Development of Power Quality Management System with Power Quality Diagnosis Functions

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Abstract - Recently, in accordance with the development of IT technology, it is prevalent for power quality monitors to be connected to each other via networks and share their data because such networks provide system-wide insights to customers concerning power quality. Those systems can alarm and display power quality events for the convenience of customers. However, if a power quality event occurs, it is difficult for customers to determine its cause and solution because the systems do not provide appropriate power quality diagnosis functions. The power quality management system presented in this paper has been developed to provide customers with various power quality diagnosis functions so that they can cope well with power quality problems with the right measure in the right place. This paper presents the structure and functions of the developed power quality management system and shows some results of the power diagnosis functions.

Keywords: Diagnosis System, Event Identification, Monitoring System, Power Quality

1. Introduction

Recently, *power quality* (PQ) has become a significant issue for both power suppliers and customers. In the past, it was sufficient for utilities to provide electric power without outage. However, customers have come to require high-quality electricity because there have been some important changes in power systems with respect to power quality [1]. First, power electronic devices are currently widespread. Since these devices have non-linear voltage and current characteristics, they deteriorate power quality. Second, electric loads have become more vulnerable to power quality. For example, high-tech IT devices, adjustable-speed drives, process-control equipment and computers are notorious for their sensitivity to power quality. They may suffer failure, misoperation, or hardware damage even during small power quality events [2].

Lastly, the deregulation of the electric power business brings significant changes to the entire power system. In the traditional electric power system, the price and service terms are set uniformly because of the monopoly utility. However, in the deregulated power system, the monopoly utility will be partitioned to many companies such as generation companies, network operators, power traders, and retail energy service companies. Each of them should have the responsibility not to deteriorate power quality to the others or to supply appropriate power quality according to contracts. Therefore, if power quality events happen, it may be difficult to examine the reason and lay the responsibility on one of them [3]. Therefore, it will become more and more important to measure power quality level precisely and identify the causes of power quality corruption. In that sense, delicate power quality monitors will be spotlighted in the future [4, 5].

Recently, in accordance with the development of IT technology, it has become the norm for power quality monitors to be connected to each other by networks and to share their data with others because such network provide system-wide insights to customers concerning power quality. In many cases, for local power quality management, the data analyzed by several power quality monitors are gathered by the graphic user interface (GUI) system through network connection. The GUI systems can alarm and display power quality events for the convenience of customers [4].

However, if a power quality event occurs, it is difficult for customers to determine its cause and solution it because the systems do not provide appropriate power quality diagnosis functions. The authors have developed the power quality management system to provide customers with various power quality diagnosis functions so that they can cope well with power quality problems using the

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Received June 1, 2005 ; Accepted September 30, 2005

right measure in the right place.

This paper presents the detailed structure and functions of the power quality management system that consists of the *power quality monitoring systems* (PQMS), *the GUI system*, and the *power quality diagnosis system* (PQDS). This paper also shows some results of the power diagnosis functions.

2. System Configuration

2.1 Overall System Configuration

Fig. 1 shows the configuration of the power quality management system. PQMSs detect power quality events after analyzing the sampled voltage and current of the line. The PQ data made by PQMSs are transferred to the GUI system through the network line. The most recommended network type is the Ethernet because the PQ data are too massive in quantity for other serial communication means.

The GUI system is usually installed in the operator's computer and it gathers the PQ data from the PQMSs, and then stores them to the database. In addition, the GUI system displays PQ event, PQ trend, waveform of voltages and currents, etc. and alerts the operator of event occurrences.

The PQDS is installed in the GUI system. When the PQDS is installed, PQ diagnosis menus are added and activated to main menus of the GUI software. The PQDS diagnoses power quality in many ways such as predicting probability of event, identifying event cause and location, proposing counter measures, and so on. The detailed functions of each component will be explained in the sections below.

2.2 Power Quality Monitoring System (PQMS)

The hardware of the PQMS comprises three parts: A/D conversion part, PQ analysis part, and data transmission part. The A/D conversion part converts the analog signal of voltages and currents measured by *potential transformer* (PT) and *current transformer* (CT) into digital signal. The sampling rate is 128 samples per cycle, that is, 7,680 Hz in order to analyze harmonics up to the 50^{th} component and the sampling resolution is 16 bit. The PQ analysis part analyzes power quality by using digital signal processing algorithms. In the last part, the results of PQ analysis are transferred to the GUI system using the fast Ethernet.

