"Smartizing" Power Quality Assessment Based on IEC Smart Substation Automation

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Abstract **--** Power Quality is a multidisciplinary systemic challenge. It involves huge data collection, many utility areas, and many other players outside the utility. Because it must connect massive amount of measured current and voltage data from various process levels to almost all utility corporate areas, allowing power conformity, energy availability and high service quality (achieving national and international standards), power quality should be the most suitable area to gain benefits from the smart grid derived concepts. However, issues like substation automation, Common Information Model (CIM) and other attributes from the IEC Smart Grid conceptual landscape are not, by themselves, enough to perform a plug and play power quality (or other area) solution. This article will first discuss the conventional power quality assessment, and subsequently will propose a new approach to "smartize" the power quality assessment from the utility power quality data collection to both its corporate treatment and the external players. The referred utility provides energy to a highly dense urban area as well as to an industrial area. Altogether, both areas account for about seven million consumers, supplied by more than 400 substations scattered over 570 municipalities.

Index terms **– Smart Grid, Substation Automation, Power Quality.**

I. NOMENCLATURE

"Smartize" and "smartizing", is a neologism that indicates the development of analytics which manipulate and convert data into information flow among Intelligent Electronic Devices (IEDs) and Information and Communication Technology (ICT) systems.

PRODIST, refers to the procedures adopted by the Brazilian power distribution utilities. These documents are elaborated by ANEEL (Brazilian Energy Regulatory Agency) to standardize and regulate the technical activities related to the operation and performance of distribution systems.

CASF (Common Access Functionality) refers to an implemented software layer aimed at promoting a unique data access method, independent from data source where the data is resident.

II. INTRODUCTION

Recently, power system voltage waveforms have been getting more and more distorted. This means that energy with less power quality is being supplied to consumers. This is mainly due to the massive insertion of power electronics equipment with switching characteristics, renewable energy generation, electronic lighting and various other devices that use thyristors and Insulated Gate Bipolar Transistor (IGBTs), among other solid state components [1]. Power Quality (PQ) related phenomena were exhaustively investigated since the 60's, and their associated costs have been studied since de 70's. In the USA, progressive costs of about US$ 10 million during the 70's, US$ 100 million during the 80's and US$ 1 billion during the 90's were reported [2]. In Europe, at the beginning of 21st century, those costs jumped to an annual average of about € 150 billion per year [3]. This means that non-PQ cost represents about 0.008% of the GDP (Gross Domestic Product).

In a simplistic correlation, making use of the GDP as a robust index of the wealth generated by goods and services, the Brazilian case showed an annual cost (due to deficiencies in the quality of power) of about US$ 50 billion. This represents an economic burden that is annually added to final prices, e.g., to society.

Along with this scenario, so as to achieve world class standards, the energy production in Brazil should present a global efficiency; quality and prices which, among other factors, will depend on how production assets respond to actual inputs involved. The electrical power, for example, is an increasingly relevant item to produce quality goods and also the life cycle management of an asset, as new production

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processes are intensively based on all-automated electric drives, critically sensitive to Power Quality issues, especially at present when power grid nonlinearities are rapidly growing.

As electricity will become more and more critical in the production chain, equaling to raw materials, labor force and taxes, concentrated efforts should be done in rationally mitigating PQ problems by intensively using new smart grid concepts, which to date are being scarcely applied to PQ area. In addition, ANEEL has not yet set assertive metrics and indexes to properly penalize Utilities and/or consumers in case of high PQ losses.

III. POWER QUALITY CONVENTIONAL ASSESSMENT

Since the 60's to the end of 90's many PQ phenomena studies, monitoring, PQ management systems, effect mitigation devices and utility arrangements to deal with bad PQ impacts, were performed. Also, during that period a sharp technology development in power electronics, computing and the telecommunications industry were witnessed. Additionally, in the 90's a strong neoliberal wave blew against electricity companies in several countries, mainly in the western world, spreading market deregulation. The post-privatization period led the power grid to increase its capacity, some substations multiplied their regular systemic function beyond the traditional transformation and regulation role. One of these new functions is the systemic control which includes: system regulation, islanding, reactive support, systemic protection, load and voltage control, “observability”, etc., with almost zero outage possibility.

