ADVANCED TOOLS AND METHODOLOGIES FOR POWER QUALITY ASSESSMENT

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Abstract- To improve power quality assessment, appropriate methodology and set of tools need to be utilized. This paper outlines a methodology that includes modeling and simulation as well as recording and analysis of field data. The software tools include standard and customized simulation packages. Several examples of the power quality assessment studies using the proposed methodology and tools are also given.

1. INTRODUCTION

Power quality (PQ) assessment is a process by which a utility company determines if it has a PQ problem, how this problem affects its customers, what may be the appropriate solutions, and what are the inherent limitations of the particular solutions. Even though some of the utilities may have a clear understanding of some of the mentioned steps, and they may have already been using certain tools and methodologies to deal with a given PQ task, it is not very common to find a utility company today that has a full procedure for the PQ assessment in place.

Typically, the PQ problems may be defined with respect to the revenue meter location that traditionally establishes a well-defined boundary between the customer and the utility. However, this boundary may be well defined as far as the revenue metering point is concerned, but it may not be a natural point of separation for the PQ issues. This is an item of potential confusion, misunderstanding, and even a major dispute between the two parties [1]. The issues become even more complex when one attempts to define a cost/performance criterion for a quantitative assessment of the PQ problem, its impact on the overall reliability of the power system operation and related revenue/loss-of-revenue consequences, the optimal choice of the required solutions, and the gains obtained by implementing selected solutions. To perform such a complex and potentially far reaching task of defining the mentioned PQ issues, a utility needs to have a set of relatively inexpensive tools and well-defined methodologies enabling efficient and precise assessment of the PQ problems and solutions.

Definition of the methodology for PQ assessment for a given utility is not a trivial task [2]. It is a complex process where the utility needs to identify what are the disturbances that may be classified as the PQ related, why these disturbances are of a particular concern to the customer, what is causing occurrence of these disturbances, how one can avoid or reduce occurrence and impact of these disturbances, who is responsible for finding and implementing the required solutions, how are the solutions to be implemented, how one can monitor the future behavior of the power system to establish the facts about the effectiveness of the implemented solution. First, this paper discusses the basic steps of such a methodology.

This paper also describes several sets of tools to be used for the PQ assessment. One set are the software routines aimed at automating analysis of the disturbance data recorded by a variety of monitoring equipment such as digital fault recorders and dedicated power quality meters. The next set of tools are modeling and simulation packages aimed at better understanding the causes for the PQ disturbances and impacts of selected solutions. Also, appropriate software tools for system-wide studies are included.

The final part of the paper gives examples of the methodology for using the above mentioned tools to perform a power quality assessment study. In particular, combination of the data analysis and modeling tools will be emphasized since such a combination may be needed to perform a comprehensive study of a complex power quality problem.

2. POWER QUALITY ASSESSMENT METHODOLOGY

2.1 The PQ Assessment Concept

This concept assumes that the final goal of a PQ study is to relate a PQ disturbance to a financial criterion to determine what are the economic impacts of the PQ solution. In order, to achieve this goal, the PQ assessment has to provide answers to a variety of questions such as the ones listed in Table I.

Table I. Typical Power Quality Assessment Questions

Question	Expected Answers
What are the PQ disturbances of interest?	Selection of a disturbance type: voltage sags or swells; harmonics; voltage flickers; spikes and transients; power interruptions; changes in the fundamental frequency.
Where in the system the PQ disturbances occur?	Identification of the location: system-wide; regional; revenue metering location; terminals of the power apparatus; customer site; customer system.
Why are the PQ disturbances present?	Classification of causes: system faults and protective relaying operation, nonlinear loads; switching actions; electromagnetic interference; starting characteristics of certain power equipment.
When the PQ disturbances are detected?	Determination of the duration: continuous; periodic; random; several days or hours; several minutes or seconds; several millisecond or power cycles; duration not known.
Who should be responsible for the assessment?	Definition of the type of study: planning; operation; protective relaying; revenue metering; maintenance; engineering design; new construction; customer relations; power delivery contracts.
How the final solution should be implemented?	Indication of possible approaches: change in the operating practices; installation of new equipment; exchange of the existing equipment; improvements in the engineering design; contractual solution.

