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Analysis of Methodologies for the Economical Evaluation of Power Quality

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Abstract.

This paper focuses on the economical evaluation of the Power Quality in power grids. The term Power Quality includes, in general, a set of boundary conditions which allow electrical systems connected to the grid to function in their intended manner, without significant loss of performance or life. Therefore, the operation of the power system outside these boundaries directly impacts on the economical performance of the whole system. The evaluation of the economical loses derived of this fact has been matter of several studies, mostly applied to individual cases.

This paper will firstly define and evaluate different existing methodologies for the evaluation of financial losses due to power quality issues. The power quality issues being considered are voltage sags and short interruptions.

A second part of the paper will focus on the development of a new methodology based on macroeconomic parameters recollected in the National Countability Register, in order to generalize the methodologies above with a more broad application. The result of this research will provide a more generalize method for power economics evaluation, which can be easily extrapolated to different environments. Results of the application of this methodology will be also provided.

Key words

Power Quality, Economical Evaluation, Voltage Sag, Harmonics, Power Economics.

1. Introduction

The Economical Evaluation if Power Quality issues is one of the main problems the power system is facing. In a world every day more depending on electronic devices connected to the power grid and with the power quality necessities of those devices increasing day after day, a bad quality of power can have a devastating impact on industries and particulars [1].

The factors responsible for this impact are sometimes unclear and very often of difficult evaluation. Therefore, the economical evaluation of this impact is even more confuse.

Different methodologies are being developed, some of them giving a reference to the general steps that should be followed in a correct evaluation [2], [3] and [4]. Some others are focussing on a particular case and solving this case, not being the methodology exportable to other environments [5], [6]. Some others are dealing with information which have confidentially issues [7]. Some others too complicates to be applicable [8] and [9]. And, some others provide just a very rough approximation of these economical loses [10], [11]. There is at the present no clear solution which can solve this problem in a general mode.

The interest of this work is directly related with analysing and proposing a general solution for the exposed problem. This solution will be based on macroeconomic factors which are public and free of confidentiality issues. The parameters which the method is based on are recollected in the National Countability Register. The European Commission, through the EUTOSTAT agency establishes a frame for the application of the National Accounting System for all the member states, which ensures the availability of the necessary data for the use of this methodology in other environments. The approach may be general but the results will show a respectable reliability with the results of more particularized methodologies.

2. Analysis of existing methodologies

Among the different power quality disturbances that can affect the supply voltage; outages and voltage sags are particularly harmful for industrial plants since they can stop production and cause large related costs – the so-called Customer Interruption Cost (CIC). The calculation of this CIC in order to evaluate the necessity of voltage conditioning devices or contracting a higher power quality to the supply company has been matter of constant study. Although the problem of its calculation remains unsolved, several approximation-methods are discussed in this paper.

The accuracy in the result of the approximation method depends mostly on the available data. An accurate evaluation will need the following inputs:

- Voltage sags profile at busbars - provides information about the density of events.
- Customer load susceptibility - provides information about the reaction of the customer loads to the different events.

This data is difficult to obtain. Therefore, different methodologies are developed to estimate in a more or less direct way the losses without the availability of the data above. This methodologies are described and a discussion about every one is provided in this part of the paper. In this discussion positive and negative points for every methodology will be presented and justified.

A. IEEE Recommended Practice for Evaluating Electric Power System Compatibility With Electronic Process Equipment [2]

This IEEE Standard develops a technical and financial analysis of voltage sag compatibility between process equipment and electric power systems. It is intended to be applied at the planning or design stage of a system where power supply and equipment choices are still flexible and incompatibilities can be resolved. Basically, it consists on a three-steps-process. First step: The development of a coordination chart, a relation between the probability of a sag (considering time and magnitude) and the disruption region for every component of the process. The sag-data is recommended to be recollected at the feeder and the data of equipment susceptibilities (voltage tolerance curves) is usually provided by the manufacturer. From the coordination chart, the number of disruption events that the most sensitive equipment will have to support will be identified. Second step: The assumption of fixed cost per sag. The value of the cost will be obtained from a survey on the different actors of the process chain. Taking as an input a scenario with a failure of the complete chain. Third step: Multiplying the value of the cost obtained from the survey per the number of events identified in the chart.

Discussion on the methodology

Positive is that it is a simple and easy methodology to apply and provides an approximative idea of the real value of the losses.