Despite such changes, many utilities kept running with simple operational controls available at the OCC (Operational Control Center) with their early domestic Energy Management Systems (EMS) used to process central SCADA applications and acting in the process by means of Remote Terminal Unities (RTUs). Other utilities went through new emerging technologies, such as digital systems, Distribution Management Systems (DMS) and Geographic Information System (GIS). The advent of the IEC61850 international standard for substation automation and PQ assessment was to some extent frustrating. This technology has been used to cope with some challenges; on this respect, even through the solutions provided by some system automation vendors [4], high level engineering functions do not show a "smartized profile".

Still, technology had caused an impact on the structure and prevailing O&M (Operations & Maintenance) features of a utility, but their general core structure, as seen in Fig. 1, were kept basically the same as those used in past decades. Functional advances had taken place, but not "that deep" and somehow in slow motion, if compared to the development of the respective PQ and other functional utility challenges.

So, despite those many efforts in analyzing and mitigating consequences of PQ disturbances in electrical systems, and still expecting more "smartizing" approaches devoted to power quality in new smart grid technologies, the PQ development was mostly concentrated in the academic side and also on PQ monitoring devices, which, if used, generated massive data and long term analyses with few of them providing friendly stand alone data. In many countries, the PQ assessment itself kept going following an outdated procedure.

The reasons may vary from expensive monitoring systems, passing through not so evident cost effectiveness due to the lack of regulation, and, in many cases, stumbling in still not updated utility organizational structures, in which Stakeholders are not adequately involved. Even today, only few players at corporate and operational levels are demanded. One of the reasons may be that computational intelligence is normally less explored in turnkey solutions due, for example, to vendor competition which imposes lower costs, short delivery terms, and startup urgency.

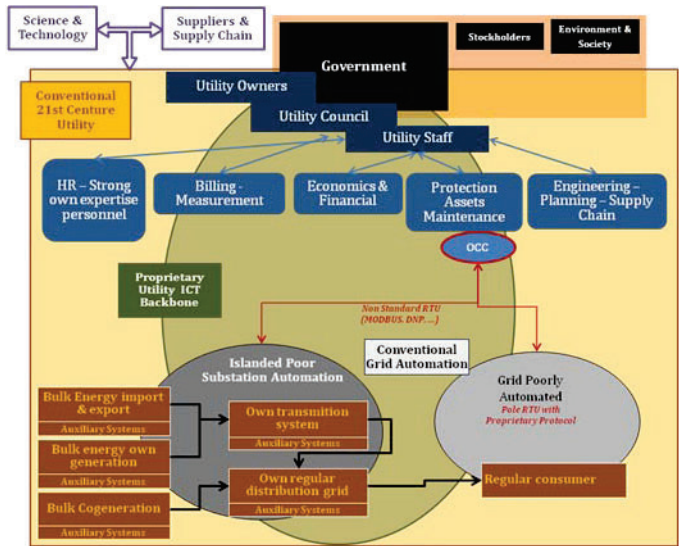

Fig.1. Typical 80's Last Century Infrastructure & Functional Layout of a Regular Electricity Utility.

On the other hand, the required high level engineering solution would cost too much to vendors, who are not so familiar with the features of the users, and how PQ intelligence should be dealt with at utility higher levels. Of course, an improved Man-Machine Interface (MMI) can be cheaply done through some operational and efficiency improvements, but it could be restricted to few tasks, mainly to shop floor level. The MMI also incorporated more data, although not necessarily pertinent information, without creating meta-engineering impacts affecting directly and deeply strategic investments, maintenance policies and other high deal corporate demands related to PQ.

To illustrate this, an example related to the Brazilian scenario is shown in Fig. 2. In this scenario, the power grid structure interconnects four main entities: the bulk generation and interconnected EHV and HV power transmission system (here called Basic Grid, comprising voltages equal to 230 kV and above), the Distribution grid, which comprises system voltages from 34.5 kV to 138 kV; and the 15 kV class MV system at feeder level, which its connected to low voltage (LV) consumers; and finally the prosumers & microgrid group.

