

Decision path for investments on solutions to power quality problems

Citation for published version (APA):

Bhattacharyya, S., Cobben, J. F. G., Myrzik, J. M. A., & Kling, W. L. (2008). Decision path for investments on solutions to power quality problems. In L. Encica, B. L. J. Gysen, J. W. Jansen, & D. C. J. Krop (Eds.), *4th IEEE Benelux Young Researchers Symposium in Electrical Power Engineering, Eindhoven, The Netherlands, 7-8 February, 2008* Technische Universiteit Eindhoven.

Document status and date:

Published: 01/01/2008

Document Version:

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

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Decision Path for Investments on Solutions to Power Quality Problems

S.Bhattacharyya¹, J.F.G. Cobben^{1,2}, J.M.A Myrzik¹, W.L. Kling¹

¹Technical University Eindhoven, Eindhoven, the Netherlands

²Continuon, Arnhem, the Netherlands

Abstract— During the last decades, power quality (PQ) related disturbances in the electricity networks have got increased attention. The customers have become more aware of the power quality of the electricity supply. They use more sensitive electronic devices that demand undistorted power supply. On the contrary, these devices often cause PQ disturbances into the network themselves. Some of the PQ problems (such as voltage dips, transients etc.) can cause large techno-economical inconveniences to the customers while some other PQ problems (such as harmonics) can have adverse impacts on the operation of the network components. As PQ problems are mostly originated from the customer side, the network operators do not want to take full responsibility of delivering an undistorted supply voltage waveform at the customer's terminals without current quality regulation. Hence, PQ related disputes among the customers, the network operators and the equipment manufacturers have increased. A number of PQ mitigations methods, with varying cost and effectiveness, are available to solve different PQ problems. PQ disturbances can cause large financial losses while PQ mitigations might need significant investments. So, the decision of investment for solving PQ problems requires a detailed cost-benefit analysis for all parties involved.

Index Terms— Power Quality (PQ), Mitigation techniques, Cost-benefit analysis, Net Present Value (NPV).

I. INTRODUCTION

POWER quality (PQ) has become an important discussion topic in the present electricity delivery environment. The increasingly high concentrations of power electronic equipment usages such as: variable speed drives (VSD), programmable logic controllers (PLC), power electronics converters, energy-efficient lighting and other appliances have changed the electric load nature. These equipments are the major producers of various PQ disturbances because of their non-linear current characteristics and simultaneously they are the major victims of PQ problems too. In the competitive market any loss of production hour for an industry, because of poor PQ, might cause large financial losses and bad reputation. Moreover, the deregulation and reorganization in the electricity supply have compelled the network operators to reduce their service price while their obligations and duties become stricter. As price and quality are two complementary terms, it is anticipated that the reduction in unit price could lead to a poorer PQ in the future network infrastructure. The customers expect to get a voltage at their point of connections (POC) that should comply with the European standard EN50160. On the contrary, their equipments might produce current emissions that mutually interact with the network's voltage and distort the

supply voltage waveform. At present, the available standards do not specify sufficiently the responsibilities of the connected parties: namely the network operator, the equipment manufacturer and the customer at the POC. As poor PQ can have large techno-economic inconveniences, disputes among these parties are increasing regarding their individual responsibility at the POC. So, a detailed cost-benefit analysis considering the impacts on the related parties is to be done while deciding on a financial investment for the improvement of PQ of the electric supply.

In this paper, a decision path flow chart is proposed for solving PQ problems and different mitigation methods that are available are discussed. In the later part of this paper, a cost-benefit analysis using a 'Net Present Value (NPV)' method is discussed for two types of PQ problems, considering the impacts on different parties connected to the network.

II. POWER QUALITY DISTURBANCES

The Council of European Energy Regulators defines the 'quality of service' as a combination of the supply reliability, power quality and the commercial relationship between the utility and the customer [1]. In this paper power quality related issues will be discussed. PQ disturbances are classified into two categories:

- 'Continuous' or 'variation type'
- '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, swells and oscillatory or impulsive transients [1].