Negative, it is the need of a huge amount of data, some of them difficult to gather together and some of them dealing with confidentiality issues of the company. Also, it is only based on the reaction of the most sensitive equipment. If it does not affect completely to the process chain, the methodology fails to give a reliable output. Although it is intended to be applied at the planning or design stage of a system, the date used is based on the experience of the different actors of the process (by means of the survey) which makes difficult its goal.

B. The Pirjo Heine Method [10]

This method is developed by the Helsinki University of Technology. It consists in estimating the three variables of formula (1).

$$Cost = V \square N \square C \qquad (1)$$

Where V, N and C are described as follows:

Voltage sag frequency (V). The estimation requires a probabilistic approach and network reliability data. These data are typically derived from permanent faults. The authors develop a probabilistic method to estimate the average annual sag frequency (for voltage sags less or equal to 50%) that the LV customers of five different distribution companies will experience because of faults in radially supplied medium voltage (20kV) distribution networks.

Number of customers (N). It was a data provided to the study. The customers where categorized into five different groups: domestic, agricultural, industrial, commercial services and public services. In order to assume similar behaviors to every component of a group.

Cost per sag (C). The cost per sag was obviously estimated for every one of the five groups of customers. The value per sag was calculated from the evaluation of real direct and indirect economic consequences of the sag. This evaluation was made by different surveys on households, agricultural and industrial customers. From the combination of the results of the three surveys an approximative cost per type of customer was found.

Discussion on the methodology

Positive is that the method uses available data form statistics originally prepared for other purposes in order to extrapolate costs in the case of voltage sags and short interruptions.

Negative is the inaccuracy in the evaluation of the sag frequency. The evaluation of the cost per sag is based on a big sample of real data, which is usually difficult to gather. It is assumed that the enormous quantity of data will be enough to give an approximation of the real costs, not even giving a clear statistical approach of the treatment of those data. It may be more desirable a small and more accurate sample focused on the objective. The results of this paper can not be extrapolate out of its context.

C. The Quaia and Tosato Method [5]

This method was developed by the University of Trieste. It consists in estimating costs of MV (10 to 20kV) fed industrial plants (up to 2-3MW peak plants). The authors also apply it to a real case (plastics sector middle sized industry) in [6]. The data required is obtained by direct survey on the target industry. However, this survey do not exclusively focus on cost estimation questions but other data concerning to plant operation, structure of the productive system, equipment sensitivity, restart procedures and many other aspects related to the interruption consequences. The reason behind is that a direct cost estimation survey presents several dangers: customers not willing to provide cost information; the data resulting is not controllable and customers tend to overestimate them; and only sensitive users are really affected by interruptions and they may be considered one third of the total MV industrial plants.

The method proposed is a complete analysis of the target industry. The pattern is developed by assuming a reference plant with n machines or production groups. Each performing different serial productive processes. In general, each machine will cause a different interruption cost, but also for any given machine the interruption cost will depend on the individual process interrupted. Then, the interruption costs calculation should be repeated for each individual machine.

It is assumed that trying to represent costs versus sag severity would be unrealistic and that outages and severe sags have the same effect on equipment operation and therefore cause equal CIC.

The costs contemplated in the CIC equation are:

$$Cost = C_{LP,D} + C_{LP,R} + C_{WM} + C_{IP} + C_{DE} + C_{EM} - S_M - S_E \qquad (2)$$

Where:
CLP,D = Cost of lost production during the supply disturbances
CLP,R = Cost of lost production during the restart time
CWM = Cost of wasted material
CIP = Cost of imperfect products
CDE = Cost of damaged equipment
CEM = Cost of extra maintenance
SM = Saving on raw materials
SE = Saving on energy not consumed

All these costs and saves are estimated in [5] and approximative values provided in [6].

Discussion on the methodology

Positive, it is an accurate method to analyse costs produced by voltage sags or short interruptions in a middle sized industry, also providing standard values for some of the variables proposed. No data about the voltage sags frequency estimation, which means that the costs evaluation would be per sag.

Negative, there is no reference to the sag magnitude, which calculation is assumed to be unrealistic. The outages and severe sags are considerate as having the same effect on the operation. This is not true. But the author expect that the error introduced to be reasonably low.