The general approach to manage Power Quality in Brazil (which also applies to modern world class utilities with smart grid projects) is to analyze and correct power quality problems occurring at a particular location. However, this is by far done in an uncertain manner. If, for example, a disturbance occurs in a distribution system affecting a specific grid area, causing the malfunction of a customer load or creating unexpected disconnections, there will often be economic and social losses, which can be critical in the case of essential loads (e.g. hospitals, utility stations, etc).

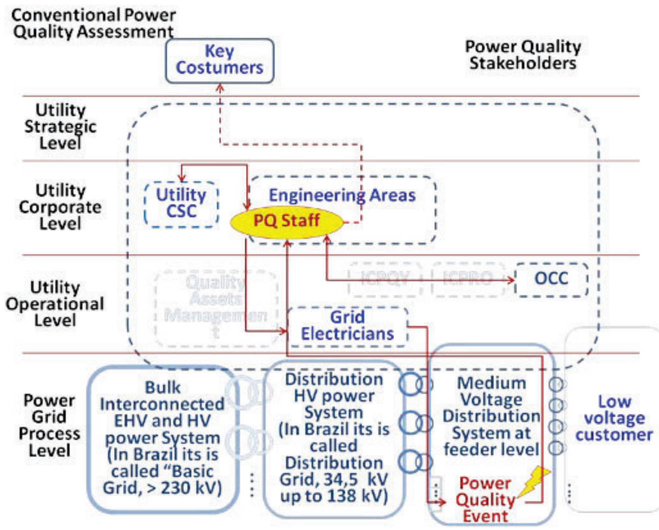

Fig. 2. Conventional Modern Utility PQ Assessment.

Often, the utility regional offices are first contacted and the maintenance team is sent to inspect the faulty section, rarely failing in spotting the problem that caused the contingency. Still, this will generate complaints by the costumers who might send a blizzard of calls to the Customer Service Center (CSC).

These claims are reported to the utility's PQ specialized staff. Investigations are then started by the specialized staff who will initially install some PQ monitor(s) in the specific affected point. Then, all the events recorded by the system information within the Operation Control Center (OCC) are searched.

In some cases, some members of the utility's commercial and technical staff might need to explain to the affected customers the cause of the abnormal condition. Sometimes no specific real-time data on power quality is available, nor even related operational system data (or protection information), or even worse, the costumer sensitive loads might not be properly registered. Processing the analytical work takes some time. If the problem is recurrent, enormous pressure on the utility is initially put by the customers. Later, it may even reach legal claims until finally the regulatory agency is contacted.

If major economic or social losses occur, even the local press can step in, which denigrates the utility image. Although the PQ staff performs an Herculean task trying to analyze a poorly monitored system without proper data flow, involving disconnected areas, an essentially reactive process is little assertive to solve such complicated systemic multidisciplinary problem, causing economic losses and penalties to the company. At this point, the top executives will take notice of the facts, creating sometimes a witch hunt turmoil, which eventually builds a problem-solving process completely inadequate. Even worse, the solution taken can be totally incompatible with the best practices of a high technological business management methodology required in a competitive environment of a world-class company.

The result of a poor automated structure can lead to some PQ disturbances, including blackouts, power cuts, and brownouts; especially at peak times, with astronomic losses for the society.

IV. Power Quality and Smart Grid

Early during the 2000's, the general increase in costs, restrictions of a centralized generation expansion, along with the falling costs of the renewable generation technology began to indicate the rise of a new scenario with a two-way power flow grid in which passive (non-monitored consumers) turned to be monitored and controlled "prosumers". These prosumers may present a massive probabilistic energy injection at all system levels, adding more complexity to the already complicated PQ problem. In this new power system structure, the transmission system includes either passive or active equipment, the distribution system became a smart power grid with integrated microgrids and its MV or LV generation became full monitored and with controlled features. Thus, every single consumer can evolve to a PQ expert capable of performing technical & legal actions against the utility. Additionally, the energy market deregulation introduces more competition and it will force utilities to improve power quality.

That means that it is not possible anymore to disregard the hidden control intelligence embedded in ICT advanced platforms within the utility, even for the PQ area. Smart grid concepts [5], [6], which emerged in the past fifteen years, should give all possibilities to better deal with power quality issues, maximizing IED and system integrated intelligences. Also, it may cause a mandatory business revolution [7], [8] that shows the way to an improved utility intelligence in the PQ area (and in all other areas) at a level possibly better than current monitoring systems.

