POWER QUALITY MONITORING DATA MANAGEMENT AND ANALYSIS FOR DISTRIBUTION NETWORKS

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Abstract

New energy technologies bring challenges regarding the management of power quality, loading and losses in distribution networks. This paper discusses the challenges in power quality data management and analysis. Vast data amounts are available from several sources, e.g. distribution automation and smart kWh meters. However, the relevant information easily remains hidden in the data. The available data are big and diverse, and complex automated pre-processing, integration and analyses are needed. Several advancements are to be made for comprehensive and long-term power quality management that bases on measurement data. Thus, there is a need to develop methods and systems for the handling and analysis of these data. The issues addressed in this paper are reflections of literature, relevant power quality projects and views of connected industry experts. To examine potential solutions, test sites were established and are presented in this paper with proposals for important future studies.

1 Introduction

The need for power quality (PQ) management remains essential as old problems are diminishing and new ones are emerging. Yet, long-term PQ management based on comprehensive utilisation of PQ related data remains uncommon in majority of distribution networks. Included in PQ management, challenges in PQ data management and analysis are posed by various data sources, large data amounts and unestablished practices in analyses. With existing systems, PQ analyses can mostly rely on customer complaints and case-by-case analyses using portable PQ analysers. Large-scale PQ data analysis requires so much effort and costs that it has very seldom been implemented. Because of the lack of analyses, the knowledge of the benefits is also inaccurate and incomplete. Methods to manage and analyse PQ data need development taking into consideration feasible implementation in modern distribution networks. Especially PQ analyses are affected by the growing numbers of renewable and distributed energy resources and power electronics connected to distribution networks. Additionally, PQ analyses should be developed further to assess the impacts of increasing amount of heat pump solutions and customers participating in electricity markets via demand response services.

PQ management can generate substantial quantities of measurement data as the data sources include various devices: permanent and portable PQ analysers, energy meters and distribution automation (e.g. protection relays) [1], [2]. Collecting and combining different types of data can create additional value for the PQ data monitoring and analysis. For example, models can be developed on how power quality affects overloading and faults and thus enable their prediction. So far, such large-scale analysis has been limited to correlation of PQ and faults [2] but the knowledge of the fault development mechanisms could also be utilised.

Proposals to integrate PQ features in energy meters and distribution automation have already been published some twenty years ago [3]–[5]. More recently, it has been proposed to include smart meters, in addition to other intelligent electronic devices (IEDs) in distribution networks and at customers, in PQ monitoring [6]. CIRED/CIGRE JWG C4.112 guidelines for PQ monitoring [7] addresses the processing and analysis of the increasing amount of PQ data and requests the development of methods to manage and utilise the continuous stream of PQ data. Standardisation organisations address PQ monitoring in the standard IEC 61000-4-30:2016 and in the recommendation IEEE Std 1159-2019. However, international level standardisation for PQ management practices and technical specifications of the monitoring systems are missing. Many network operators, such as Enel, have developed their own methods for PQ monitoring and data management [8].

The diversity (e.g. data formats) and amount of PQ related measurement data makes pre-processing and analysis challenging tasks. In general, it has become evident that blindly increasing the amount of data will eventually reduce the forecasting and analysis performance, and data transfer and storage may cause issues. Thus, suitable methods to manage and analyse PQ data are needed. A PQ project in Australia is a good practical example how PQ data can be gathered in long-term and large-scale from distribution networks [1]. The project also highlights challenges in PQ data management, such as the variety of data formats and transfer methods. Similar activities must be initiated in the future in other countries to monitor the evolution of PQ conditions in distribution networks and to develop needed PQ data management and analysis methods. Eventually, the analyses may partly define what measurement data is required, thus the data management and monitoring features may be developed based on analyses.

This paper aims to discuss the current state and challenges of PQ data management and analysis and outlines directions for new studies. At the same time, the paper considers the big picture of comprehensive and long-term PQ management based on PQ data in distribution networks. The discussions rely on connected industry experts, academic publications, working group reports and standardisation. Additionally, test sites of a modern office building and microgrid are described and their utilisation in the development of PQ data management and analysis is highlighted.

2 Power quality management

According to [9] power quality management is designed to continuously improve power quality, increase electric installation uptime, and optimise equipment performance, efficiency and lifetime. A methodology similar to ISO 50001 on energy management can be applied to power quality comprising a power quality policy, planning, implementation and operation, and a continuous review process. These are enabled by measurements, monitoring, results, interpretation and analysis, with corrective and preventive actions. Here we consider that PQ management also includes visualisation and reporting. In other words, PQ management covers major part of, if not all, power quality related issues in distribution networks, and PQ management should be an integral part of distribution network design, operation and maintenance.