In the last decade, PQ complaints among the customers every where in the world have increased. From the first PAN-European survey, conducted by the Leonardo Power Quality Initiative (LPQI) among various customers in European countries, it was concluded that voltage dips, short interruptions and transients are the main problems that cause financial losses, especially to the industrial and commercial customers; while the power system harmonics is found to be a significant growing problem in the European networks [2]. It was found from the survey results that on an average the absolute share of impacts of the PQ disturbances are due to voltage dips (23.6%), short interruptions (18.8%), long interruptions (12.5%), harmonics (5.4%), transients and surges (29%) and other PQ related

problems (10.7%). Different PQ problems have varying importance for different types of customers and for the utility. In the survey, the total annual costs of poor PQ were estimated to be more than 150 thousand million euros for EU-25 in 2003-2004 [3].

III. TECHNO-ECONOMIC IMPACTS OF POOR POWER QUALITY

The customers typically complain on PQ problems when the functioning of their sensitive devices is affected leading to data loss, corruption or damage of data, loss of synchronization of process equipment, physical damage, flickering of computer screens, dimming of lights, nuisance tripping of contactors, mal-operation of devices etc. The origin of PQ disturbances can be divided into four main categories:

- Natural phenomena and human errors (storm, lightning, digging of cables etc.).
- From neighbours having variable disturbing load demands.
- From the customer's own installation because of their own disturbing loads.
- From the utility grid due to the switching operations.

Poor PQ can have significant techno-economic consequences both to the customers as well as to the network operators. PQ problems cause business down time for the commercial customers, production hour loss for the industrial customers, revenue loss for the network operators and extra maintenance cost for the damaged equipments to all parties. It is often difficult to specify the exact amount of financial losses. Field surveys, interviews and case studies are carried out to estimate the costs of poor PQ. The PQ costs can be categorized in three parts: direct cost, indirect cost and non-material inconveniences. Direct costs include damage in the equipment, loss of productivity, salary cost during non-productive hours etc. Indirect costs are generally difficult to estimate. It includes costs of lost sales, premature equipment failures, costs associated with poor reputation for non-delivery etc. Non-material inconveniences are most difficult to express in terms of money and are related to loss of leisure hours, entertainment etc. Consequences of a PQ disturbance in a production company are discussed below [3]:

- Staff cost – this is the cost because of personnel rendered unproductive due to the disrupted work flow.
- Work in progress – this category includes the costs of raw material involved in the production which is inevitably lost, labour costs involved in the production, extra labour needed to make up for lost production etc.
- Equipment malfunctioning – if the equipment is affected, the consequences can be the slow down of the production process, extra 'idle' time.
- Equipment damage – if the equipment is affected, the consequences can be complete damage of the device, shortening of device's life time, extra maintenance, need of stand-by equipment etc.
- Other costs – this category includes the costs because of penalties due to non-delivery or late delivery,

environmental fines, costs of personal injury (if any), increased insurance rate etc.

- Specific costs – this category cost includes extra energy use due to harmonic pollutions produced by the non-linear operation of the devices, fines incurred by the utility for generating harmonic pollution in the network. Reduction of personal working efficiency and related health problem due to flicker can also be included in this cost category.
- Savings – there are some savings in the production because of PQ disturbances. It includes the saving from the unused materials, saving from the wages that are not paid, savings on energy bill etc.

The costs as a result of PQ disturbances have been estimated from the LPQI survey for the EU-25 countries during year 2003-2004. It was found that 50% of the PQ cost because of a voltage dip event belong to the work in progress category while process slow down accounts for another 30% of the total cost [3]. The damage caused by a dip event depends on the dip's depth and its duration, and the type of production process influenced.

A voltage dip event can disrupt the operation of sensitive process devices which might lead to partial or complete interruption of the customer's plant operation. A device's immunity to a voltage dip event depends on its voltage tolerance performance curve. It is noticed from case studies from Laborelec that computers, variable speed drives (VSD) and contactors are the most sensitive components in a process industry [4]. PQ costs for a voltage dip event in different industries are shown in Figure 1.