To do so, the old PQ monitoring process must evolve inside a new utility structure, with much more completeness and complexity, as well as some added players, as indicated in Fig. 3. This new structure will be named "Smartized" Utility.

In order to increase the level of integration and corporate synergy [9], an integrated process like PQ management requires a full implementation of analytics that can perform "smartizing" PQ in the sense that the utility is not only a smart utility, but it is smartly seeking key devices and system elements for PQ management and decision support at all its key levels.

So, general analytic layers (including PQ analytics) begin with the Low Level Analytics (LLA), that is the default IED vendor parameterization, plus an extended parameterization to provide key functional data, needed to develop key information at a bay level.

The "smartization" process passes to Medium Level Analytics that covers all substation inter-bay functionalities, and run in an industrial computer (like a host) for protection, power quality, metering, maintenance, and operational control.

These processes also control all the data and information flow from/to the respective centers of the automated area. At this level, the operational control data can be hard real time or soft real time data, depending on data purposes; and monitoring data is online or historical data. Much of the processing functions are performed locally, to take real advantage of local intelligence, and provide smarter functions to upper levels.

Then, the "smartization" process passes to a Higher Level Analytics, that covers all functionalities performed at ICMED (Measurement Center Area), ICPROT (Protection Center Area), ICMAT (Maintenance Center Area), ICQTY (Intelligent Center for Energy Quality) and EOCC (Enhanced Operational Control Center), by means of operational enterprise service bus supported by IEC61968/61970, and the Service Oriented Architecture (SOA) concept.

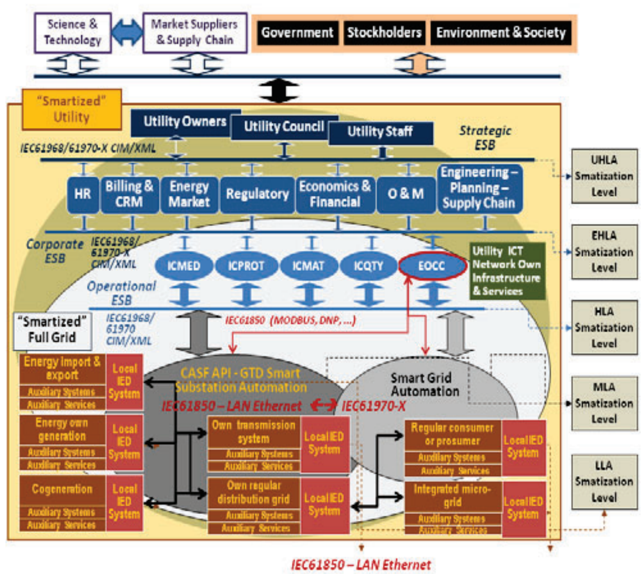

Fig. 3. "Smartizing" utility approach.

Subsequently, the "smartization" process moves on to an Extra High Level Analytics that covers all the interaction between corporate managers and operational areas. Its final aim is to get up-streams to connect with the higher level management staff with another bidirectional connection to all decision makers in the Utility organizational structure (Human Resources, Billing & CSC, Energy Market, Regulatory, Economics & Financial, O&M, Engineering, Planning, Supply Chain, etc.). This is done through a Corporate Enterprise Service Bus, which in turn has also bidirectional connection to the highest Company level comprising major Utility staff, Utility council and Utility owners. Key data and information are exchanged by means of a software architecture based on Web services (named Strategic Enterprise Service Bus - ESB) whose functionalities include the last analytic layer, or so called Ultra High Analytics (UHA).

V. Power Quality Smart Assessment

Under this concept, and to illustrate it through a real example and its smart PQ implementation, a 10 GW (peak demand) electric distribution company in Brazil is considered. The company is relatively large supplying power to a highly dense urban area and to an industrial area. It includes nearly seven million consumers fed by more than 400 substations scattered over 570 municipalities.

The CPFL distribution company has been developing a power quality monitoring device for distribution substations (different to other power quality devices available) in that it executes a smart chain from voltage and current measurements at shop floor level up to the uttermost utility's corporate tasks. It is integrated with protective relay data, including online connection to critical related players, like the utility regulatory area and key costumers, among others.

