

Advanced Software Developments for Automated Power Quality Assessment Using DFR Data

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Abstract

The power quality (PQ) meters are usually designed to provide information relevant to the particular type of the disturbance. This is quite adequate if the disturbances that are being monitored are of a given type that matches the performance characteristics and design features embedded in the instrument. However, if there is a need to detect a variety of disturbances and classify their types, a better solution may be a generalized application of a Digital Fault Recorder (DFR) which can capture "raw" data. This allows the user to design a customized PQ assessment tools. This paper describes a software tool, which can detect and classify the disturbances recorded by DFRs automatically. The software is implemented using advanced signal processing and intelligent system techniques. The detailed characterization of the event given the software can provide the operator with comprehensive information about a given disturbance.

Keywords:

Power Quality, Digital Fault Recorder, Automated Analysis

I. INTRODUCTION

With the increased use of sensitive electronic circuitry, customers become more concerned about the electric power quality (PQ). In the new open-access and competitive power market, electricity consumers are in a unique position to demand a higher quality of service. The utilities or other power providers have to ensure a high quality of their service to remain competitive and retain/attract the customers. Efficient power quality assessment tools are needed to help achieve this goal [1,2,3].

PQ assessment is a complex subject and may include diverse aspects such as power system and equipment modeling, PQ problem mitigation and optimization, and data analysis [3]. In most cases, automated PQ assessment is desirable because manual analysis may be difficult to carry out due to lack of time and expertise. Specialized software tools can make use of intelligent techniques to automate the PQ assessment for improved accuracy and efficiency. Among various PQ phenomena, PQ disturbances like voltage sags, swells, and switching transients are of particular interest. This paper will describe such a power quality assessment software developed at Texas A&M university.

The paper is organized as follows. First, the needs for automating the power quality assessment are presented.

Then, the architecture of the software tool is described. The functions of the tool are listed next. And at last, an example to demonstrate the usage of the software is given.

II. AUTOMATED POWER QUALITY ASSESSMENT

Essentially, the power quality measuring and monitoring is a continuous process, and the volume of recorded data can easily become overwhelming. Manual processing is tedious and error-prone. Automated assessment is preferred. Automated tools can speed up the assessment process and thus improve the overall processing ability. With higher processing ability, more events can be monitored and elaborate studies can be performed efficiently. A fast response to the events occurring suddenly is also a good warranty of the quality of service in deregulated environments.

Power quality assessment is a complicated process, and usually expertise related to various fields is required. By "hard coding" the expertise gathered from the experts and/or previous experiences using intelligent techniques like fuzzy logic, expert system and genetic algorithm, the experience get reused and the accuracy and ability to perform efficient assessment can hopefully be improved.

III. SOFTWARE ARCHITECTURE

Power Quality Analysis Tool (PQAT) is a software package based on MATLAB/Simulink[4]. The software comprises of the following modules:

- Data conversion library for EMTP files, DFR files, COMTRADE files, and PQDIF files
- Analytical signal generators for voltage sag, transient, harmonic, impulse, flicker and notch.
- Power Quality Event library for voltage sag, arc furnace, bus transfer, flicker, capacitor switching, harmonic, transient, fan type load and induction motor.
- Power Quality Assessment modules for characterization, detection and classification.
- Tools for modeling and simulation
- Optimal capacitor placement
- Database

- Data Compression
- Fault Location

The data conversation module is in charge of converting waveforms recorded by DFRs or simulated by EMTP/ATP to MATLAB Simulink format. Once converted, the waveforms can be viewed in Simulink. Simulink has “scope” module to display the waveforms and MATLAB commands are also available to plot the waveforms.

The analytical signal generators can generate the most commonly occurring power quality events including voltage sag, transient, harmonic, impulse, flicker and notch. The most significant signatures of the events are coded in the generators. The users can also adjust the parameters. The outputs of the generators can be used in Simulink.

As a counterpart to the analytical signal generators, the event library contains the typical power quality events obtained through simulation. The event library is built using Power System Blockset (Powerlib), which is a user-friendly simulation tool. In this sense, the event library can also act as set of examples on how to use the Powerlib.

Depending on the relationship to Simulink, the assessment modules can roughly be classified into two categories: online mode and batch mode. The online mode modules are used with Simulink for online simulation, whereas the batch mode modules can read multiple files. Typical characterization results are displayed in a tabular form as shown in Figure 1.

