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Automated Analysis of Power System Disturbances

M. KEZUNOVIC, Y. DONG
Texas A&M University
U.S.A.

SUMMARY

This paper proposes a new tool for analysis of power system disturbance. The information from proposed analysis method is useful to many control, operation and protection applications such as reliability analysis, asset management and outage management. Development of automated disturbance analysis and fault location software is introduced. Concerns in implementation, including source of data, communication requirements and standardization are also discussed.

KEYWORDS

Disturbance, Power quality, Fault location, Intelligent Electronic Devices (IEDs), Electromagnetic transients

1. Introduction

When looking into the problem of disturbances, one can classify the issues into two categories: interruption of continuity of service and waveform distortion. The first category refers to voltage magnitude dropping to very low value or zero due to fault or disconnection from the system, which is also referred to as Loss of Load (LOL); the second category refers to voltage fluctuation, voltage dips and spikes, harmonics, induced low frequency voltage, oscillatory transients and frequency variation that distort the sinusoidal waveform and "pollute" the quality of power supply [1]. Such issues affect the power system in several ways. First, it has a negative impact on the operation of certain types of load which are basically motors and other inductive loads; secondly, it deteriorates the "health" of power system assets; thirdly, it causes misoperation of power system equipment and result in unwanted outages.

There are several aspects to studying disturbances: 1) Sensitive detection and classification of power system disturbances, namely analysis of disturbance waveforms, 2) Real time measurement of the parameters of signal components caused by power system disturbances, namely monitoring the pattern features of waveforms induced by power system disturbances, 3) Quantification of the extent of power system disturbances (or waveform distortions) and their negative impact on power systems. 4) Identification of the types, location and causes of power disturbances [2]. Many metrics have been proposed to assess the impact of disturbances. Various Power Quality Indices (PQI) such as the Total Harmonic Distortion (THD) and VT product (voltage distortion index) have been proposed [3]. New indices such as WDR (Waveform Distortion Ratio) are being proposed as the research goes on [4].

kezunov@ece.tamu.edu

Lightning strikes cause various voltage and current disturbances in power systems, some of which may result in faults and trigger operations of protective devices. They create electromagnetic transients and may have diverse impact on power system operation or "health" of the equipment. On one hand, surge arresters at the power system level and SWC protection secondary level protect primary and secondary equipments from such disturbances while on the other, detecting such event, analyzing their impacts and assessing mitigation strategies are important tasks for operations, protection and maintenance personnel. Facilitating such tasks through automated means saves time and improves consistency of the analysis.

This paper discusses issues with automated analysis of such events and illustrates the implementation approaches for specific applications. The core of the paper is focused on the cases of automated analyses of power quality events, power system faults, and circuit breaker operations. While each of the applications was developed independently for specific purposes, the approach to implementing an automated solution has many common elements.

The paper elaborates on the common elements of an automated solution for analysis of power system disturbances. Section 2 is devoted to background of disturbance classification and the Intelligent Electronic Devices (IEDs) used to capture the power system waveforms. In Section 3, signal processing techniques commonly used for the extraction of signal features are introduced. The use of signal features in a knowledge based system aimed at performing cause-effect analysis is also elaborated on. In Section 4, various issues for data management and communication are mentioned. The role of standards is explained in Section 5, followed by conclusion.

2. Background

Classification of Power System Disturbances

Based on the cause, disturbance in power systems may be classified into lightning transients, transformer surge waveforms faults, and switching transients.

Lightning transient starts with lightning stroke injecting large current into the system. The current flows through transmission lines and power apparatus as travelling wave and dissipates into the soil through the grounding system. The current may surge to its peak value in 2μS and decrease in an exponential manner [5]. Lightning-induced voltage is created by the electromagnetic field generated by the current wave. Although the imposed current decreases fast, the over-voltage and the resonance may persist for many more cycles.

When lightning strikes occur, resonance over-voltage is generated by the surge current passing through the transformer, the line and secondary wiring. Resonance over-voltage is characterized by offset of voltage as well as high-order harmonics. The frequency of resonance is determined by the natural frequency characteristics of the transformer winding. The resonance over-voltage may cause insulation failure to transformer winding and hazard other components in the system at the same time [6].