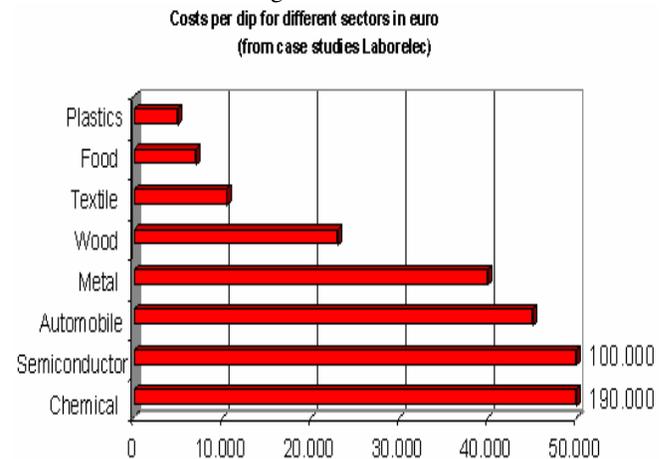


Figure 1: Total costs as a result of a dip event [4]

The total financial losses due to voltage dips can be calculated with the following equation (1) [4]:

$$D_{tot} = \sum S_{tot} \cdot D_{dip} \cdot N_{mean} \quad (1)$$

With:

D_{tot} = Total damage in euro

S_{tot} = Total installed electrical power (kW) for each sector connected to MV or LV

D_{dip} = Mean damage for a sector in euro/kW

N_{mean} = Mean number of process interruptions

Power system harmonics is another important PQ problem that can have large impacts. When there are only linear loads present in the power system, the network current consists of the fundamental component of the current waveform only. With non-linear loads in the network, harmonic currents are generated in the power system. These harmonic components of currents get added to the fundamental current component and increase the total harmonic current distortions in the network. The increased level of harmonic current emissions can result in overloading, extra energy losses and thermal stresses to the customer's neutral conductors and the components in the network (such as cables, transformers etc.), eventually causing degradation and early ageing of the components. Harmonic currents cause distortions in the network voltage waveform too. The presence of harmonic voltage limits the immunity of the customer's rotating machines against voltage unbalance. Moreover, the presence of large harmonic current components changes the power factor ($\cos\Phi$) of the system to a lower value (as shown by equation 2 and derived in [7]) and increases the demand of total apparent power in the network.

$$\cos \Phi = \frac{\text{Displacement Power Factor (DPF)}}{\sqrt{1 + (\text{Total Harmonic Current Distortion})^2}} \quad (2)$$

The Displacement Power factor (DPF) is the ratio of the active power and apparent power for the fundamental components. So, when there is no harmonic present in the network (which means total harmonic current distortion is zero), DPF and $\cos\Phi$ of the system will have the same value. The equation 2 is valid for the cases where the total harmonic voltage distortion is less than 10% and harmonics power loss in the network is small compared to the fundamental component of active power [7].

It is often difficult for the utilities to impose penalties (harmonic tariff) to the harmonic producing customers because of the lack of proper measuring device. The important cost effects of the power system harmonics are:

- Shorter equipment life.
- Reduced energy efficiency.
- Susceptibility to nuisance tripping.

The cost of nuisance tripping can be significant as it can cause unplanned supply interruption. The cost of shortening equipment life time can also be high, especially for the expensive equipments such as transformers, network cables etc. A transformer is expected to have a life time of 30-40 years. It might be possible that the transformer has to be replaced much earlier than its expected life time due to its aging effect because of high harmonic pollutions in the network. It is quite difficult to estimate precisely the costs of harmonics as a full harmonic spectrum is needed to calculate the losses due to harmonics. Most of the time, the effects of harmonics are hidden and not immediately visible. A detailed calculation of various energy costs because of harmonic losses in the transformers, cables and motors is described in the paper [5].

From the LPQI survey, it was found that two third of all harmonic related costs in the EU-25 are because of slowing down the process, while 25% is related to damage or premature failure of devices [2].

IV. SOLUTIONS TO POWER QUALITY PROBLEMS

A. Decision making process to PQ solutions

Poor PQ can cause large financial losses to different types of facilities. A wide range of technologies exists for either mitigating the consequences or solving the problems. The financial benefits of these technologies can be evaluated by estimating the improvements in the performance of the production facilities and the resulting cost reductions. In order to take a decision on investment, it is required to evaluate the economic impacts of poor PQ and compare it with the costs of various alternative improvement schemes. In Figure 2, a decision making flow chart is proposed for PQ solutions.