D. The Lee, Albu and Heydt method [7]

This method consists in the definition of a power quality index to quantify the supply voltage quality of each duration class (defined by IEEE 1159) based on the impact of that class of disturbances. A series of measured voltage disturbances are represented as points on the CBEMA curve (this curve represents the sensitivity of a device to voltage sags) and grouped according to common disturbance duration class. The calculation consist in the application of two different indexes: average load drop index (LDI) and average load drop cost (LDC). The method for the calculation requires as inputs:

- The sensitivity curves of every different load present in the load composition.
- The percentage of every load presents in the process.
- The voltage sag profile in the busbar
- The average cost of every class of disturbance defined by IEEE 1159

Discussion on the methodology

Positive, it is an elegant method to evaluate power quality costs and it considers different costs for different sag severities.

Negative, it needs the sensitivity curves for every load. It is not represented the relation between loads. If a load can impact the failure of others. The costs of every class of disruption is taken as a constant value which can be just a rough approximation to the real cost.

E. Crozier and Wisdom [1]

More than a methodology it is the statement of the necessity of a relation between CIC and kWh sold for energy producers to proper evaluate the expenditure decisions. It relates existing PQ&R measures with its failure to approx costs. While a CICs/kWh approach could be a good estimation of costs as well as be also applied to evaluate PQ problems.

Discussion on the methodology

It is just the justification of the need of a more economical oriented approach to the PQ problems.

F. The McGranaghan and Roettger method [3]

It presents a conventional approach for the evaluation of cost savings experienced by different PQ-solution technologies (Also a custom power approach is presented in [4] with an example solved by the same authors).

The methodology consists on a four steps process.

Step 1: The characterization of the system power quality performance. Basically the analysis of the frequency of occurrence of mainly voltage sags and short interruptions.

Step 2: The estimation of costs for power quality variations. Dividing the costs in three main categories:

product related loses, labor-related loses and ancillary costs. It refers to IEEE 1346 Standard for a more accurate list of factors to be considerate. These costs must be evaluated by survey on the actors of the process or approx data. Costs will typically vary with the severity (magnitude or duration) of the PQ disturbance. This relationship is defined by a matrix of weighting factors.

Step 3: Characterizing the cost and effectiveness for solution alternatives. It considers four main options:

- supply system modifications and equipment that affect multiple customers
- Service entrance technologies that affect a single targeted customer.
- Power conditioning at equipment locations within a facility.
- Equipment specifications and design.

Each solution technology must be characterized in terms of cost and effectiveness. For costs the paper adds a table with typical costs per technology and for effectiveness also a table which relate this effectiveness with the severity of the PQ disturbance.

Step 4: Performing comparative economic analysis. First the total annual cost for each alternative must be determined. This annual cost is represented by the costs associated to the power quality variations as well as the implementation cost of the solution. With the annual cost determined, a comparison between technologies will be done. The best rated solutions will need more detailed investigation.

Discussion on the methodology

Positive is that it is a useful and clear method which takes into account the main points presented in PQ economics.

The paper gives also some typical data but only applicable to a particular case of industry.

Negative, there is just a rough explanation of how to calculate the different factors presented and no references to more detailed documentation about.

G. The Pohjanheimo and Lehtonen Method [8]

The method is a probabilistic approach to the determination of the best solution in PQ disturbances mitigation. The method takes into account: technical and economical impact, annual frequency of sags and effect of possible mitigation devices already available in the process. The author proposes a combination of two-dimensional arrays (rows representing the remaining voltage during a sag / columns representing sag duration), everyone representing different characteristics of the system. Example: array E: Weighted event cost array; array P: Sensitivity of a process; array I: Frequency of sag oriented plant interruptions. Mathematical equations are proposed for evaluating the different parameters of the system. The parameters defining the characteristics of the system inside the array can be discrete states (0,1) or probabilistic values (0 to 1).

Discussion on the methodology

Positive, it creates a platform able to integrate all the parameters presents in PQ technical and economical evaluation. The result seems easy to implement on a spreadsheet or any software suitable to calculate with mathematical arrays.

Negative, the method needs many factors as input, most of them difficult to calculate. It does not give any approach to the calculation or approximation of parameters.