It is obvious that the questions and expected answers given in Table I are not all inclusive. The PQ assessment has also to include a number of other issues such as the required investments and expected returns, responsibility for definition of the solution and its implementation, and the impacts on the customer relation and satisfaction.

2.2. The Methodology Steps

In order to carry out an assessment study, a utility needs to implement a number of methodology steps as follows:

- Classification of the type of PQ studies.
- Characterization of PQ disturbances.
- Design of PQ assessment procedures for each type of PQ study.
- Study of causes and impacts of PQ disturbances.
- Definition of the criteria for PQ evaluation.
- Assessment of the technical and financial aspects of PQ improvements.

Classification of Power Quality Studies. Power quality studies can be broadly classified into two categories from the perspective of the electric utility:

1. Service interruption
2. Compliance to standards

The first category includes studies related to events that result in temporary or permanent service interruptions to the customers. These events may be faults, switchings or other system disturbances that may cause voltage dips or swells at various points in the system [3]. As a result of the changes in the system voltage, sensitive equipment may be disconnected via intelligent relays and/or fuses.

This first category of studies can be further broken down into studies involving:

- Voltage sags and swells
- Switching or fault transients
- Improper grounding

The second category pertains to the harmonics and voltage flicker issues. Harmonics generated by nonlinear loads and solid state switching equipment, must be evaluated in order to ensure that the recommended practices and/or standards are properly adhered. While these studies appear to apply more to the large customer loads, such as industrial plants, utilities may also be interested in running these studies to explore possible ways of minimizing harmonic problems at the customer end.

Characterization of PQ disturbances. The characterization entails a precise quantitative specification of the disturbance waveform perameters such as: length, magnitude, frequency content, energy distribution of the waveform components, percentage change in a given time period, rate of

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Characterization of PQ disturbances. The characterization entails a precise quantitative specification of the disturbance waveform perameters such as: length, magnitude, frequency content, energy distribution of the waveform components, percentage change in a given time period, rate of change, etc. In order to come up with the quantitative description of a disturbance, a set of analytical techniques has to be defined and utilized. Typical examples of the techniques are: digital signal processing, wavelets, neural nets, expect systems, fuzzy logic, parameter estimation, model identification, etc.

Once an event is characterized and associated with one of the PQ categories, than a corresponding power quality assessment procedure will be applied as discussed next.

Design of PQ assessment procedures. Power quality assessment procedures will depend upon the type of event studies. However, no matter which type of event is studied, the following steps must be executed:

Step 1. Compiling system and equipment data for the part of the system to be studied.

Step 2. Modeling the system in enough detail to allow the correct representation of studied event.

Step 3. Simulation of the event under study.

Step 4. Verification of the model and simulations via the recorded field data.

Step 5. Using a customized intelligent system software to recognize the power quality problem and carry out its assessment.

Study of causes and impacts of PQ disturbances. It relates to a clear identification of the sources and consequences of the disturbance. As it is well known, these are may be a number of reasons for a disturbance to occur such as: selection of inappropriate equipment, inherent property of the needed equipment, inadequate operating practices, by-product of required switching sequences, use of unsound engineering practices, economic constraints in implementing the system design. In any case, it is very important to identify the final source of the disturbance, which typically falls into one of the following categories: equipment, engineering design, operating practice, and economic decision.

Definition of the criteria for PQ evaluation. This requires a selection of the cost function associated with an intended optimization procedure. In addition, the means of monitoring of the quantitative indicators, as well the approaches for comparison of these indicators against the criteria, need to be specified. Finally, a possibility for automating the PQ evaluation process has to be explored.