Fig. 2 shows the representative structure of the PQMS with decentralized processing architecture. This structure

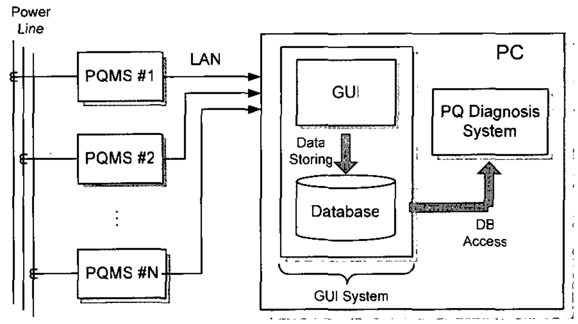

Fig. 1 Configuration of power quality management system

integrates all the above-mentioned parts into one hardware system. Most companies are producing this type of PQMS system.

Fig. 3 presents the structure of the PQMS with concentrated processing architecture. The main idea of this architecture is to detach the A/D conversion part from the others and put the part in a separate device, known as the *PQ meter* (PQM). The role of the PQM is only to sample voltages and currents and transfer them to the *PQ analyzer* (PQA). The complicated and time-consuming PQ analysis algorithms are concentrated in the PQAs. The strong point of concentrated processing structure is that the cost of PQMs can be reduced by using relatively low-speed processors because PQMs need not to execute complicated processing. Therefore, this structure can be an economical and competitive solution for the PQ diagnosis system that deals with numerous nodes and devices. The disadvantage of this structure is that the communication burden between PQMs and the PQA may be heavy. However, the current Ethernet technology can solve this disadvantage and furthermore, the data communication technology is rapidly improving [5, 6].

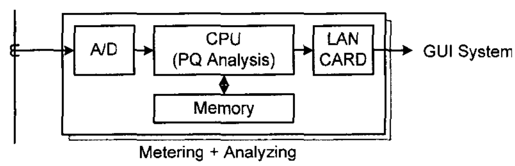

Fig. 2 PQ monitoring system with decentralized processing architecture

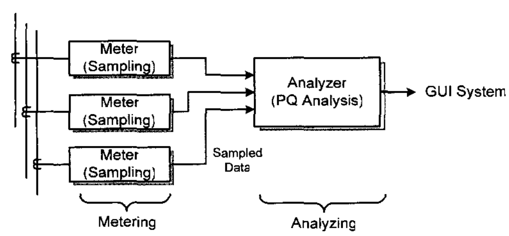

Fig. 3 PQ monitoring system with concentrated processing architecture

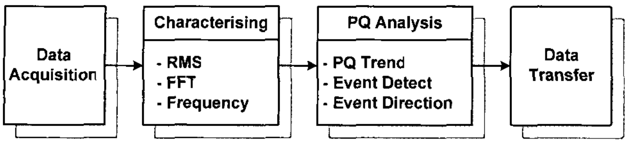

Fig. 4 PQ analysis procedure of the PQMS

Fig. 4 indicates the PQ analysis procedure. The first step is the *PQ characterizing step* that calculates the RMS values of voltages and currents, harmonic components and system frequency using digital signal processing algorithms. The RMS values are calculated once during every half cycle, and harmonic components represented by the magnitude and phase angle of each individual harmonics are calculated once during a cycle using *Fast Fourier Transform* (FFT), especially *128-point 2-radix FFT* [7].

There are many algorithms for system frequency measurement such as *Discrete Fourier Transform* (DFT) method [8], *Prony's estimation* method [9], *Smart Discrete Fourier Transform* (SDFT) method [10] and so on. In this paper, we modified the SDFT theory and applied it to the developed system because of its strong points: accuracy, especially when system frequency deviates from nominal value; calculation speed and; immunity to harmonic noises.

Table 1 Power quality data generated by PQMSs

Category	Kind
Trend data	Vrms, Irms, power, energy, frequency, power factor, DF, THD, TEHD, TOHD, TDD, K-factor, flicker index, unbalance factor, etc.
Event data	Sag, swell, interruption, undervoltage, overvoltage, unbalance, flicker, transient, harmonics, over-frequency, under-frequency, event direction
Raw data	64 samples per cycle
Harmonic data	0~50th harmonics

The second step is the PQ analysis step. Table 1 shows the categories of analyzed data: *trend data, event data, raw data* and *harmonic data.*

Trend data represent the characteristics of PQ variation that are usually slow and continuous compared to event data. This data are generated every 30 cycles and averaged once every 30 minutes. Trend data consist of the RMS of voltages and currents, power (unit: W, Var, and VA), energy (unit: Wh, Varh, and VAh), system frequency, power factor, unbalance factor, and harmonics such as *total harmonic distortion* (THD), *total even harmonic distortion* (TEHD), *total odd harmonic distortion* (TOHD), *distortion factor* (DF), *K-factor*.