Measurement data used in PQ management may be, for example, from temporary case studies with analyser, fixed measurement units, IEDs of distribution automation (e.g. protection relays) or energy meters. These measurements may be supplemented with data from appliances such as solar power plant inverters and weather data. PQ monitoring may include continuous collection of measurement data from various sources to see the conditions in the network or alarms based on thresholds of certain parameters. PQ analysis can consist of case analyses of recognised problems, defining of disturbance source and estimating energy losses and causes of faults etc. Visualisation of PQ can be used in operation of the networks and to deliver information to PQ reports. PQ reports gather information such as long-term trends and event descriptions to people at different levels of organisations and to various parties, e.g. customers and regulators. Finally, prevention of PQ disturbances includes network planning, investments and maintenance, and mitigation considers, for example, passive and active filtering solutions, voltage regulation and network reconfiguration.

International and national standardisation should lay the basis for PQ management. For example, many national standards use the European standard EN 50160 as the foundation for setting limits for voltage quality at the connection point of the customer, and it is expected that customer devices operate within the limits of certain international EMC compatibility standards. However, PQ management as an entity is only guided by reports and recommendations. The situation is going to change as the standard series IEC TS 63222 is being developed currently. The series aims to define use cases for PQ management and to provide guidance on instantiating a PQ monitoring system. Examples of the technical level guidance are data formats, communication protocols, data storages and ways to manage PQ data, e.g. data queries and data quality management.

Currently, a few PQ challenges have been recognised in distribution networks that would benefit from data-based PQ management. Inertia of distribution networks decreases, which requires development of more dynamic frequency measurement methods. Interharmonics and supraharmonics have been observed to increase, thus their measurements and monitoring are needed. Voltage stability weakens due to reduced short-circuit powers as distributed energy resources become more common, thus voltage changes have to be monitored appropriately, e.g. with rapid voltage change (RVC) measurement.

3 Power quality data management

The aspects of PQ data management comprise what data and when are collected, how the data is transferred for pre-processing and analysis, and what methods are used to pre-process and store the data. In general, data management would benefit from open and common data format, standardised communication protocols and flexible databases. Data management is made easier if not all the data available is collected. Anyway, PQ data management is a key enabler in PQ management in the future.

Distribution management system (DMS) and supervisory control and data acquisition (SCADA) represent already available systems for PQ data management in distribution networks, and they have been proposed to include also PQ management [3]. These systems already have methods for data collection, transfer and storing and have standards such as IEC 61850 series. In fact, IEC TR 61850-90-17:2017 describes ways to model and transmit data in PQ context. Other PQ data formats include COMTRADE for event data and PQDIF that is designed for wider range of use. Furthermore, Enel has developed their own global standardisation for PQ data format [8].

Few large-scale and long-term PQ monitoring campaigns have been performed in national or international level. Examples of big PQ monitoring campaigns are [2] in China and [1] in Australia. These have proven that PQ monitoring data from thousands of sites generate enormous amounts of data, possibly hundreds of gigabytes a day. Transforming these data to a uniform form and a flexible and efficient database is needed. Similar activities should be initiated in other countries also to go towards more common methods in PQ data management. The effort by Enel is an evidence that PQ data management still requires development [8].

Pre-processing of data is an important aspect of PQ data management because relevant information in the data needs to be compressed and the data must be made compatible with the different assumptions of analysis methods. For example, many machine learning methods may be sensitive to outliers and erroneous data or may assume stationarity, normal distributions etc. Thus, it is important that pre-processing can be tuned to fit 1) the purpose of the analysis, 2) the properties of the data, and 3) the limitations of the analysis method. Not all the data is required to be sent to a back end system, rather the data can be filtered [10], compressed and aggregated at the edge devices, e.g. at the measurement device or in a some kind of data collector, or embedded computer as in [11]. Back end specific tasks can include e.g. time synchronisation of the measurements and detection of anomalies. Development of pre-processing methods is essential in order to reduce the volume of data, ensure a certain quality of data and combine data of different types from various sources.