Encapsulating the modules as Simulink blocksets makes them easy to integrate with the other blocksets in MATLAB, such as Simulink, DSP, and Powerlib. Simulink's graphical interface provides a user-friendly environment where the power circuit and the control system are represented in the same diagram. The results are displayed while the simulation is running.

The Simulink/Powerlib offer a variety of models (machines, power electronic devices and control blocks, etc.), allowing fast development of models for drives, FACTS and custom power devices. The processing power of MATLAB allows the designer to perform complex post-processing on simulation results.

In Extralib, the models of arc furnace, flick meter and rectifier circuit are provided. The Optimal Capacitor Placement module can use loss and THD as objective

functions. The data compression module compresses the waveforms using wavelet transforms. The database part, which uses Database toolbox, can save the results and events.

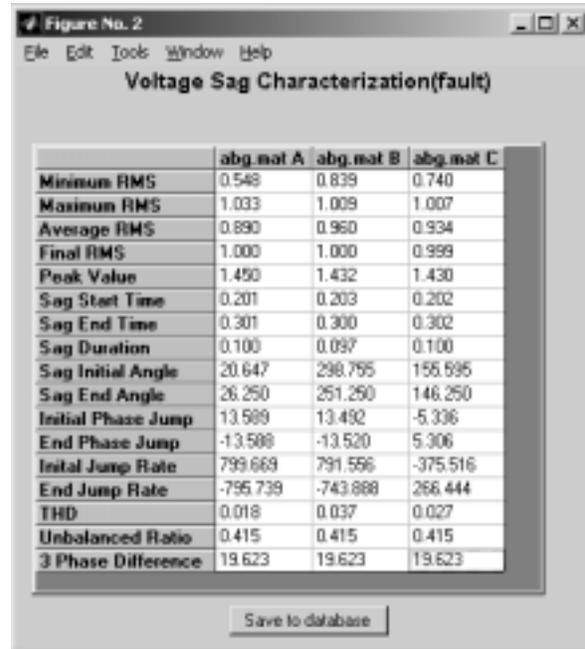


Fig. 1. Characterization results

The fault location part is a separate module developed in Visual C++ and it needs PTI PSS/E to run. The inputs are the recorded waveforms as well as the network data in PSS/E format. The output is the location of the fault.

All the modules can be accessed through the menu shown in Figure 2.

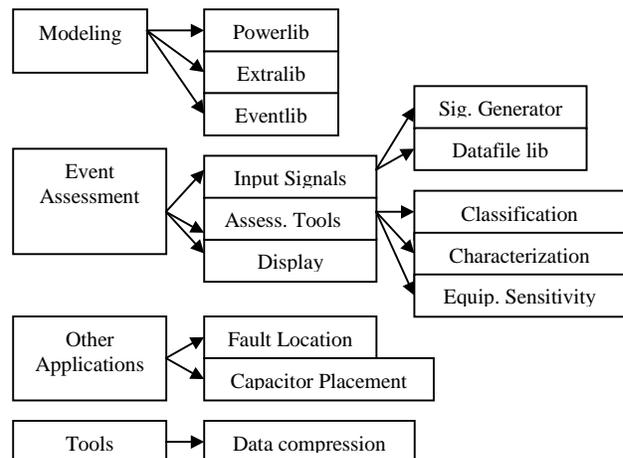


Fig. 2. PQAT menu structure

IV. FUNCTIONS

The general process of power quality assessment may include monitoring and classifying, understanding the causes, testing the equipment, and user interfacing. These functions are the basic requirement for a power quality assessment tool.

A. MONITORING

Compared with the dedicated power quality monitoring devices – PQ meters, the DFRs usually have higher sampling frequency and the ability to capture “raw” data. This allows the user to design a customized PQ assessment tools.

Once the waveforms are recorded, they need to be converted to a common format. It is more practical that the signal processing module and the detection/classification module handle only one type of data format. In PQAT, the data conversion module converts the inputs from a specific recording device or simulation package format into a MATLAB Simulink format.

The detection and classification modules first extract the unique features pertinent to specific events and then use fuzzy rule-based inference technique to find out the types of the events.

FFT and wavelet-analysis based feature extraction

A number of power quality events of various types have been simulated and corresponding waveforms obtained. The following eight distinct features inherent to different types of power quality events have been identified: 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 referred to in [3].