H. The Wang, Chen and Lie Method [9]

It is a method for estimating the load performance and obviously economical impact due to voltage sags. The main point of the study is that it uses fault tree analysis to estimate the response of the load (built up of different equipments with different sensitivities) to a voltage sag. The main focus is to convert the voltage sag disturbance in a reaction of the individual components of a system and after linking them to the load performance.

Discussion on the methodology

Positive, it is a simple idea applicable only to the assembling of a global load composed by many different equipments with different sensitivities (another way to see the weighting factors).

Negative, it that as always, it does not give any clue to estimate the loss per case studied. If the process is complex, the fault tree analysis becomes very complicated.

I. WTP and WTA method [11]

The Willingness to pay and the willingness to accept are two methodologies based on indirect evaluation of costs.

In the WTP method, the customers are asked to inform how much they are ready to pay in order to avoid an voltage sag or a short interruption. The difficulty with the method is that the customers usually are not aware about all the activities or functions which are interrupted by that. They also tend to consider planned outages, which leads to the underestimation of the costs of unexpected interruptions.

An alternative approach is to ask the customers their willingness to accept compensation for having had an outage (WTA). In a normally working market situation the WTA and WTP methods should give identical results. However, in actual studies, the WTA values have been substantially higher than WTP values.

Discussion on the methodology

They are useful especially for such customer categories, the outage costs of which are difficult to estimate directly in monetary terms.

3. Methodology proposed

The methodology proposed in this paper is based on the evaluation of power loses as benefit not produced. The benefit produced by the different activities which composed the economical system in Spain is evaluated and accounted by the Spanish National Countability (CNE) [12] system. The CNE provides a list of parameters which conforms basic statistics. The data used for constructing these statistics are provided by different sources which are confronted by a single countable frame. The statistics are given annually, but three times a year the estimations are examined and evaluated until they became definitive. All this proceeding targets to obtain a reliable source of data to estimate the national accounts, in an effective and reliable way. The statistics are gathered together in three groups of activity branches disaggregation. The given data depends on the degree of disaggregation of the activity branches.

5 activity branches disaggregation. The data provided in this case is used in calculation of the added value at basic prices (current prices and volume variations) and total employment in the estimations with advance character (A) and first estimation character (1E).

22 activity branches disaggregation. The data provided is used for the variation of volume of the gross added value at basic prices in the definitive and provisional estimations.

27 activity branches disaggregation. The data provided is used for the added value at basic prices (current prices), remuneration of salaries, gross exploitation surplus / gross income and total employment calculation in the definitive and provisional estimations.

Based on the statistical information provided by the 27 activity branches disaggregation, the benefit per hour of the different activity branches is provided. This benefit per hour can also represent the lack of benefit (or losses) if one hour the activity stops. Therefore, the lack of energy supply would produce the activity to stop and therefore produce those losses.

A. Boundary conditions

The statistical information available does not provided data for calculating the losses due to recovery process after a short interruption or sag. Therefore, the methodology proposed does not include partial loses. The production in the industry is also evaluated as constant per hour, not considering different impacts of an interruption or sag at different hours.

B. Example of application

An example of application of the methodology is provided as follows for the evaluation of losses in five representative regions in Spain: Andalucía, Cataluña, Galicia, Madrid and País Vasco.
Due to the lack, at this moment, of reliable data for voltage sags or short interruptions, data provided by the Energy Agency [13] of the Spanish Industry Ministry [14] on more than 3 minutes interruption (TIEPI) has been used.
Two different scenarios have been analysed:

- Scenario one is the use a single weighted middle value of the time interruption in different regions for all the industry in this region.
- Scenario two distinguish between two different weighted time interruption middle value for two different areas: rural and urban. It makes the results more accurate since the time interruption is different for rural and industrial areas.

Fig. 1 and 2 show the result of the calculation of gross added value lost for the five regions analysed in the two scenarios.

