sub-grouped as follows and are shown in Table I:

- Parameters with limiting values
- Parameters with indicative values
- Parameters without any given values.
which would satisfy the ‘minimum standard’ requirements.

and development to define the optimum power quality standard monitor 5th and 11th harmonics in their network. In 1996, the

Signalling voltages

Unbalance

Frequency

Harmonics

Signalling voltages

Dutch grid is considered ‘good’ (class B). [20] the classification methodology [4], the power quality of the

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program, 20 permanent locations in the high voltage network as reference data for the whole Dutch network. In this new

selected carefully so that the monitoring results could be used

continuous monitoring. The PQ measurement points were

II, the extra high voltage network was also included for

previous data as stated in the previous PQM program. In PQM

interruption and voltage dip are also very important parameters

voltage variations, fast voltage variations, asymmetry and

harmonics data were recorded. From the PQM program it was

noticed that the power quality of the Dutch grid was quite good

harmonics, unbalance, slow voltage variations, dips and over-

voltage will be monitored continuously for a duration of

week in a year. The measurement was mainly done to assure

that the Dutch grid meets the requirements of EN50160 and the

Dutch national ‘Grid Code’. During this measurement: slow

voltage variations, fast voltage variations, asymmetry and

harmonics data were recorded. From the PQM program it was

noticed that the power quality of the Dutch grid was quite good and it met the requirements of the standard EN50160 and the

‘Grid Code’. [19]

It was found from other research projects that short term interruption and voltage dip are also very important parameters to
define the quality of power supply. Therefore, in 2003 another PQ monitoring program (PQM II) was introduced to
register these data for a period of one year along with the previous data as stated in the previous PQM program. In PQM
II, the extra high voltage network was also included for continuous monitoring. The PQ measurement points were
selected carefully so that the monitoring results could be used as reference data for the whole Dutch network. In this new
program, 20 permanent locations in the high voltage network along with all the connection points of extra high voltage
network were chosen for continuous monitoring. On basis of the classification methodology [4], the power quality of the
Dutch grid is considered ‘good’ (class B). [20]

A. History of PQ Monitoring Activities

From 1989, network operators of the Netherlands started to monitor 5th and 11th harmonics in their network. In 1996, the
PQ monitoring (PQM) program had been extended for low, medium and high voltage networks at 150 locations throughout
the country to measure the power quality for duration of one week in a year. The measurement was mainly done to assure
that the Dutch grid meets the requirements of EN50160 and the Dutch national ‘Grid Code’. During this measurement: slow
voltage variations, fast voltage variations, asymmetry and harmonics data were recorded. From the PQM program it was
noticed that the power quality of the Dutch grid was quite good and it met the requirements of the standard EN50160 and the
‘Grid Code’. [19]

B. PQ Monitoring at the Point of Connection

With the introduction of large numbers of decentralized generations (DG) and more sensitive end-use devices, PQ of the
network is getting increasingly influenced by the customers’ loads. To identify the sources that cause poor PQ, continuous monitoring at the customer side is required. In the programs PQM and PQM II, the main focus was on medium, high voltage and extra high voltage grids at which more number of customers are connected. It is noticed from various surveys that the disputes on PQ disturbances have increased among the network operators, the equipment manufacturers and the customers at the point of connection where these parties meet each other. Under the KTI project, main attention is given to the individual customer’s connection point and therefore mainly medium voltage (MV) and low voltage (LV) connection points are considered. Twenty measurement locations are chosen where each location has its own specific characteristics. At the POC, a DG such as wind generator, solar panels, combined heat power (CHP) plant or a customer’s load with power electronics devices or a large industrial load might be connected. Various voltage characteristics such as: flicker, harmonics, unbalance, slow voltage variations, dips and over-voltage will be monitored continuously for a duration of minimum one year. The selected PQ monitoring locations for KTI project are shown in Table II.

### TABLE I. CLASSIFICATION OF VOLTAGE PARAMETERS IN EN50160

<table>
<thead>
<tr>
<th>Group -1 Parameters with limiting values</th>
<th>Group -2 Parameters with indicative values</th>
<th>Group -3 Parameters without given values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>Voltage dips</td>
<td>Temporary and transient overvoltages</td>
</tr>
<tr>
<td>Slow voltage variations</td>
<td>Short and long interruptions of supply voltage</td>
<td>Interharmonics</td>
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<tr>
<td>Fast voltage variation</td>
<td></td>
<td></td>
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<tr>
<td>Long-term flicker</td>
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<tr>
<td>Unbalance</td>
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<tr>
<td>Harmonics</td>
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<tr>
<td>Signalling voltages</td>
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</tbody>
</table>

### TABLE II. PQ MONITORING FOR ‘KTI’ PROJECT

<table>
<thead>
<tr>
<th>Measurement Location Main PQ parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 locations of wind mills (2 nos. at MV grid and 2 nos at LV grid)</td>
</tr>
<tr>
<td>2 locations at Photo-voltaic (PV) plant in LV grid</td>
</tr>
<tr>
<td>3 locations at MV grid for Power Electronics devices</td>
</tr>
<tr>
<td>Iron factory (1 location in LV grid)</td>
</tr>
<tr>
<td>Steel factory (1 location in MV grid)</td>
</tr>
<tr>
<td>Assimilation lighting + CHP plants (3 locations in LV grid)</td>
</tr>
<tr>
<td>Micro CHP plants at 2 locations (MV/LV grid)</td>
</tr>
<tr>
<td>Decentralized power plants (DG in LV grid- at 1 location)</td>
</tr>
<tr>
<td>Bio-energy power plant and variable speed drives (1 location at MV/LV grids)</td>
</tr>
<tr>
<td>Connection to Railway service (1 no. at HV grid)</td>
</tr>
</tbody>
</table>

All measurements will be done by using PQ monitoring device ‘Alptee 2444d’. Voltage and current data will be recorded and downloaded on weekly basis using GSM for flexibility. After that the downloaded data will be analyzed and the power quality performance of the POC at the measurement location can be determined. More information would be available at the ‘KTI’ project website [21].

### VI. CONCLUSION

In the last couple of years, power quality related problems and disputes have increased among the network operators, the equipment manufacturers and the customers at the point of connection (POC). Due to the lack of defined optimal quality at the POC, these parties are not aware of their individual responsibilities concerning the power quality of the electricity supply. By developing PQ regulation for the POC, it might be possible to define the responsibility of each connected party at the POC that is economically optimal. Continuous PQ monitoring of the electricity grid is identified as the primary step towards the development of the power quality regulation. It is also noticed from the discussion of this paper that some of the PQ parameters (for example voltage dip, harmonics, slow
voltage variation and transients) are very important as they occur often in the network and might have large financial impacts. The European Standard EN50160 specifies limiting values for most of the PQ parameters while for the others it does not give any definite value. Therefore, a ‘minimum standard’ is to be developed that will define each PQ aspects, specifying limiting values. The need of PQ regulation is getting an increasing interest among the electricity regulators, governmental agencies and standard developing organizations in different countries. In the Netherlands, PQ monitoring activities for the high voltage network was started in the last decade. Presently, continuous monitoring of the low and medium voltage grids is also considered important and the Dutch network operators have taken active initiatives to implement it. In the project ‘KTI’, continuous PQ monitoring of the low and medium voltage grids has been started and it is expected that by the end of this year some interesting results can be obtained from the monitored aspects.

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