Next, the statistical properties of the parameters for various power quality events can be obtained. Extensive studies have shown that the extracted parameters resemble distinctive patterns under different types of events. Based on these distinctive patterns, appropriate fuzzy rules can be established for distinguishing between different types of events as shown below.

Fuzzy expert system for detection and classification

The core of the rule set of the implemented fuzzy expert system is illustrated as follows.

The characterization of power quality events is aimed at extracting distinctive and pertinent parameters for describing specific waveforms [1-3]. These parameters may be useful for system planning, troubleshooting and system control. Particularly, these parameters may play an essential role in the equipment sensitivity study that aims at improving the immunity or ride-through ability of the loads sensitive to specific types of power quality events, as will be illustrated in the next section. Hence event characterization is an important step for making a successful power quality contract.

Because different types of waveforms require different parameters for description, the waveforms need to be classified before characterization. The detection and classification system presented above can be used for accomplishing this task. After the type of the event is identified, the corresponding characterization algorithms can be selected for extracting more accurate and pertinent parameters.

The inputs are the recorded waveforms that have already been identified as certain types by the detection and classification system. The outputs are the waveform parameters pertinent to the input waveforms. The "Fourier and Wavelet Analysis Based Characterization" module is used to process the voltage waveforms utilizing signal-processing techniques to obtain the waveform parameters of interest. The wavelet analysis is used for better localizing the time-related parameters, while the Fourier transform is utilized for obtaining the magnitude related parameters.

B. UNDERSTANDING THE CAUSES

After a disturbance is recorded, it is desirable to find the causes of the disturbances, so that appropriate measures can timely be taken to correct the problem. Faults and switching transients are examples of the disturbances of interest. The following section presents the tools for troubleshooting these two problems by using both simulated and recorded data.

Locating Faults [5]

To fully understand and remedy a fault, locating the fault is normally the first step. In our study, it is assumed that recorded data is coming from sparsely located recording devices. To improve the accuracy for fault location, the “waveform matching” based approach may be used. In this approach, simulation

studies are carried out to obtain simulated waveforms under specified fault conditions. The simulated waveforms are then compared with the recorded ones. By iteratively posing faults in the system, running simulations, and comparing the simulated waveforms with the recorded ones, an optimal estimate of the fault location may be obtained. It may be determined as the one specified in the simulation studies that allows simulating the waveforms that best match the recorded ones. PSS/E software is utilized to carry out the short circuit studies to obtain the phasors used in waveform matching [6].

The fault location estimation has been mathematically formulated as an optimization problem in which the fault location and fault resistances are unknown variables. An efficient GA based searching scheme is developed for obtaining the globally optimal solution. After the optimal solution is found, the fault waveforms can be replayed. A clearer picture of the scenario associated with the fault can be depicted.

Evaluating Capacitor Switching Transients [7]

Capacitor switching usually causes switching transients. Simulation studies can help us finding out exactly why such a transient happened. There may be a discrepancy between the switching times of different phases of the switches closing the three-phase capacitors. This complicates the simulation of the recorded transients.

We have developed a GA based optimization tool for evaluating the recorded transients considering the above facts. The switching times of different phases are unknown parameters. The optimization objective is to generate simulated waveforms that best match the recorded ones.

In this way, the recorded waveforms can be re-generated through simulation studies. This provides the means for validating the system model as well as the basis for taking further remedial measures.

C. TESTING THE EQUIPMENT

After a disturbance is detected and characterized, quite often it may be needed to study how the disturbance affects the behavior of the sensitive equipment of interest [3]. This involves the modeling and simulation aspect of the power quality study.

Power System Blockset provides the models for most power system devices, including machines, power electronic devices, etc. Simulink is ideal for modeling

the control systems. For devices whose models are not provided, the Simulink's graphics interface is a great aid and makes the process of building new models relatively easy.

The simulation is the basis for understanding the power quality phenomena and solving various types of power quality problems. Among various types of simulation tools, the Power System Blockset (PSB) and Electromagnetic Transients Program (EMTP) are the two very popular packages. Both tools can be used for time-domain simulation of the events and related transients. In comparison, the PSB is more user-friendly and easier to use, while it is much slower than EMTP. Our experience reveals that PSB is handy for simulating small power systems and EMTP more adapts to larger systems. The role of the modeling and simulation in the PQ assessment is illustrated next.