If data management is performed at the measurement device level, it should be considered, what needs to be measured continuously and what measurements can be triggered or data queried from the storage of device on demand. As mentioned in [10], collecting all measurements required by the standard EN 50160 is not feasible. However, some increasingly important limit values of PQ quantities that need to be monitored are still missing from EN 50160, such as interharmonics. The corresponding IEC 62749 Technical Specification and EN 50160 are now otherwise harmonised but IEC 62749 limits also the levels of interharmonic groups and total distortion. Novel communication technologies such as 5G and NB-IoT give improved range, low delay and high rate of data transfer, thus data transfer may not be a problem in the future.

4 Power quality data analysis

A large variety of PQ data analysis methods and applications for distribution networks have been studied in literature. The data analysis methods vary from waveform analyses of transient events to long-term trends. Applications of machine learning are a topical subject also in PQ data analysis. McGranaghan has conducted a fundamental list of types of PQ phenomena and the ways to analyse them [12]. The analysis methods feasible in practice for PQ management in modern distribution networks remain to be determined.

The analysis tools should be able to handle increasing quantities of data of various sources and types, and enable and prove financial benefits of PQ management. Market mechanism-like PQ regulation may not be excluded. Additionally, the analysis should consider the current and emerging PQ issues, e.g. interharmonics and voltage variations. CIGRE/CIRED JWG C4.24 has published a comprehensive report regarding PQ issues in the future [13]. Well-established analysis methods can define the input data needed and its pre-processing, thus a blind collection of all data is not necessary.

The development of PQ analyses can alter the role of a PQ expert when the analysis is increasingly automated. For example, fault locating is a PQ related analysis application that automatically gives results. This development may free the PQ expert to more challenging cases or development of the PQ management in the company. In addition to mitigating PQ disturbances, the analyses could prevent PQ disturbances, e.g. fault or breakdown of a device or overloads can be predicted based on condition monitoring with PQ measurements. The quality of the prediction could be increased with different types of data such as disturbance history and weather data. These kind of forecasts or predictions are a promising area for applications of data mining methods, such as machine learning, that are able to digest large and heterogenous sets of data.

Other interesting aspects of large-scale and long-term PQ data analysis are trends and aggregated indices. Gasch et al. define a single PQ index that aggregates measurement sites, PQ parameters and time depending on the view needed [10]. Elphick et al. keep PQ parameters separate and estimate the PQ compliance of the whole network based on a statistical approach [1]. These methods simplify the analysis results for reporting and utilise a large variety of data. They can also aid in network design, recognising arising issues and set limits for alarms in monitoring. It would also be interesting, if based on the same data, the sources of voltage distortion could be localised or resonances identified in distribution networks.

5 Test sites

PQ measurement and data collection test sites have been implemented by Tampere University and research and industry partners in two different locations, a modern office building and a microgrid. The test sites use PQ meters to measure a large variety of PQ parameters and events. Also, measurement data from power meters of the building and solar power plant inverters are collected. The test sites have identical data collection platforms that collect, pre-process, transfer and store the data in a uniform form in a database. The data can be analysed online or offline depending on the application. The test sites offer platforms to develop PQ measurement data management and analysis methods for the purposes of PQ management, e.g. distributed storage of data may be demonstrated or control signals may be generated based on the analyses. The test site of the modern office building has been functional for two and a half years and half a year in case of the microgrid.

5.1 Modern office building

The building was completed in 2016 and has university and business premises. The low voltage network (400 V) of the building is divided into two main distribution boards that are supplied by two 20/0.4 kV 1000 kVA transformers. The building is also fed by a 57 kW solar power plant and it has charging stations for eight electric vehicles. A modern building automation system controls the ventilation and cooling of the premises.

Nine PQ meters have been installed to measure the following network locations: the supplies of the two main distribution boards, ventilation, two cooling machines, two elevators, solar power plant and electric vehicle charging stations. Power meters meter the two main distribution boards and the point of common coupling of the transformers at the 20 kV side. The data collection platform also reads the data registers of the solar power plant.

5.2 Microgrid

The microgrid is a 20 kV network that has two 2 MW solar power plants, two battery storages (2.4MW/1.6MWh and 1.6MW/1.3MWh), six gas engines (total 8.1 MW) and a fuel cell (130 kW). Each of the resources has their own distribution transformer. The length of the 20 kV network is 9 km and it is normally operated in ring configuration. The resources of the microgrid and the distribution automation are controlled with a smart grid system that is able to separate the microgrid into island or to make the resources participate in markets of fast ancillary services.

When establishing a test site four PQ meters were installed in the microgrid to measure the primary side of the distribution transformers of the two solar power plants and the two battery storages. It is also planned to collect the data from the solar inverters.

