Power Quality Assessment Using Advanced Modeling, Simulation And Data Processing Tools

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1. INTRODUCTION

Quality of power is becoming a very important requirement in the new, deregulated and restructured power industry [1]. The importance is associated both with a need to have a "cleaner" power delivery due to a variety of sensitive loads and with a goal to provide a premium service to gain a competitive edge. A major part of achieving higher quality of power is the ability for assessing the quality [2]. This paper is concentrating exactly on that task and discusses various tools and methodologies available for assessing power quality.

Once the appropriate tools for assessing power quality are readily available, various devices affected by the power quality disturbances as well as the operating practices causing power quality disturbances can be properly understood and the measures for mitigating the impact and eradicating the causes can be dealt with much more efficiently than otherwise. This paper presents results of a development of software tools and methodologies aimed at providing more flexible and efficient ways of assessing power quality using both recorded and simulated data. The general background is introduced first. Automated analysis of recorded data is discussed next. Modeling and simulation approaches are also outlined. The use of digital simulators to replay the recorded and simulated data is presented at the end.

2. BACKGROUND

The power quality assessment tools can be classified in two major categories: the ones dealing with recorded waveforms and the ones allowing creation of simulated waveforms using models of power system components and controllers.

2.1. Analyzing the recorded PQ events automatically

When recorded data for power quality events are available, significant effort is needed to sift through the enormous amount of recorded information to decipher the causes of the event and its relevant parameters. Facilitating this effort by providing the tools for automated analysis of the waveforms can indeed be beneficial.

The tools should be able to provide an interface for converting the native data file formats used by various PQ meters into a common file format used for the analysis. After the importing of the files is done, event detection, classification and characterization needs to be performed automatically. Based on the outcome of the analysis, further actions may be needed to better understand the causes of the events. Additional tools may then be needed for carrying out further analysis of the causes. Traditionally, the mentioned step in the analysis are performed manually and there are no readily available tools for performing such tasks automatically. To provide the appropriate tools for this purpose a custom development has to be pursued.

2.2. Studying the impact through simulation

Power quality event analysis may require modeling of the system at a much more detailed level when compared to the steady state studies such as power flow. There is no commonly accepted simulation environment to accomplish this, even though there are several software tools that can carry out different parts of the analysis such as transients simulations, harmonic analysis, data processing, mitigation studies, modeling of unconventional loads (adjustable speed drives or arc furnaces), etc.

Power quality events can be analyzed by simulating them. An investigation of their sensitivities to parameters of the system, which can be controlled for possible mitigation of the event, is quite commonly needed. This allows flexible corrective action design by the planning engineer before actually installing and testing hardware and software solutions at the site.

Recent introduction of Matlab's Power System Blockset, allows such simulations to be carried out and various signals to be captured in time domain as the simulation is running [3]. Furthermore, Simulink Library provides a diverse set of signal processing capabilities to design or model unconventional devices, such as the arc furnace, within the same simulation environment. In addition to the existing Powerlib library of Matlab Power System Blockset, specialized libraries can be developed using these modeling capabilities in Matlab. Two such libraries are created and utilized in the simulations presented in this paper. The first one is the Extralib, which contains newly developed models for unconventional devices such as arc furnaces. The second one is the Eventlib, which contains a number of cases of typical power quality event simulations. The objective of creating such an event library is to show the user how to utilize the power system elements library while implementing the desired power system. Moreover, there are also exist some cases for which the actual recorded data is available and user can perform comparative studies between the actual and simulated data.

3. AUTOMATED ANALYSIS OF PQ EVENTS

This section presents advanced techniques for automated detection, classification and characterization of various types of power quality disturbances [4]. Disturbance records in the form of sampled data are assumed to be available for this purpose.

3.1 Performing event detection, classification and characterization

The flowchart of the proposed solution for PQ event detection and classification is shown in Fig. 1. The sub-module "Data Format Conversion" converts the inputs from a specific recording device or simulation package format into a common data format comprehensible to other modules of the software. The "Fourier and Wavelet-transform Based Feature Extraction" module obtains unique features pertinent to specific events and "Fuzzy Expert System for Detection and Classification" module reaches a decision regarding detection and classification, as discussed next [4].