In order to reduce the time spent in its analysis, the processed data are collected at smart substation levels, and locally pre-processed regarding the Brazilian regulatory quality indexes.

The "smartization" of the power quality monitoring devices enables its integration to the CPFL computational corporate system, which provides access through graphical and text forms to the calculated indexes published centrally by the corporate intranet tool using the "Intelligent Center for Energy Quality" facilities.

The power quality monitoring system acquires the instantaneous voltage and current values from feeders, computes their RMS (Root Mean Square) values, as well as all other power quality indexes like: harmonic distortion, frequency deviation, voltage unbalance, voltage swells and sags, supply interruptions, all according to Brazilian standards.

The architecture of this system is composed by low cost IEDs designed to collect current and voltage snapshots with a 3 kHz sampling rate from each phase of the feeders. After that, the indexes computation are locally performed following the methodology established by the regulatory agency ANEEL [16], specifically making use of the PRODIST guidelines [16].

These indicators are first calculated at intervals of 3 seconds and then formatted according to the IEEE standard COMTRADE [15], and saved into a Substation's local database. The calculated indexes, as well as the related voltage and current oscillography, can be accessed directly from the substation using web pages in order to meet the demands of high priority consumers.

At the end of each day, a software agent performs a local preprocessing task considering the indicators stored in the substation database. This is done by grouping them at intervals of 10 minutes, totaling 144 samples per day for each index. Then, the resulting indexes are modeled according to the CIM (Common Information Model) semantic-oriented model [10] and expressed as XML files for its transmission to the corporate system.

CIM is a model based on UML (Unified Modeling Language) and aimed at exchanging the electrical grid information. It integrates both the heterogeneous hardware environment and software. Additionally, the choice of the CIM model enables the integration of substations with different SCADA architectures and power quality equipment from multiple vendors into a single ICQTY (Intelligent Center for Energy Quality).

The information exchange among substations and the ICQTY is based on the IEC/GID (Generic Interface Definitions) service [12]. Information such as data access, publish/subscribe, high speed and historical data are exchanged through this service. This standard is aligned with the services expected by the corporate ESB (Enterprise Service Bus) [14], thus, ensuring the interoperability of information even considering incompatible hardware and software environments.

The implementation added a Package to the CIM model, which contains class and specific information related to PQ data for the CPFL power quality device. Two possible approaches to represent this type of information into the XML documents were devised:

- Wrapping oscillography and power quality files within an XML document, or
- Parsing these COMTRADE files to encode them in XML documents.

In [13], a method for storing PQDIF data in an XML file was proposed. This method can be adapted to the embedded COMTRADE file in an XML file.

The initial implementation follows the first approach, because we believe that the transmission of the XML file could be more efficient in this scenario. However, plans to implement also the second approach, so as to test which one is more beneficial for the company [14], are also underway.

Fig. 4 shows the new utility PQ smart assessment process, under the "Smartizing" concept. It is a systematic, high level adding value analytics operated by means of a structured set of intelligent PQ hardware and related functions developed on a CASF layer.

The new approach shows how to deal with strictly regulated PQ problems. When worked out in terms of some features like the power conformity, energy availability and high quality of services, the PQ smart assessment connects massive power quality current and voltage measurements (not enough itself to answer every power quality problem) through a workflow that includes all related information. It begins with local automation intelligence on the IED System level (stand alone or integrated CAN/LAN) at both bay and process levels, supported by IEC 61850, to thereafter go through the CASF API - GTD Smart Substation Automation.

A Corporate Service Bus provides a bidirectional connection to an inter-operational main Utility functional Center, which integrates ICMED (Measurement Area), ICPROT (Protection Area), ICMAT (Maintenance Area), ICQTY (Quality Area) and EOCC (Enhanced Control Center) through an operational enterprise service bus supported by IEC 61970.

These automated data exchange supplies PQ related information such as the tripping of protection relays and their oscillography (Protection area), current system topology (Operational area), and the affected customers (Commercial area), constituting a specialized team of technicians, and providing a harmonic integration among the various utility corporate areas.