An example of equipment sensitivity study under voltage sag events is used. As well known, some customer loads may trip or mis-operate due to the voltage sags. With the advent of electronic devices, the trip or mis-operation may no longer be just attributed to the sag magnitude and duration. Instead, other factors like point-on-wave, unbalance ratio, and phase angle shift may also play an essential role in the behavior of the modern loads during voltage sag events. Through equipment sensitivity study, the software can help understanding as why the specific load failed during a sag event, or predict how well a load will perform during an actual sag event.

The overall structure for evaluating the equipment behavior under voltage sag events is depicted in Fig. 3. The inputs are the voltage sag waveforms that can either be recorded in the field or generated by specific simulation packages. The outputs are the operating characteristics of the equipment during the specified sag events. The block "Voltage Sag Characterization" computes various sag parameters. The block "Sag Parameter Tuning" allows the user to tune or edit the sag parameters, obtained from the block "Voltage Sag Characterization", to certain values. The "Recorded Voltage Sag Waveforms" provide us with a set of initial sag parameters based on which further tuning can be made. The recorded waveforms are optional and if they are unavailable, the user can input any desired initial sag parameter and then tune them for testing. In either case, by tuning the sag parameters such as the sag magnitude, sag duration, phase angle shift, etc., the software allows the user to observe and study how specific sag parameters affect the operating characteristics of the equipment under test. This is what we call the equipment sensitivity study. The block

“Voltage Sag Generator” reconstructs the voltage sag waveforms based on the selected sag parameters. The constructed voltage waveforms serve as the voltage source for testing the equipment. The voltage sources can either be one phase or three phase depending on the equipment being evaluated. The “Equipment Model” allows development of mathematical models for the equipment. Equipment sensitivity study during other types of disturbances can be performed similarly.

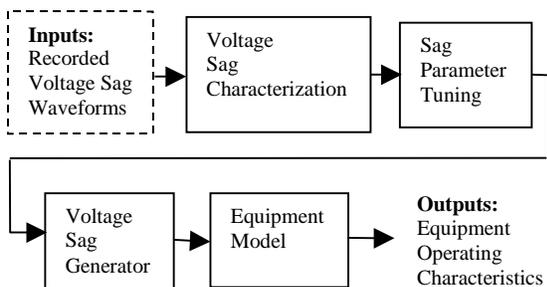


Fig. 3. The overall structure for equipment behavior evaluation

D. USER INTERFACING

The MATLAB/Simulink provides many display modules for viewing the data and results. Besides that, PQAT also utilizes ActiveX control to display the data in tabular format as shown in Figure 1.

Most of the modules conform to Simulink interface, and they can interact with each other in any sequence, so the user can control the assessment steps. Figure 4. shows a case, in which the characterization module is cooperating with classification module.

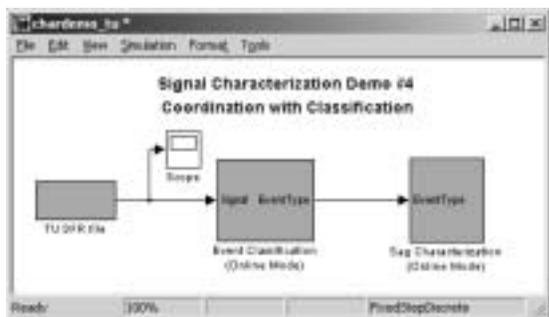


Fig. 4. Classification and characterization

With the support of the plethora of toolboxes and blocksets in MATLAB, the post-processing becomes an enjoyable work. For example, the task such as performing statistical analysis and comparisons can easily be done via the help of the statistic toolbox. The database module provides the support to save the waveforms and results into database, thus SQL

language can be used to retrieve the events of interest in the future.

V. EXAMPLES

This section presents examples illustrating the applications of the tool for automated analysis.

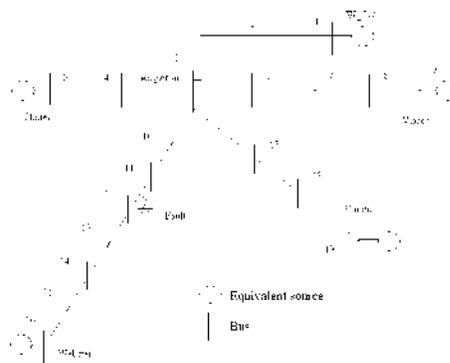


Fig. 5. A sample power system

Fig. 5 depicts a portion of the 138 kV Reliant Energy HL&P transmission system that is used here for illustration purposes.

