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A review on economics of power quality: Impact, assessment and mitigation

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ABSTRACT

The quality of electrical power supply directly influence the function and operation of the electrical devices feed by the electrical power system distribution network. Poor power quality(PQ) can cause peculiar operation of electrical devices which causes heavy economic loss to the customer and network operator. Poor PQ includes many phenomenon in which some are; voltage sag and interruptions, harmonics, surges, flickers, etc., and for each phenomenon the behaviour of electrical devices varies, which makes the quantification of losses due to poor PQ a complex subject. Among various PQ problems, voltage sag is more focussed by researchers from the mid of 90 s, because voltage sag directly affect the operation of electrical devices by causing interruptions (either small or large) in the process which further causes heavy economic losses. But the input (information) needed to quantify economic loss due to poor PQ varies from one method to other, and this makes a need to study the proposed methods and come to a meaningful conclusion. Quantification of cost of poor PQ (except voltage sag) is a research topic which has to be addressed to know the need of expenditure for smooth power supply. This research work includes some case studies to show the effect of PQ problems in various regions of the world. The paper includes a discussion on various indices and methodologies proposed by researchers in past to quantify PQ phenomenon, and some curves which shows the sensitivity of various equipments towards PQ problems. In this work one method is proposed for voltage sag cost calculation. At the end, proposed solutions of poor PQ problems and their implementation costs are also discussed and concluding remarks for the study is presented.

1. Introduction

Poor power quality (PQ) phenomenon rises rapidly with the growth of electronics and power electronics equipments in the electrical power distribution network. Today, the customer is more profound of the use of controllable and efficient devices, which uses power electronics converters and switched mode power supply (SMPS). Some such kind of devices are personal computers (PC), dryers, printers, variable speed drivers (VSD), programmable logic controllers (PLC), etc. These devices are also highly sensitive to PQ disturbances in the power supply network [1]. PQ phenomenon is a common name of poor PQ, hence PQ phenomenon is now onwards represented by PQ disturbance or PQ problems to show the bad nature of PQ.

PQ disturbances, like, voltage dips and interruptions, harmonics, surges and others [3] can be generated by the customer or the network operator (utility) or by both. Generally, both are responsible for poor PQ in power supply. In a study at United States of America, it is projected that approximately 70% of PQ disturbances are customer originated and 30% are caused by network operators [2]. Not only the cause, the economic losses incur on the customer and network operator due to poor PQ also varies over a wide range. In a study published for European countries, it is mentioned that the revenue loss for customer due to voltage sag and interruptions is 56% and due to harmonics is 5%, on the other hand, revenue loss for network operators due to harmonics can increase only 0.15–0.20% in total loss [4]. Due to highly variable nature of the economic losses due to poor PQ, the quantification of PQ loss becomes more rigorous.

Quantification of poor PQ problems is difficult because it may or may not have direct effect (instantly visible) on the system, for example if voltage sag leads to interruption then the electrical machines stops and the process breaks, this shows the direct effect of poor PQ, but if there is a case of voltage swell then it leads to premature aging of the electrical equipment which reduces the life of the equipment and this is not visible instantly and hard to predict. It is a tedious task to quantify those effect of poor PQ which are not instantaneously visible. Some PQ phenomenon like voltage sag, transients and interruptions shows instant effect on the system and also these phenomenon shares majority of losses incur by PQ problems [5–8], hence they are widely focussed while quantifying the PQ problems. To quantify the impact of poor PQ many countries have developed their own standards (e. g. European

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standard EN 50160) and other countries adopted some internationally approved standard codes given by IEEE and IEC.

This paper consists of five different parts. In part 1, introduction of poor PQ problems has been discussed. In this part a brief introduction about the cause of poor PQ and consequences of poor PQ is presented. An attempt is taken to show the importance and problems in quantification of PQ problem has been taken. In part 2, studies done by different surveys to show the effect of poor PQ in different region of the country is discussed. Part 3, describe the classification of PQ problems. In this part three different types of classification has been taken, First is based on the type of irregularities poor PQ introduces in the electrical power supply, second is based on the cost related attributes of poor PQ, third is based on the events and duration of poor PQ, whether PQ problem is continuous or event based. In part 4, an approach is presented to quantify poor PQ. This approach is based on the bifurcation of the cost poor PQ incur on customer and network operator. Part 5, shows various methods proposed by the researchers in past to quantify PQ problem is shown. At last in part 6, a discussion about the proposed method, their advantages and disadvantages has been discussed and a conclusion is presented.