Upon occurrence of a fault, the system will encounter a transient voltage waveform which settles after a few cycles, followed by a post-fault steady state which usually associates with dips in voltage waveform. The length of steady state depends on time for fault location and isolation. However if the fault involves arcs, the transient state will be much longer as arcs extinct and reignite repeatedly with very high order harmonics.

Switching transients are cause by operation of circuit breakers upon protection, fault isolation and reclosing. Although the operations are required, the transient may negatively affects loads and equipment system-wide [7].

Characteristics of disturbances are outlined in Table 1, where F_1 represents fundamental frequency and F_H represent frequencies for harmonics.

Table 1: Characteristics of power system disturbances

Type of Disturbances		Duration	Frequency Range
Lightning current transient		10-70μS	DC offset
Transformer resonance over-voltage		<100μS	F_H, offset
Fault voltage	Transients	<100mS	F_1, F_H, offset
	Steady State	From several mS to hundreds of mS	F_1
Switching Transient		<100mS	F_1, F_H, offset

Sources of data

As a part of Smart Grid deployment projects, Intelligent Electronic Devices (IEDs) for monitoring, protection, and system automation have emerged in transmission systems. The IEDs are located in substations and capture impact of disturbance induced transients on transmission line and substation equipment. Their types vary, as well. Some provide samples (digital fault recorders), some provide samples and synchronized phasors (digital protection relays), and some provide energy measurements and power quality indicators (power quality meters) [8].

IEDs that provide samples of voltage and current can all be utilized in disturbance analysis Meanwhile data from IEDs providing synchronized or unsynchronized phasors may assist in various fault location approaches. Among others, these IEDs include Power Quality Meters (PQMs), Digital Fault Recorders (DFRs), Digital Protective Relays (DPRs), Phasor Measurement Unit (PMUs), etc.

Power Quality Meters (PQMs) are installed at some substations where industry loads are connected, to continuously monitor quality of delivered power. PQMs record voltage and current waveforms, as well as real and reactive power. Calculation of PQIs like THD and power factors is also incorporated. The sampling rate of a PQM is high enough for harmonic analysis through 55^{th} harmonic or higher. Although monitoring of waveforms is continuous, if everything is considered normal the waveforms samples are overwritten by new samples after certain short period of time (a few cycles), and extended recording of waveforms is triggered by detection of disturbance events.

Digital Fault Recorders (DFRs) record voltage and current waveforms once a fault is detected and instruments are triggered. DFRs are capable of recording pre-fault and post-fault waveforms for a fixed length (usually under 20 cycles). The number of samples per cycle is between 50 and 100 on a 50Hz system based on survey of technical documents.

Digital Protective Relays (DPRs) are installed in substations. Their number and placement depends on schemes for substation protection and feeder automation. Recording of waveforms is triggered by detection of disturbance and/or switching operation. The sampling frequency of DPRs are lower than DFRs since most calculations in the relays are based on fundamental frequency phasors and signal frequencies in vicinity of the fundamental frequency and antialiasing filters are band-limited.

Phasor Measurement Units (PMUs) are installed at some substations. In some cases, PMU measurement algorithms are imposed on relays and digital fault recorders. Such devices are then called MPU-enabled IEDs. They measure voltage and current phasors continuously. Waveform samples and calculated phasors from all over the system are time-synchronized to allow for comparison of sample alignment phase angles. Some PMUs allow export of waveform samples with time stamps. In such cases, PMU-enabled IEDs may also be a source of transient waveform records with high precision sampling clock and time-stamp synchronization.

3. Transforming Data to Knowledge

Software Structure

A disturbance assessment tool (software implemented in MATLAB) has been developed in a previous study and described in [9]. The software consists of four application modules and two interface modules, as shown in Fig. 1. “Graphical User Interface” provides a friendly environment for using the software. “Database Management” facilitates data saving, retrieving as well as exchanging the internal or external data. The application module “Detection and Classification” automatically detects and classifies the type of the disturbance captured in the recorded or simulated waveforms. The types of disturbances include the voltage sag, swell, outage, harmonic, notch, flicker, impulse and switching transient. After the disturbance is detected and classified, the waveform is further processed by the module “Waveform Characterization”. Eight different sub-modules corresponding to the eight types of events have been designed. The software automatically selects the appropriate sub-module for computing parameters pertinent to the event. Then, one may proceed to the module “Equipment Sensitivity Study” for evaluating how various waveform features affect the behavior of the equipment during the event. Finally, the module “Event Location” aims at accurately pinpointing the location of the event occurrence.