Event data represent the summary of PQ events such as voltage sag, swell, harmonic event and so on. Event detection follows *IEEE Standard 1159*. For example, voltage sag means 10~90% voltage reduction for cycles between half to 1 minute. Each event data consists of event duration, event type, start time, end time, mean value, and min or max value. Event data also contain the event direction data that represent relative location of event sources. If the event source locates in the territory of the PQM, the event direction is downstream. If the event source locates out of the territory, the event direction is upstream. Voltage event direction is decided using various detection methods that utilize the current and power during or after the event [11]. Harmonic event direction is determined by the direction of harmonic power flow [12]. The event direction data are used to find the event source location in the PQDS.

Raw data are the sampled voltage and current waveform data. The voltage and current data sampled by PQMs are 128 samples per cycle as explained previously. However, in order to relieve communication burden, raw data transferred to the GUI system are down-sampled to 64 samples per cycle.

Harmonic raw data are the magnitude of each harmonic component from 0 order to the 50th harmonic. Raw data and harmonic raw data are used for accurate diagnosis in the PQDS or real time display.

2.3 GUI System

The GUI system has three major functions: display function, PQMS management function, and database management function. First, the GUI system displays various PQ graphs and charts, event data, and waveforms of line voltage and current instantly.

Second, the GUI system manages and controls PQMSs that are connected to the GUI system. The GUI system sends standard time signals to PQMSs for synchronizing the time of PQMSs to the time of the GUI system. Therefore, the time of the whole system can be synchronized and the time stamp of each data can be meaningful. In addition, the GUI system periodically checks the status of PQMSs by communicating notification signals.

Last, the GUI system manages and inventories data received from many PQMSs in appropriate databases using *open database access* (ODBC).

2.4 Power Quality Diagnosis System (PQDS)

The process of the PQDS is illustrated in Fig. 5. The input of the PQ diagnosis system is the data stored in the database of the GUI system. The main diagnosis functions are event trend diagnosis, stochastic diagnosis, power quality indexing, and event identification. Those functions will be elaborated in the next chapter.

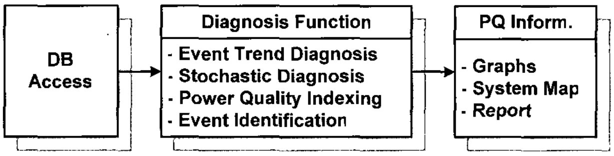

Fig. 5 Data processing procedure of the PQDS

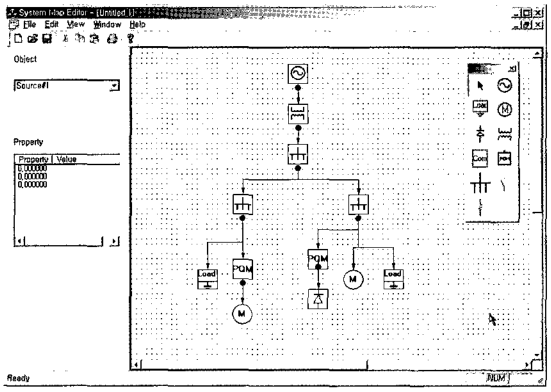

Fig. 6 System Map that shows power system topology

To identify the exact location of event source in the distribution system, the PQDS should have the power system topology data. In the developed PQDS, users should construct exact system topology on the System Map and input some data needed by the System Map. Fig. 6 indicates the System Map that shows the configuration of the local power system and the interconnections of PQMSs. If a PQ event happens, the GUI system immediately notifies which PQMS detected the PQ event on the System Map. Moreover, after event identification of the PQDS, the event source is indicated on the System Map.

3. Diagnosis Functions

3.1 Event Trend Diagnosis

Event trend diagnosis functions are used to statistically summarize the trend of PQ events listed in Table 1. The results of event trend diagnosis are provided as hourly plots, weekly plots, monthly plots and time plots. The hourly plot, the weekly plot, and the monthly plot show the trend of events during a day, a week, and a month, respectively. For instance, through the hourly plot, users can find the time zone when the corresponding PQ event occurs most often in a day. The time plots display the number of events in the form of cumulative graph and summarize the event in the diagnosis period. This plot gives customers clear information of the trend of events in time sequence.

3.2 Stochastic Diagnosis

Stochastic diagnosis function provides several standard charts, voltage event graphs, and harmonic event graphs.