2. Effect of PQ problems in different regions of the world

In past few years, economic losses due to poor PQ has been seen apparently From customer to network operator a variable heavy burden of economic loss is seen, like, in a manufacturing industry, where a continuous operation is required, a single interruption can cause a loss of millions of dollars [8,15]. In some other industry harmonics can be a problem and so on. The PQ problem faced by the world is not unique and it is validated by the studies shown below.

A PQ survey conducted by Leonardo Power Quality Initiative (LPQI) [4] in 8 European countries reveals the share of different type of PQ problems faced by the countries. Percentage distribution of different PQ problems faced by the countries are shown in Fig. 1.

Voltage sag and interruptions (both long and short) covers a majority of 55% share in PQ disturbances, are generally caused due to switching phenomenon at consumer premises and lightning or faults at network operator side. Transients and surges are some other problems which covers a 29% of total PQ problems.

Another survey conducted by Electric Power Research Institute (EPRI) in 24 utilities of United States of America [9] concluded that the customers faces mostly problems due to supply standards related to restoration after fault interruptions. It was concluded that the PQ related problems shared by customers are voltage sag/swells (48%), harmonics (22%), wiring/grounding (15%), capacitor switching (6%), load interactions (5%), others (4%). In the survey apart from voltage sag/swells, harmonics has a major contribution. Harmonics problems can be further classified as:

- Overheating of neutral conductor
- Unwanted tripping of protective devices
- Additional zero crossing causing malfunctioning of equipments

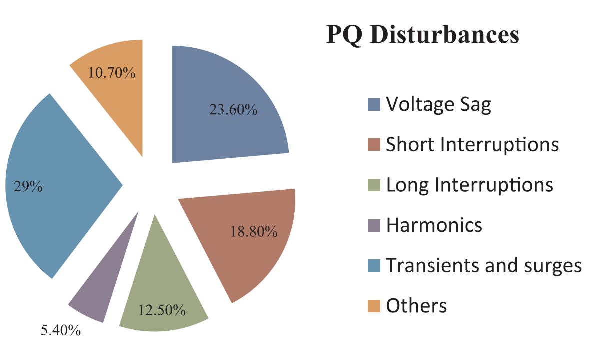

Fig. 1. LPQI Survey, PQ disturbances types [4].

- Overstressing insulation

The countries (Like South Africa), in which overhead lines captures large part of electricity infrastructure, voltage sag and transients are major problems.

In Australia, distribution voltage level is normally on the higher side of the voltage range. Hence, the chances of overvoltage is higher. Overvoltage causes premature aging of the devices which reduces the life time of the device [10].

In conclusion, different countries faces different type of PQ problem. Like in European countries, harmonics shares a majority of only 5% in all PQ problems but in American countries, harmonics shares a majority of 22% in PQ problems. Hence, a general calculation is not applicable for all types of PQ problem. A more specific and accurate prediction of cost is needed.

3. Classification of PQ phenomenon

PQ phenomenon is a wide subject and researchers have made several attempts to classify it. In general PQ phenomenon is classified by the type of irregularities it introduces in the electrical power supply, like it is classified as voltage sag and swell, harmonics, transients, etc.

Some researchers have classified the PQ problem based on the costs attributed to PQ [10,16]. The cost incur due to poor PQ can be bifurcated into direct cost and indirect cost.

Direct Cost Includes:

- Loss of production during continuous operation
- Loss of resources and time
- Waste in semi-finished production
- Restart of process
- Equipment damage
- Costs associated with human safety and health
- Environmental financial penalties
- Utility costs due to interruption

Indirect Cost Includes:

- The costs to company due to production delay
- The financial cost of loss of market share

One more classification is proposed in the literature for poor PQ. The classification is done between the events which are continuous in nature(continuously persists) and the events which are not continuous and occur in certain frequency known as: (i) continuous PQ index, (ii) event-based PQ indexes [2].

3.1. Continuous PQ index

Continuous PQ problems are deviation of actual waveform (voltage or current) from desired waveform for considerably longer time. The difference between actual waveform and desired waveform is known as quality loss and the magnitude of quality loss is measured by the depth of deviation. Continuous PQ indexes can be further divided in two intervals, namely qualified and unqualified. The basis of division lies in the range to which the effect of particular index is not considered significant. In qualified range economic loss is not visible, hence to quantify losses in continuous PQ indexes only unqualified range of deviation is considered. Table 1 shows interval division of continuous power quality indexes on a 10 kV power supply system.

To quantify the continuous PQ index, the law of probability and statistics is used. By estimating the time during which continuous PQ indexes resemble unqualified interval in the total evaluation period, probability of individual index can be given by Eq. (1)

$$P_{ki} = \tau(k)/T \quad (1)$$