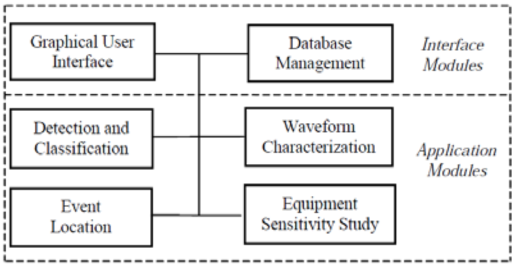

Figure 1. The software structure.

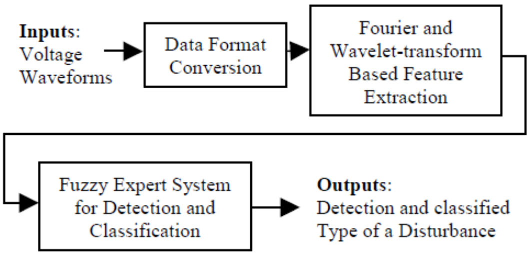

Figure 2. Flowchart for "Detection and Classification".

Detection and Classification

The core function in this PQ analysis tool is Detection and Classification. Fig. 2 shows the flowchart for "Detection and Classification" module.The detection and classification problem consists of two steps. The first step is feature extraction, during which the distinct and dominant features (or patterns) of various events are selected and obtained using appropriate techniques. The second step is called decision making, during which the extracted features are further processed by an inference engine to determine the types of the events. In order to guarantee the performance, feature extraction combines Fast Fourier Transform (FFT) and Wavelet Transform (WT) for calculation of the PQIs, and Fuzzy Expert System is used in the sub-module of classification.

Eight distinct features inherent to different types of disturbances have been extracted: the Fundamental Component (V_n), Phase Angle Shift (α_n), Total Harmonic Distortion (THD_n), Number of Peaks of the Wavelet Coefficients (N_n), Energy of the Wavelet Coefficients (EW_n), Oscillation Number of the Missing Voltage (OS_n), Lower Harmonic Distortion (TS_n), and Oscillation Number of the rms Variations (RN). The formulae for computing these features are given in [9] and [10].

One rule for detection and fifteen rules for classification have been incorporated in the Fuzzy Expert System. The fuzzy partitions and the corresponding membership functions can be obtained based on both the statistical studies and the expert's knowledge. Opinions from operators can be conveniently incorporated into the system in practical applications.

The output for the detection part is the variable "Detect" whose value reflects the credibility that certain disturbance exists. The outputs for the classification parts are fuzzy variables "Flicker", "Impulse", "Outage", "Swell", "Sag", "Notch", "Transient", and "Harmonic" whose values represent the degree to which the event belongs to each of these categories. The type of the event will be the one with the largest membership. In cases where two or more types of disturbances have the same largest membership value, all of them will be outputted for further analysis.

Location of Disturbance Events

From the previous step, if the cause of disturbance is identified as fault, the event location module will trigger an optimal fault location approach. This approach first selects the most appropriate fault location algorithm based on the availability and location of the data measured, and then starts locating the fault. Phasor-based single-ended, symmetrical-component-based single-ended, synchronized double-ended and unsynchronized double-ended fault location algorithms are integrated in the approach, and the selection process is described in the flowchart shown in Fig. 3 [11].

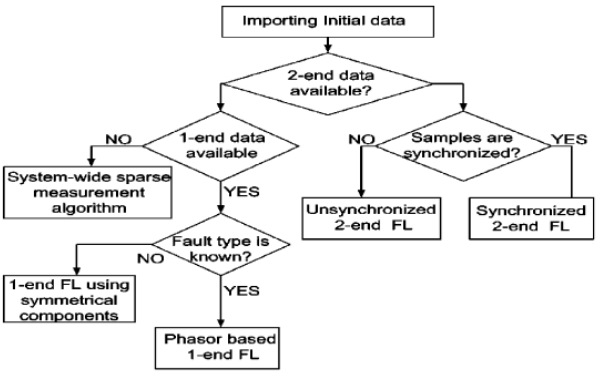

Figure 3. Flowchart for fault location.

4. Implementation Issues

Since IED data of multiple types from multiple sources is utilized in proposed disturbance analysis tool, new requirements for data management and the integrated approach arises.