Assessment of the technical and financial aspects of PQ improvements. This represents the most critical part of the overall assessment. This step needs to produce precise relationship between the PQ performance criteria and related technical improvements as well as the required cost. This approach may result in different types of financial solutions such as: capital investment in the required equipment changes; increased operating cost of improved diagnostics and maintenance; additional purchasing funds for expandable monitoring and control instrumentation; change in tariffs and billing procedures.

3. POWER QUALITY ASSESSMENT TOOLS

3.1. Commercial Software for PQ Studies

There are several programs for power quality and related studies. Not all of them are designed exclusively for PQ analysis. Available programs can be divided into two classes:

- Steady-state harmonics programs
- Time domain transient simulators

The first class of programs can be designed as linear equation solvers, where the phase domain nodal admittance matrix is built at harmonic frequencies and the solution of system bus voltages are obtained based on the assumed harmonic bus injections. There are also more advanced versions of the steady state programs, which are the harmonic power flow programs. Harmonic power flow programs can take into account the terminal V-I behavior of the harmonics sources (as opposed to considering them as constant harmonics injections) and can solve a multi-phase multi-harmonic power flow. These programs are much more accurate than the linear equation solvers, however at a substantially higher computational cost. They also require a prespecified harmonics model for each of the harmonics generating component.

Unlike the above discussed steady state programs, time domain transient simulators do not require a harmonics model for any system component. Instead, each and every component, whether it is linear or nonlinear, is modeled in time domain by a discrete time model based on some numerical integration rule used by the program. A commonly used transients simulator is the electromagnetic transients program, several versions of which are available [4]. The essential advantage of using a transients program is its flexibility and accuracy in modeling unconventional system components as well as switching scenarios. One shortcoming however, is the lack of robust initialization schemes for transient simulations involving several nonlinear elements. This necessitates the simulation to be run for long enough time to let the transients die out, so that the steady state harmonics can be recovered from the resulting simulation records. Despite this shortfall, transients simulation programs remain to be popular choices as tools to evaluate power quality problems.

3.2. Commercial Recording Instrumentation

One of the most important steps in a PQ study is to acquire field data related to PQ disturbance. The uses of data may be different, depending on the type of study. Table II shows some examples of the use of recorded data and related requirements.

Table II. Typical Uses of and Requirements for Recorded Data

Study	Data Recording Requirements
Verification of existence of PQ disturbance	Sensitive recording instrument capable of capturing a variety of different PQ disturbances
Compliance with Standards for a specific PQ disturbance type	Recording instrument designed to continuously record specific type of PQ disturbance
Validation of modeling and simulation for a given PQ disturbance type	Recording instrument that can be programmed to trigger on the events of special interest for the validation process
Revenue metering under a new type of PQ standard	An instrument capable of producing high accuracy measurement of the standardized waveform parameters

As a result, a variety of recording instrument are available on the market. These instruments are capable of not only data recording but also analyzing the recorded data. A number of dedicated software packages are being developed to facilitate user interfacing required to set-up the instruments and to prepare study reports.

One problem with the existing data recording instrumentation is that it is developed to accommodate needs in the areas where there has been a standardization of the PQ disturbance definition and characterization. Typical examples are harmonics, flickers, and revenue metering of energy. In those areas, there is well established line of dedicated instruments such as Power Harmonic Analysers from Fluke, BMI, Voltech, California Instruments, etc. Once the data recording needs are beyond the PQ applications that are standardized, and into such applications as voltage sags and swell as well as transients, spikes and noise, it becomes more difficult to select the most appropriate recording instrument. In those cases one may have to utilize some of the existing instruments originally not aimed at those applications, but capable of recording the PQ disturbances of interest after some customized changes in hardware and/or software are made.

3.3. Digital Simulators

The use of analog and hybrid simulators in studying some disturbances such as electromagnetic transients is a well known practice. Recent developments in this area have resulted in a number of low cost digital simulator products capable of generating transients for a variety of power system models [5]. These simulators have a very flexible user interface allowing for an easy way of building the models of power system components and specifying the conditions for the power system event simulation. In addition, these simulators are equipped with input/output (I/O) interfaces allowing for an external device to be connected to the simulator for the purpose of testing using the simulator-generated output waveforms as test inputs to the device. The test waveforms can also be recorded in the field and replayed through the simulators. Such simulators have been extensively used in the protective relay testing area [6, 7].