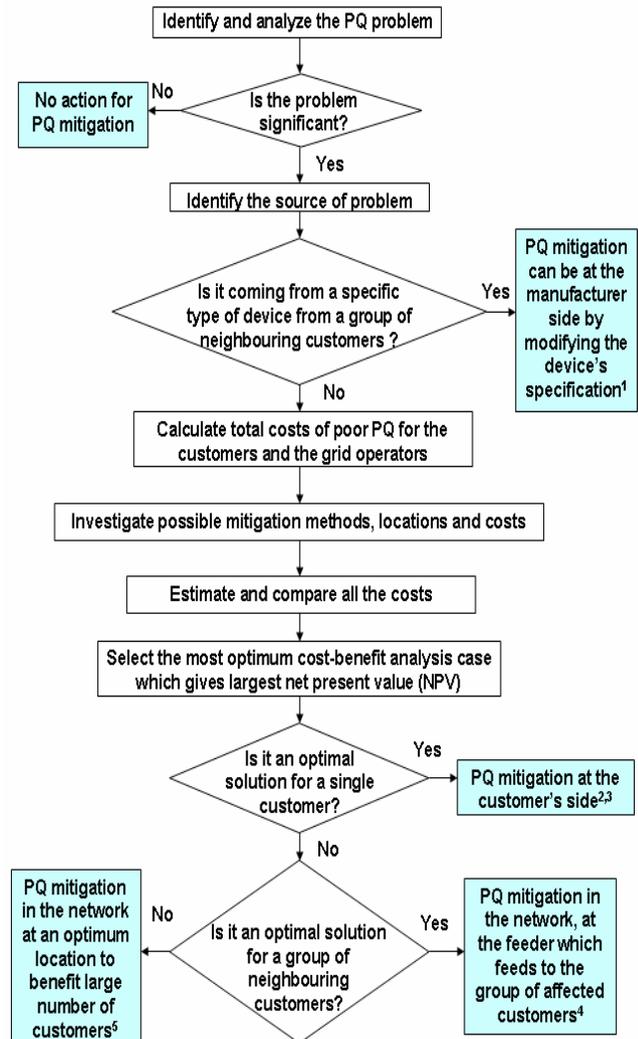


Figure 2: Decision making flow-chart to PQ solutions

In Figure 2, the analysis steps to choose a PQ mitigation method is proposed. Various locations of mitigations are indicated as superscript (1, 2, ..., 5 in reference to Figure 3 of this paper). While making a decision to a PQ solution, first it is required to identify the type of PQ problem that is present and the sources of its origin. The next step is to find out the victims of PQ problem. If a group of customers in the same neighbourhood complains on a specific type of PQ problem, it might happen that the origin of PQ problem is due to the usage of a particular type of device which might be producing a high amount of PQ pollution. In this case, the device manufacturer should be responsible to solve the problem, but it is not always possible due to its complexity. This can be explained by a simple example. Presently, the energy saving lamps are gaining popularity due to their excellent energy saving feature. On the contrary, with the present design of energy saving lamps, it is noticed that the harmonic current pollution coming from this type of lamp is quite high [6]. When a large part of the residential customers in the same neighbourhood start using such energy saving lamps, the total harmonic voltage distortion (THD_v) in the feeding network could exceed the European Standard allowable limit, as specified in EN50160. Extra losses in the network would be high and the supply voltage waveform might be significantly distorted. As a consequence more customers will start complaining. In this case, the grid operator could try to insist the device manufacturer to improve the device design or to take other preventive action to restrict the emission level of the device. However, this measure is relatively difficult to implement as it demands for regulation and a design modification of the device and this might take longer time. On the other hand, it is also unrealistic to convince the customers to restrict the use of such type of device.