CBEMA, ITIC, and SEMI charts are the representative standard charts of voltage for computer-based devices or semiconductor manufacturing equipments [2].

Voltage event graphs consist of voltage event charts and a voltage sag coordination chart. The voltage event charts show the number of voltage events distinguished by voltage magnitude and duration of voltage events on three-dimension charts. The voltage sag coordination chart is proposed by IEEE Standards 493 and 1346 [2]. This chart indicates the estimated number of voltage event occurrences annually. If users know the voltage tolerance of their equipment, they can determine how often their equipment will suffer voltage events per year.

In the harmonic event graph, the numbers of harmonic events are displayed in the form of a bar graph according to THD. This graph generates harmonic index, namely, *CP95* that means the THD value corresponding to 95% of cumulative number [13].

3.3 Power Quality Indexing

To evaluate PQ level, a number of PQ indices have been developed. PQ indices should quantify complicated PQ problems and help customers understand PQ level easily. These indices can also be used as bases when customers contract electric power provision with power companies.

The representative conventional PQ index is $SARFI_x$ (System Average RMS variation Frequency Index), which means the ratio between the number of customers experiencing voltage sag with magnitude below X% and the number of total customers [14]. However, this index cannot reflect the magnitude of voltage sag. For example, if X is 70%, 60% voltage sag and 20% voltage sag will show the same duration result in the same index value.

In that sense, Sag Score defined by Detroit Edison is more efficient to apply to power provision contracts. The Sag Score is defined as (1) where V_a, V_b, and V_c mean three-phase voltages in per unit measurement [15]. However, this index cannot consider the duration of voltage sag.

$$Sag\ Score = 1 - \frac{V_a + V_b + V_c}{3} \tag{1}$$

In the developed PQDS, a new voltage sag index is used. This index is calculated by multiplying the voltage difference between the RMS voltage determined by the contract between power companies and customers (V_{ctr})

and the average RMS voltage by the duration of the event (d) as (2). Therefore, this index can represent both the magnitude and duration of the event, not the magnitude only.

$$I_S = \left(V_{ctr} - \frac{V_a + V_b + V_c}{3} \right) \cdot d \qquad (2)$$

In fact, the effect of voltage sags is different according to the duration of voltage sags as we can see in the ITIC chart. Therefore, for reflection of the duration-dependent feature, V_{ctr} in (2) should be a function of time for the future.

In addition, the total PQ event index is calculated by adjusting weighting factors to PQ events. Users can define the values of weighting factors considering their own condition. For instance, the weighting factors of voltage sag and interruption are 2 and 3 respectively while those of the others are 1. This index shows overall PQ states of corresponding power systems.

3.4 Event Identification

Event identification has three categories, which are event location identification, event cause identification, and solution suggestion as illustrated in Fig. 7.

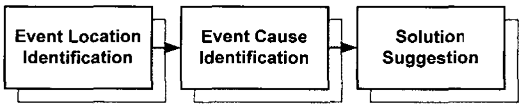

Fig. 7 Procedure of the event identification

Event location identification is necessary to find the exact position of the event source. This is important when solving PQ problems because it makes it possible to remove the faults rapidly and to find a more suitable compensating method. The more PQMSs are installed in the local system increases the opportunity of obtaining a more exact location. To identify event location, the PQDS uses the event direction data and the system configuration data. The event direction data are generated by PQMSs and stored in the database of the GUI system. The system configuration data can be obtained from the System Map. The detailed algorithm finding event location is elaborated in [16].

The event cause identification is also significant because this function gives the solution of improving the PQ. The developed system can identify two kinds of events: voltage events and harmonic events. First, to identify the source of voltage events, the PQDS calculates voltage RMS continuously using a sliding window from voltage waveform raw data, and then evaluates deviation of the RMS value to classify the faults. If, for example, the fault characteristics correspond with a certain pattern previously evaluated, the PQDS can determine the cause of the voltage event. Therefore, as much information as possible concerning equipment fault is needed in order to achieve better determination. The voltage event source identification algorithm is being studied [17].

Second, the source of harmonic event can be identified using harmonic spectrum data. If the harmonic spectrum of the event matches something in the event cause list, the PQDS can identify the event cause. Currently, the PQDS can identify six-pulse converter, twelve-pulse converter, transformer saturation and so on. The harmonic event cause identification is also still being studied [18].

The PQDS suggests solutions to improve PQ. It proposes the type of PQ compensating devices and suggests their ratings suitable to the events.