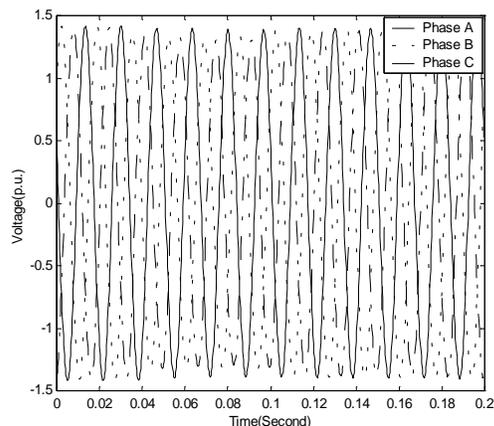


Fig. 6. A recorded sag waveform

A short circuit fault has caused the voltage waveforms as shown in Fig. 6. The waveforms were recorded at Angleton substation. First, the sag disturbance captured in the waveforms is identified using the fuzzy expert system. Then the waveform parameters are extracted using the proposed characterization approaches as listed in Figure 1.

Then a variable speed drive modeled in MATLAB as shown in Fig. 7 is subjected to the recorded waveforms and its operating characteristics can be obtained as listed in Table 1 [3]. In Fig. 7, the block “DFR” imports the voltage waveforms from the recorded data file. The block titled “Rectifier” provides the DC voltage for the

block titled “Variable Speed Drive”. The scopes are used for examining quantities of interest.

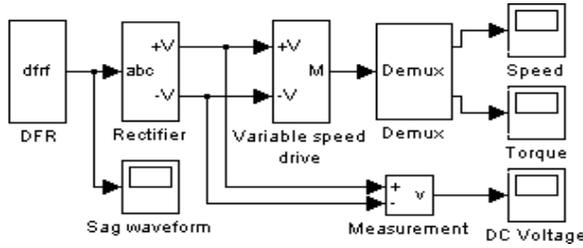


Fig. 7. The testing diagram for the VSD

Table 1. Changes of VSD parameters due to the sag disturbance

Parameters	Normal Value	During Sag Value	Change	Percent Change
Stator current in rms (A)	12.8	12.3	-0.5	-3.9
Rotor current in rms (A)	18.2	18.0	-0.2	-1.1
DC voltage (V)	352.0	311.4	-40.6	-11.5
Rotor speed (rpm)	1785.5	1673.6	-111.9	-6.3
Electromagnetic torque (N. m.)	23.2	19.8	-3.4	-14.7

It is seen from Table 1 that the largest drop of the rotor speed is 6.3% of the normal speed. This is due to the DC voltage drop caused by the sag. This study tells us that the variable speed drive would have had a 6.3% speed drop if it had been powered through bus 3. If the maximum allowable speed drop is 5% for example, then pre-cautions are needed for this drive.

The next step is to locate the short circuit fault that has caused the sag using the genetic algorithm based approach [5]. The GA uses the following parameters: population size: 30, crossover probability: 0.85, mutation probability: 0.05, coding binary string length for fault location: 9, and coding binary string length for fault resistance: 8. Fault location ranges from 0 to the sum of the length of all the lines, as shown in Fig. 4. Fault resistance ranges from 0 to 0.4 p.u. The fault is found to be between bus 11 and bus 12 with an error within 1 mile.

After the fault is located, additional short circuit studies can be performed along the line between Angleton and Webster with changing fault location, fault resistance, fault type and fault clearing time. Then the voltage waveforms under these fault conditions can be generated. The variable speed drive tested above can be subjected to these simulated waveforms for testing. Statistical testing results of the operating characteristics can be obtained, and a general picture of how the drive

behaves under different fault conditions is thus acquired. Better pre-caution measures can be taken to prevent the mis-operation or trip of the drive during various types of faults.

It is noted that the results, such as those shown in Table 1, as well as the fault location result are saved in a database, and can conveniently be retrieved and presented to the operator when needed.

VI. CONCLUSIONS

This paper presents the software for automated analysis of PQ disturbance. It can be observed that the software allows the following assessment tasks to be performed automatically:

- Event detection and classification
- Event characterization
- Investigation of causes of event occurrence
- Evaluation of equipment behavior under given PQ events

VII. ACKNOWLEDGEMENTS

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