If the PQ problem in the network is not because of the operation of a specific kind of device, but rather due to the mutual interactions of different types of equipments, then the impacts of poor PQ to various parties have to be estimated in detail to obtain a broader overview. Many case studies are conducted at the customers' side to estimate the costs of poor PQ for the customers. Relatively less number of studies has been done on investigating the financial impacts for the grid operator because of poor PQ. When a PQ problem is originated at the network side and the customers are mainly suffering, the network operator should be responsible for it. It is expected that some preventive action will be taken to solve it. Hence, an investigation on the selection of appropriate mitigation method has to be done and the relative benefits to all the parties have to be analyzed. The choice of a mitigation method depends on several factors as indicated below:

- Who is causing the PQ problem and who is responsible for it?
- What is the nature of disturbance generated and /or to be prevented?
- Who are being affected by the problem?
- What is the required level of performance; what are the practices, regulations and limits?
- What are the financial consequences of malfunctioning?
- What kind of mitigation method has to be adopted and where should it be located?

- What is the amount of investment needed to solve the problem?

If a single customer in a feeder complains on a PQ problem and the source of it is at the network side, the network operator might be held responsible for it. But, when the PQ disturbance is originated at the customer's side, the network operator will not take the responsibility. On the contrary, when a number of customers in a neighbourhood complain on a specific voltage quality related problem; the network operator should take an effective action to solve it for satisfying the group of customers. For selecting a proper mitigation method, a cost-benefit analysis has to be done to obtain a socio-economic optimum solution.

A vast range of potential solutions, with varying degrees of cost and effectiveness, are available to mitigate problems associated with poor PQ. The solutions can be applied at different voltage levels and locations within the power system: at the network utility level, at the end user's point of connection or within the customer's installation. In Figure 3, various locations where mitigation methods can be implemented are shown. Modification in the equipment itself (location 1) is the easiest solution to implement. It means that the equipment is more immune to a PQ problem; it will not respond to the disturbance and it will produce less PQ emission too. This is not always a feasible option as it demands a stricter specification custom-made device that might not be readily available in the market. But, if more numbers of similar types of devices suffer from or produce a specific type of PQ problem or if more customers require a particular type of device, the equipment manufacturer would probably be ready to manufacture it.

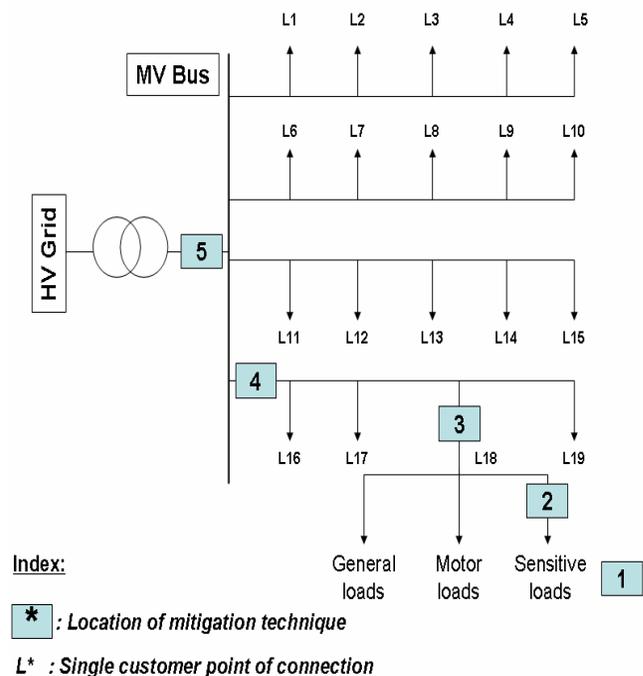


Figure 3: Mitigation methods used in a power system

Modifying the grid (location 5) is often not a possible option as it is likely to be very expensive and requires design change in the grid topology. This mitigation method is called a utility level solution. Such a solution could include taking advantage of the ancillary service that distributed energy resources (DER) can provide and also the incorporation of energy storage (such as: battery, super capacitor, fly wheel etc). These possibilities are a challenge to the utility for improving the PQ of the grid. An adequate planning and design are essential to adopt this solution.