With further needs for modeling, simulation, and testing being defined through a new methodology for PQ assessment, the role of digital simulators in PQ studies may dramatically increase. As an example, PQ studies related to the fault events, such as voltage sags and swells, can be conveniently studied using existing digital simulator developed for relay testing. The simulators can be enhanced to provide a useful study tool for other PQ disturbances such as flickers, harmonics, spikes, etc.

The main features of a digital simulator are shown in Figure 1. As it can be observed from Figure 1, there is a variety of methodological study steps that can be accomplished using digital simulator features. When tied with data recording instrumentation, digital simulators can provide a study environment for evaluation of PQ disturbances by performing modeling and simulations as well as comparison with recorded data and testing of impacts on various devices. Future use of digital simulators in PQ assessment studies is yet to be explored and further developed.

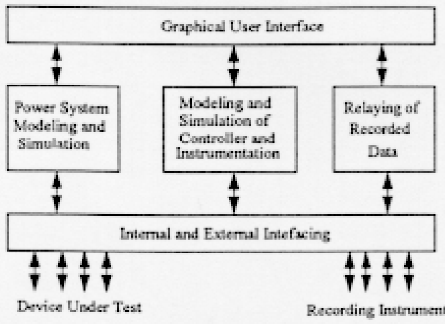

Figure 1. Digital Simulator Features

3.4. Customized Tools

The customized tools are needed when commercial solutions are not readily available for some new applications. Typical examples of such applications are the uses of software packages for automated detection, classification and characterization of PQ disturbances aimed at monitoring of occurrence of these disturbances in a power system.

One such customized solution shown in Figure 2 is under development at Texas A&M University. This software package has software routines based on signal processing, neural net and wavelet techniques. The "raw" data samples are first processed to detect any PQ disturbance of interest. The processing combines a variety of signal processing, neural net and wavelet techniques to extract waveform information relevant for the detection procedure. In addition, samples are processed to extract waveform properties needed to classify the type of PQ disturbance. After that, an expert system is used to perform the classification step. Finally, the PQ disturbances are characterized based on a member of indices that are obtained through perameter estimation procedures. As a result, several PQ indicators are computed for the PQ assessment purposes.

The software package can be used to perform the mentioned processing steps automatically. The front end instruments that can be utilized for data sampling are digital fault recorders (DFRs). These recorders can be retrofitted with this software to offer a new system for automated monitoring and analysis of PQ disturbances [8].

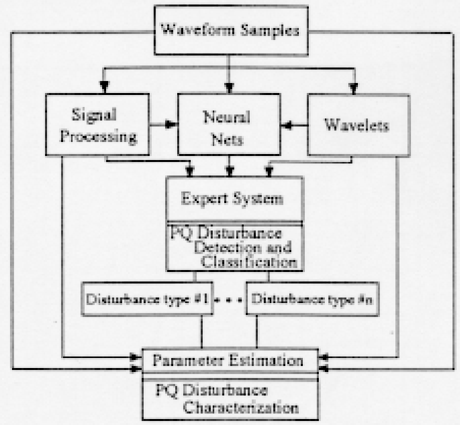

Figure 2. Customized Software for PQ Disturbance Detection, Classification and Characterization

4. SAMPLE CASE STUDIES

4.1. Fault Initiated Voltage Sag

Consider the system shown in Figure 3. The utility system behind the transformer is represented by a Thevenin equivalent (short circuit equivalent). The part of the system studied is a radial section with a tail composed of two parallel lines of about the same length, terminating at the common load bus 5. We study the effect of a mid point fault along one of the parallel lines on the load bus voltage. It will be assumed that the fault is of temporary nature and it clears itself allowing reclosing of the line at both ends. The two circuit breakers are assumed to operate and isolate the fault and then reclose 0.08 seconds after the clearing of the fault. Load bus voltage transients are simulated using a transients simulation program and the waveform shown in Figure 4 is obtained. As can be observed, the load voltage goes through a temporary sag during the fault. Depending on the type of load connected to bus 5, this sag may or may not allow the connected equipment to "ride" through this system disturbance. Proper modeling of any existing sensitive load is therefore of utmost importance for successful power quality assessment of such a system.