Data Collection

The proposed method is based on data from multiple sources. Although some vendors claim that their PQMs , DFRs, DPRs and other IEDs can be connected to SCADA system, data from most IEDs cannot be collected in traditional ways used for SCADA. New communication system for IED data collection is needed. The collected data should also be accessible to other applications from operations, protection and maintenance. Fig. 4 shows the layout of collection and transfer of IED data from substation to control center.

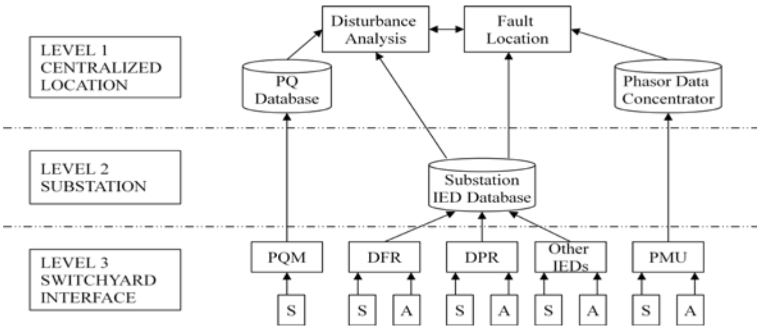

Figure 4. End-to End solution of data transfer.

Data Processing

Since the proposed application requires samples of voltages and currents, the volume for transfer and storage can be huge. Hence it is beneficial to adopt hierarchical processing. For example, the software can take calculated THDs from PQ Meters, instead of requesting samples from them. This also applies to other IEDs that have calculation module for feature extraction or are programmable.

Data Redundancy

As is discussed in Section 2, the sampling rate and accuracy of data from different IEDs are different. When data is abundant, the application should rely more on data with higher sampling rate and higher accuracy. Data with lower sampling rate and accuracy becomes redundant and should be discarded to unload communication channel and save calculation time.

Another aspect of redundancy is about data with overly-high sampling rate. For example if the cut-off frequency of the PQ analysis is considered as 13rd of fundamental frequency, it may be beneficial to collect the data with 120 samples per cycle from a PQ Meter and scale it down to 30 samples per cycle. Data compression techniques are also highly desirable when storing and communicating data with high sampling rates.

Adaptivity of Algorithms

To handle data with different sampling frequency, feature extraction algorithms should have the ability to adjust themselves in order to yield useful results for variety of data sampling rates. Self-adaptive FFT and WT algorithms must be developed.

5. Standardization

Standardization is another important issue in implementing the new application. There are three layers in the standards coordination process: a) identification of related standards; b) mapping of existing standards to realize interoperability; and c) development of new standards to fill the gaps in existing standards. One example is the modeling of IED data. IEC61970 is a standard for integrating number of complex applications developed by different vendors in the same semantic framework using Common Information Model (CIM) to represent the SCADA data [12]. CIM approach mainly focuses on modeling operational data and corresponding substation components. It is object oriented and extensions are possible. Practice shows that the published (CIM) version cannot meet the requirements of some important field device representations for real time applications such as FL.

CBM, DFR and some other IEDs that may introduce new functionality do not have CIM representation. Extension of CIM such as currently done for PMUs is needed.

While IEC61970 provides a detailed description of connectivity between various equipment, substations and their static and dynamic information, IEC61850 has the most detailed description of substation equipment and their monitoring and control aspects [13]. IEC61850 defines a tree of objects for modeling IEDs, starting from the server object (representing physical IEDs), and containing a hierarchy of Logical Devices (LDs), Logical Nodes (LNs) ad Data Objects (DOs). The issue of missing IED Model in CIM can be resolved through harmonization of CIM and IEC61850 [14]. Current standardization efforts are under way to allow straight forward implementation of the harmonization between 61850 and 61970.

6. Conclusion

This paper discusses new information exchange needs and requirements for implementing a new disturbance analysis tool. The conclusions are as follow:

- Analysis of system disturbance can benefit from availability of variety of IED data;
- The implementation of the analysis tool requires new communication structure, which transfers IED data and has interfaces with traditional SCADA system;
- Data management must be selected to reduce the volume of transferred data and reduce volume of calculation;
- Algorithms utilized in the analysis tool must adapt to different data properties;
- Standardization is needed for collecting and transferring new types of data.

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