Other mitigation methods can be implemented at the customer control panel level (location 2). At this point, PQ solutions are used to protect critical loads only. A Dynamic Voltage Restorer (DVR) is used mainly to support voltage dips [8]. A Transient Voltage Surge Suppressor (TVSS) can be used to protect sensitive devices from transient voltage surges while a Static Var Compensator (SVC) is used for regulating the voltage and eliminating flicker [8]. An active or passive filter is used to eliminate undesirable harmonics from the power system.

When a customer wants to protect his whole installation from PQ disturbances, the mitigation devices should be installed at plant level (location 3). At this location an Uninterrupted Power Supply (UPS) can be used. Small scale distributed generators (DG) can also be used as back up emergency generators to provide power to the loads in case of islanded operation from the grid [8].

A mitigation method can be implemented at location 4 too. When more than one customer is connected at the same feeder and the majority of them complain on the PQ problem; the network operator will probably implement a PQ solution at the beginning or at a suitable location of that feeder to solve the problem of multiple customers. But when more customers, who are located in different feeders of the same substation, complain on PQ disturbances; the network operator might adopt the mitigation method at location 5.

B. Cost-Benefit Analysis

As discussed in the previous section, PQ mitigation options need to be evaluated in a systematic manner: considering the financial impacts of PQ problems for all parties involved and the costs associated with different alternatives to improve PQ performance. The selection of an optimum location for the mitigation method is a big decision for the network operator and the customer. One of the main influencing factors on the decision making is the number of complaints that the network operator gets from the customers because of poor PQ of the supply. Depending on this, the network operator may either ask the customer to implement and pay for the solution or the network operator himself has to investment money on the mitigation method to satisfy more customers. Thus, the following situations are possible while deciding on an investment for a PQ solution:

- A mitigation method is chosen at the customer's terminal or in his installation and the investment is also done by the customer.
- Mitigation method is adopted at the customer side, but the investment is done by the network operator.
- A mitigation method can be implemented in the network (such as: network a reconfiguration, laying an extra cable, installing storage or filters, etc.) while the investment can

be shared by the network operator and the customer, depending on the situation.

For deciding on an investment for improving PQ of the power supply, a detailed economic analysis has to be done considering various costs of reduction possibilities. All the alternative mitigation options have to be compared on an equal basis. This decision process is called 'capital budgeting'. In this method, all the project's cash flows are calculated considering the 'time value of money'. In this method, it is important to identify all the critical factors that influence the cash flows and the degree of accuracy in forecasting various cost figures. The main elements of an investment to be investigated are:

- The capital cost or initial investment (for PQ mitigation).
- The cost of capital (that depends on discount rate).
- Cost saving (because of PQ mitigation measures).
- Operating and maintenance cost for the investment.
- The economic life time of the investment.

The main purpose of the 'cost-benefit' analysis is to look at the project's performance over time. Several evaluation methods can be used to decide on an economic feasibility of an investment decision. A 'cost-benefit' analysis using the 'net present value' (NPV) method is commonly used to make a decision on a public investment. In this evaluation method, the whole life cycle costing is analysed. It considers all the project's cash flows and the time value of money. The NPV is calculated as the present value of the project's cash inflows minus the present value of the project's cash outflows.

The NPV method uses a discount rate. It is also called 'opportunity cost of the capital'. A company's 'cost of capital' is the discount rate which should be used in capital budgeting. The typical value of the discount rate lies between 5-15%. The weighted average cost of capital (WACC) reflects the company's cost of obtaining capital to invest in long term assets. Other important issues such as tax, depreciation, and a salvage value at the end of the project lifetime can also be incorporated in the NPV analysis. For simplicity, these issues are excluded here. The projects with a positive NPV are expected to increase the value of the investment and these are considered to be economically feasible. When choosing among mutually exclusive projects, the project with the largest positive NPV should be selected.