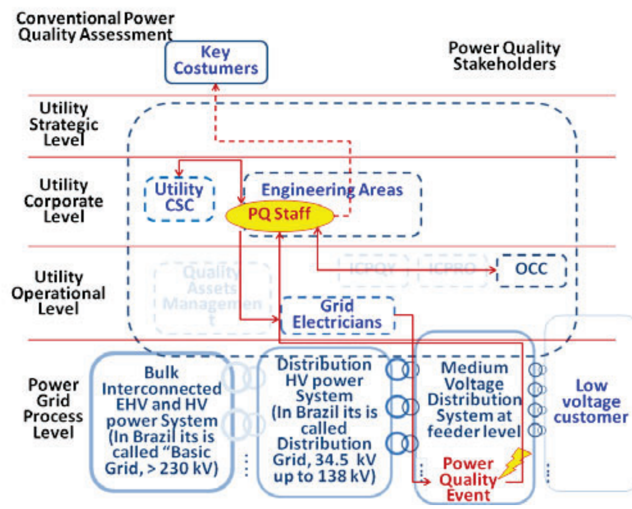

Fig. 4. PQ Smart Assessment.

The key utility areas involved are:

- ICQTY: Intelligent Center for Energy Quality. It provides complete computational support based on soft real time PQ indexes performed at the substation level. Also, it accepts data from meters and "oscillography". ICQTY is connected to many points of the MV an LV power Grid, with low cost measurements provided by "indicadometry" (measurement of pre-calculated standardized local indexes for both current and voltage). Thus, the utility can have an online quality operation center which provides automated analytical studies, support reports and other data provided for analysis. This will allow taking predictive and preventive actions and initiatives involving high costs to the dealership and the industry, meeting the legal requirements of supply using a small staff, i.e., with less implementation costs and reduction of both operation and maintenance costs.

- ICPRO: Intelligent Center for System Protection. The substation protection is autonomously done by proper parameterized IEDs (Relays), according to the standards and the philosophy of the utility. As part of ICPRO, the local protection IEDs functionality was expanded, improving system performance through protection logic functions and an automated on line diagnosis of protection actions restricted to the substation. These features intend to exchange data with ICQTY and EOCC to help the online PQ analyzes at the back-office;
- EOCC: Enhanced Operating Control Center. The integration of EOCC with ICQTY is intended to exchange data about the grid topology and other operating events, either as a utility system or as an interconnected system.

As a final result of the PQ "smartizing" process, an effective integration among the main utility automated core area centers is achieved, making easier the PQ process when dealing with complex PQ conditions.

The smart PQ assessment establishes true PQ Stakeholders that are all the players predicatively involved. For instance, if a voltage sag occurs at shop-floor level the automated workflow will follow an information protocol, such as: the process monitoring device (after measuring the VTCD - Short Duration Voltage Disturbance) will send by exception a real-time information to the ICQTY, as well as data requested by the EOCC and ICPRO, related to contingencies at the VTCD neighborhood. Next, the ICQTY shows all (sensitive) costumer loads that may be affected after performing a VTCD analysis. Then, a report is sent to the Utility's Customer Service Center (CSC). A manually filtered list of costumers may be produced and quickly notified about any future event. In this way, all real players are involved in a pro-active way.

In similar a manner, for all other PQ issues, all control and management functions of higher hierarchical levels are managed, keeping the process quality in an integrated realm that includes Utility Strategic Level, Utility Corporate Level and Utility Operational Level. With this integration the back-office communication flow of information is optimized, improving efficiency and providing a high degree of integration up to (depending on the type of event and its importance) the maintenance crew, Area Managers, Chief Executives, Board – CEO, Key Costumers, Regulatory Agency, and eventually the Press.

VI. Conclusion

Smart Grids increase the level of monitoring and control in a complex power system, achieving a high information sharing level among grid components.

Under the "smartizing" concept, the PQ Smart Assessment can be seen as a systemic high level adding-value analytics, which is done by means of a structured set of intelligent PQ hardware and functions developed over the CASF software layer, with a minimal hardware adaptation inside a digitalized solution and/or distribution grid devices. This concept is based on minimal key data from parameterized substation digital systems, and from developing smart substation's analytics tools which focuses on the technical & economical relevance of generated information and knowledge (not data). This will maximize the operational benefits and the profits of the stakeholders in Quality processes and their connection to Protection, Maintenance, Metering, and Monitoring of systems.

VII. Acknowledgment

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