4. Developed System

The developed PQMS and the GUI system were explained in [6]. This paper presents the development of the PQDS.

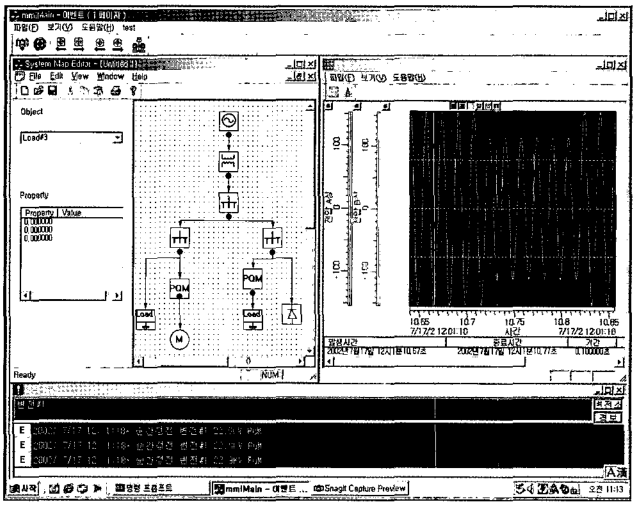

Fig. 8 Main screen of the GUI system including the PQ diagnosis system

Fig. 8 shows the main screen of the GUI system including the PQDS. The left window of the main screen shows the System Map editor and the right window shows the detailed data of the PQ events. The bottom window shows alarm signals that are displayed when a PQMS detects PQ events. Fig. 9 presents the hourly plot of voltage events. Users can diagnose the event trend for any period that they wish. Therefore, this plot will help users consider a counter plan to improve power quality. Fig. 10 indicates the voltage events on the ITIC chart. The horizontal and vertical axis of the charts represents event duration and voltage magnitude, respectively. Each dot signifies one event and two curves signify the voltage tolerance curve. The voltage events outside the ITIC curve are harmful to the customer's device.

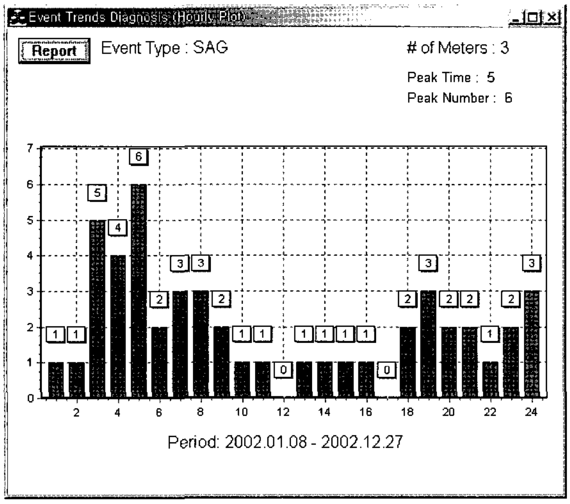

Fig. 9 Hourly plot for voltage sag event

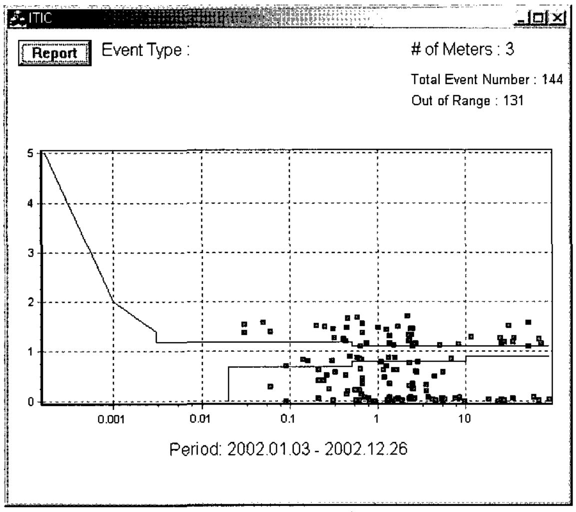

Fig. 10 ITIC Chart

5. Conclusion

This paper presents the developed power quality management system including the PQDS. The PQDS has four diagnosis functions; the event trend diagnosis function, the stochastic diagnosis function, the power quality indexing function, and the event identification function. This paper describes the detailed features of the diagnosis functions. The results of these functions can lead customers to improve and manage power quality.

Recently, the developed PQ management system is practically tested in several industrial fields. For more accurate event identification, more dynamic characteristics of various actual loads should be studied and actual field data should be examined.

Acknowledgements

This work was supported by LS Industrial Systems Co. Ltd.

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