The calculation of the NPV for an initial investment C_0 for solving for instance a voltage dip problem is shown in the equation (3) [9]:

$$NPV = -C_0 + \sum_{n=0}^{n \text{ life}} \frac{(f_n \cdot C_{\text{sag}} - C_{\text{main}})}{(1 + r_r)^n} \quad (3)$$

- C_0 = Initial investment (for mitigation)
- f_n = Number of dip events to be mitigated in year n
- C_{sag} = Outage cost per event
- C_{main} = Yearly maintenance cost
- r_r = Discount rate / Opportunity cost of the capital
- n_{life} = Investment lifetime / project duration

From a number of practical case studies, it was noticed that voltage dips cause large financial losses mainly to the

customers. Most of the time, different mitigation devices can be adopted at the customer's side to protect the sensitive customer's devices from the voltage dips. A number of alternative mitigation methods and their relative cost-benefits in solving voltage dip problems with variable speed drives are explained in the paper [9]. The network operators have relatively less trouble because of a voltage dip event, except on the revenue loss. As it is quite difficult as well as expensive to eliminate a voltage dip event completely from the network, the network operators are not very enthusiastic to solve this problem by themselves. If a group of customers, using similar type of devices, suffer damage because of a voltage dip of similar nature, the affected customers can either ask the device manufacturer to improve the device design, or can approach to the network operator to take mitigation measures.

Harmonics often have indirect financial impacts to the network operators as well as to the customers. A cost-benefit analysis to solve the harmonics problems can be done for different parties. The cost of mitigation device against harmonics is mainly investment, while the benefits are generally the summation of three costs as follows:

- Operating cost for the customer and / or the network operator.
- Aging cost of devices and components.
- Penalties (for high harmonic current emissions) and / or compensations (for bad quality).

It is observed that the customers often do not notice the impacts of harmonics directly except incidental overheating of devices and /or the neutral conductor; or nuisance tripping of a contactor or a relay. While the network operators do notice the impacts of harmonics as the network components can get overloaded and overheated leading to excess energy demand and /or a mal-operation of network relays. If a cost-benefit analysis for solving a harmonics problem is performed by the network operator, the following aspects have to be taken into account. The operating costs are the costs of the incremental energy losses caused by harmonic flow in each network component; while the aging costs are referred to the incremental costs caused by premature aging of components because of the harmonic pollution. The penalty cost is decided by the network operator against those customers who are injecting excessive harmonic pollutions in the network. Penalty costs might be set by the regulator. A number of case studies on the relative cost-benefits have been analysed in paper [5].

To obtain an optimum solution, it is required to compare the investments of the customer and the network operator, with reference to a single customer. The cost-benefit analysis using the NPV method generally gives a solution that is socio-economically optimal [10]. The single customer's investment is ' $NPV_{customer}$ ' for solving the PQ problem at his terminal while the investment made by the network operator is ' $NPV_{network}$ ' to solve the problems of 'n' number of customers connected to the network. Both the above NPV values (as shown in the equation (4)) are compared for obtaining the optimum decision on the investment [10].

$$(NPV_{network} \cdot K_{exp}) / n \Leftrightarrow NPV_{customer} \quad (4)$$

K_{exp} is a factor which considers extra weighting value to the network operator's experience of handling and solving similar kind of network related problems. When a PQ solution is

implemented by a customer, it is generally less effective than if the same solution is implemented by the network operator. So, the ' K_{exp} ' value is assumed to be smaller than or equal to '1'. If the left part of the expression is bigger than the right part, it is preferable to implement the network solution.

V. CONCLUSION

PQ is an important issue in the electricity sector in which different parties are mutually connected to each other namely: the network operators, equipment manufacturers and the customers. As poor PQ can cause large amount of financial losses to all the parties, it is important to consider the problem seriously for finding out an optimum solution. A decision flow chart is proposed to find out the best solution to PQ problems. A wide range of potential solutions are available with varying degree of price and effectiveness. Depending on the significance of the PQ problem and its influence, a proper mitigation method has to be selected at the most appropriate location. Hence, cost-benefit analysis using the 'net present value (NPV)' method is required to be done for the different parties to find out the best solution: at network level, at individual equipment level, at a single-customer's terminal or somewhere in between to satisfy a group of customers' mutual needs.

ACKNOWLEDGEMENTS

The work presented in this paper is part of the research project 'Voltage quality in future infrastructures' - ('Kwaliteit van de spanning in toekomstige infrastructuren (KTI)' in Dutch), sponsored by the Ministry of Economics Affairs of the Netherlands. Further information at: www.futurepowersystems.nl.

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