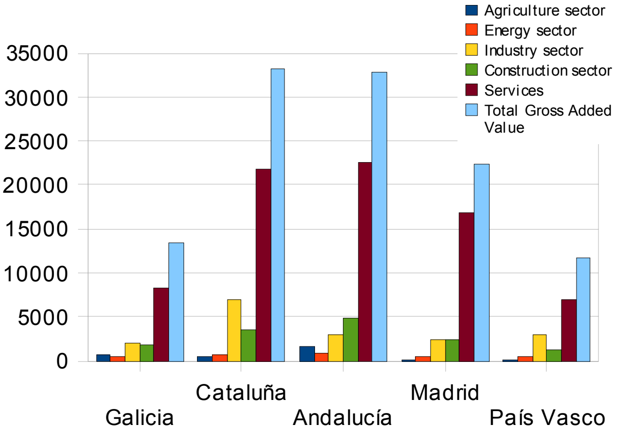

Fig 1: Gross added value [m€] of the losses for scenario 1 in 2006

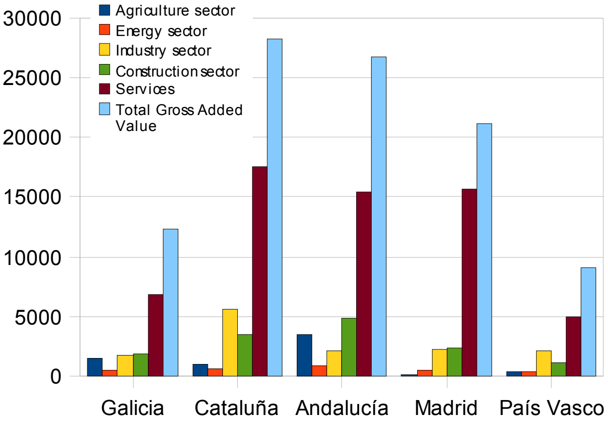

Fig 2: Gross added value [m€] of the losses for scenario 2 in 2006

C. Analysis of results

The results provided shows the high dependency of the loses on the time of interruption. Since this time interruption differers from region to region, the loses will be equally different. Scenario one shows slightly higher loses than scenario two (see on fig.3), specially in regions where the weights of agriculture and industry are more equally distributed, such as Andalucía. The reason behind is the better supply (less time interruption) in urban areas than rural areas. In regions where agriculture has a minimal representation, the incidence of scenario one or two in loses calculation will be minimal, such as the case of Madrid.

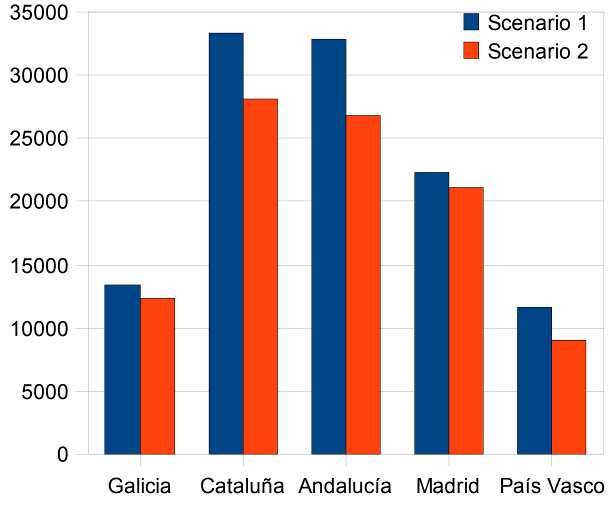

Fig 3: Comparison of total Gross added value [m€] of the losses for scenario 1 and scenario 2

D. Validation of the methodology

The results provided in the example above are consistent with the order of magnitude of the data provided by the Spanish government. Further work is required at this point to exactly evaluate the accuracy of the methodology.

4. Conclusions

This paper has evaluated different methodologies to calculate the loses an industry is facing due to voltage sags and interruptions. After stating the difficulties of the available methodologies on evaluating these loses in a easy and reliable way, a new methodology is proposed. This methodology is based on data from the government statistics and therefore not subjected to confidentiality issues for determined industries, which is one of the main issues the other methodologies are facing. Although, the limitation of this methodology is the lack of data regarding to the response of determined industry to different depths of voltage sags or different length of interruptions. Therefore, in this first evaluation of the methodology, voltage sags will be evaluated as interruptions and all the interruptions will produce similar loss of benefit. Further work will focus on the reaction of the industry to different types of sags and interruptions. Also, this first evaluation lacks of considering other costs the industry is facing other than the quantified by the government. Further work should also be done in evaluating these other costs, as for example lost of confidence from a customer when there are delays in a production, etc.

This paper represents a first approach to the resolution of the problematic of evaluating costs of voltage sags and short interruptions in a general and simple way, with available data from a reliable source. The preliminary results of the methodology application are encouraging but further work is required in order to increase accuracy.

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