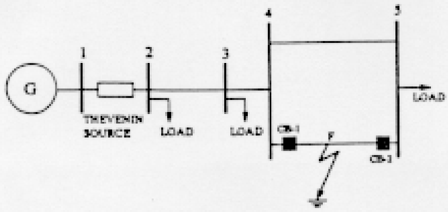

Figure 3. Voltage Sag Example

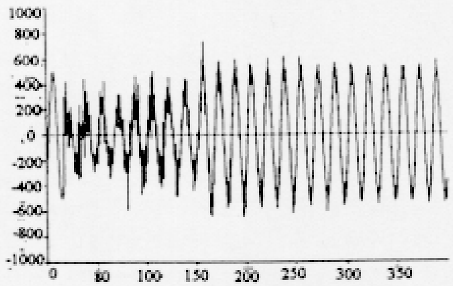

Figure 4. Voltage at Bus 5

4.2. Harmonic Pollution at the Utility Bus

This case illustrates the power quality related problems generated by non linear loads, such as a diode bridge rectifier connected to the utility system and driving a variable speed a.c. motor via an inverter. A simple diagram of such a system in shown in Figure 5, where the utility system is again modeled by a short circuit equivalent behind a transformer. The primary of the transformer is monitored to make sure that the distortion in the system voltage is in compliance with the IEEE 519 [9] recommended practices and standards. A transients simulation program is used again to obtain the sampled voltage waveform at bus 2 as shown in Figure 6. A Fourier analysis is carried out excluding the initial transients and the results given in Table III are obtained. As expected from the theory of 6 pulse diode bridge operation the voltage at bus 2 has significant 5^{th}, 7^{th} and 11^{th} harmonic components. The calculated total harmonic distortion (THD) level of 8.7% is also higher than the threshold set by the IEEE 519 standard which is about 5% for the voltage at the common coupling point. Hence, in this particular example, the harmonic contamination at the utility bus is found to be unacceptable with respect to the IEEE standards.

Table III. Harmonic Spectrum of V_2

Harmonic Number	% of the fundamental
1 st	100.0
5 th	7.04
7th	2.73
11 th	2.96
13 th	2.27
17 th	1.47
19 th	1.56
THD%	8.7

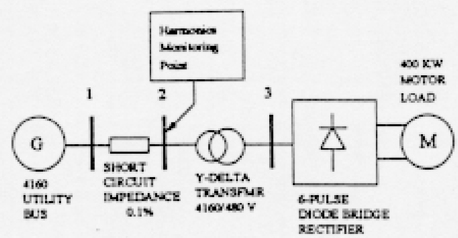

Figure 5. Harmonics Compliance Example

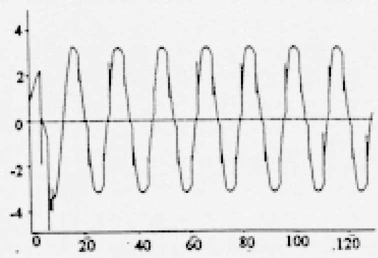

Figure 6. Voltage at Bus 2

5. CONCLUSIONS

Discussion given in this paper indicates that:

- A full assessment of PQ disturbances needs development of a comprehensive PQ assessment methodology.
- Availability of a variety of study tools is essential for implementation of the methodology.
- PQ assessment is quite often based on a combined use of modeling and simulation as well as data recording and processing which requires development of dedicated study environments and user interfaces.

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