5.3 Power quality measurements

The sources of data in the test sites that can be considered useful for PQ management purposes are the PQ meters installed, power meters and solar power plant inverters. The main source of data are the PQ meters but the power meters and the inverters may represent supplementary sources of data as they record basic parameters, e.g. voltages, currents, powers and energies. Additionally, portable PQ analysers can be brought to the sites for reference measurements or studies that require more detailed data.

The PQ meters, eQL Quality Meters, could also be described as smart meters with advanced power quality measurement and monitoring features. They are able to measure 179 electrical parameters at one second interval. The PQ meters have been temporarily tested to record data at 100 ms interval but this would overwhelm the data communication and storing system in longer measurement periods. The measurements include several PQ parameters such as total distortion in voltage and current, harmonic voltages and currents until 40th order, voltage unbalance in forms of negative and zero sequence components to positive sequence component and DC voltage. The PQ meters have an accurate and dynamic fundamental frequency measurement and they record total and fundamental frequency active and reactive power. It is worth noting that the total distortion and total power measurements contain also interharmonic and subharmonic frequencies in addition to harmonic frequencies. The bandwidth of the measurements is 0-2 kHz. Subharmonics and interharmonics are still loosely limited in standardisation due to missing practical experience of their levels.

The PQ meters can also be configured to record events of voltage dips, rapid voltage changes (RVC) and non-intrusive appliance monitoring (NIALM). Also flicker and voltage deviation measurements are possible. Alarms can be set based on threshold values of a measurement. All the configuration can be done remotely at the test sites.

5.4 Data management and analysis

The test sites have a data collection platform that consists of a data collector computer and an IoT platform. The data collector gathers the data from the different sources over Ethernet network with data source dependent protocols. The data are unified to a common form for a database in the data collector using software-based adapters. Databases are located at the data collector computer at the test site and at the IoT platform at the back end at the university. The data collector transmits the data to the IoT platform that is used for data storing, analysis and visualisations. The data collector stores the raw data and filters it before sending to the IoT platform. Furthermore, the data collector can perform buffering of data to manage the varying data flow. Fig. 1 presents how the communication at the test sites is implemented principally.

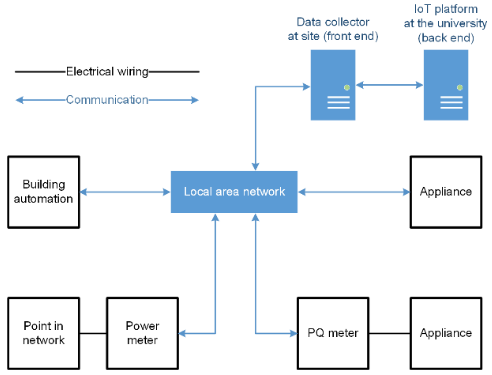

Fig. 1 Communication principles of the data collection platforms

The data collector operates in a Linux environment that allows flexible implementation of additional code, e.g. to test data management algorithms for PQ data. The data can also be forwarded to an external application, e.g. a battery storage. The IoT platform may be used to perform long-term analysis such as trends of PQ data with time or spatial aggregations, which then can be visualised in dashboards or reports. Based on the analyses, the IoT platform can deliver parameters or controls back to the data collector or an external application from which, e.g. the solar power plant inverter may receive a new setpoint for reactive power.

6 Future directions

The test sites may be utilised in the next studies proposed here:

- Defining what to measure and what data to collect for PQ analysis purposes.
- Examining PQ data management and analysis methods needed to integrate smart kWh meters and distribution automation in PQ management.
- Demonstrating PQ data pre-processing and analysis implemented at front end (e.g. a measurement device or a data collector) and at back end.
- Initiation of long-term and large-scale PQ monitoring campaigns in national level to gain experience of needed methods in PQ data management and analysis.
- Founding national or international database for PQ data and PQ related data.
- Following and influencing PQ management standardisation work (IEC TS 63222 series).

7 Conclusion

The paper highlighted developments and challenges in PQ data management and analysis. The focus was on large-scale and long-term PQ monitoring. The variety of data sources and types, data formats and large data amounts demand flexible databases and automated analyses. There is a need to collect practical experience to develop data management and analyses that can be implemented in many solutions and included in standardisation. The solutions must adequately also meet the requirements of new expected and emerging PQ problems such as interharmonics, supraharmonics and voltage variations. We presented the implemented test sites and pointed out their potential for research of the PQ challenges. The paper also gathered possible directions for the next studies. The authors are open for collaboration opportunities.

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