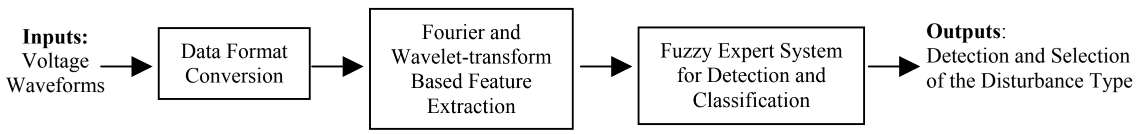

Fig. 1. Detection and classification flowchart

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 [4].

Next, the statistical properties of the parameters for various power quality events can be obtained. Extensive studies have evinced that the extracted parameters display 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.

A Fuzzy expert system for detection and classification. The core of the rule set of the implemented fuzzy expert system is illustrated as follows [5].

a) Detection: For detection, one rule is used as follows
Rule 1: if THD_n is A_2 **or** PS_n is B_2 **or** V_n is C_3 **or** V_n is C_1 **then DETECT=1**

b) Classification: fifteen rules are used as follows
Rule 1: V_{n+1} is A_4 and N_n is F_1 and OS_n is G_1 then IMPULSE=1
Rule 2: V_n is A_1 or V_{n+1} is A_1 then INTERRUPTION =1
Rule 3: V_n is A_6 or V_{n+1} is A_6 then SWELL=1
Rule 4: V_n is A_5 and PS_n is C_1 and PS_{n+1} is C_1 and EW_{n+1} is D_1 and $\{TS_{n+1}$ is H_2 or $[TS_{n+1}$ is H_4 & TS_{n+2} is $H_1]\}$ then SWELL=1
Rule 5: V_{n+1} is A_5 and $\{PS_n$ is C_2 or PS_{n+1} is $C_2\}$ then SWELL=1
Rule 6: V_{n+1} is A_2 then SAG=1

Rule 7: V_{n+1} is A_3 and $\{PS_n$ is C_2 or PS_{n+1} is $C_2\}$ then SAG=1
Rule 8: V_{n+1} is A_3 and $\{PS_n$ is C_1 and PS_{n+1} is $C_1\}$ and $\{THD_{n+1}$ is B_1 or $[THD_{n+1}$ is B_2 and OS_{n+1} is $G_4]\}$ then SAG=1
Rule 9: V_{n+1} is A_3 and PS_n is C_1 and PS_{n+1} is C_1 and OS_n is G_2 and THD_{n+1} is B_2 and THD_{n+2} is B_2 and THD_{n+3} is B_2 then NOTCH=1
Rule 10: V_{n+1} is A_3 and N_n is F_2 and OS_n is G_2 then NOTCH=1
Rule 11: V_{n+1} is A_4 and PS_n is C_1 and PS_{n+1} is C_1 and THD_n is B_3 and THD_{n+3} is B_1 and $\{OS_n$ is G_4 or OS_{n+1} is $G_4\}$ then TRANSIENT=1
Rule 12: V_{n+1} is A_4 and TS_{n+1} is H_3 and TS_{n+2} is H_3 and TS_{n+3} is H_3 and OS_{n+1} is G_4 then HARMONIC=1
Rule 13: THD_{n+1} is B_4 and THD_{n+2} is B_4 and THD_{n+3} is B_4 and OS_{n+2} is G_4 then HARMONIC=1
Rule 14: TS_{n+1} is H_4 and TS_{n+2} is H_4 and TS_{n+3} is H_4 and OS_{n+2} is G_4 then HARMONIC=1
Rule 15: If RN is K_1 then FLICKER=1

In the above rules, A_i, B_i, C_i, D_i, F_i, G_i, H_i, and K_i are the membership functions for the input patterns, where the common trapezoidal and triangular functions are used.

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", "Interruption", "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 selected 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 selected for further analysis. Evaluation studies demonstrated a correct identification rate of 99%.

After the type of the event is identified, the corresponding characterization algorithms can be selected for extracting more accurate and pertinent parameters. The overall structure of the proposed approach for event characterization is depicted in Fig. 2. The inputs are the voltage waveforms that have already been identified as certain types by the detection and classification system described above. 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.

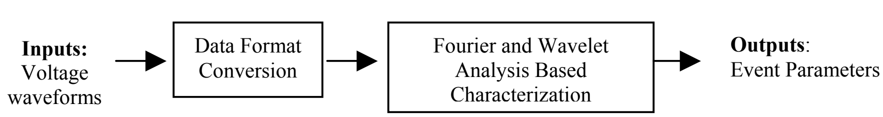

Fig. 2. Event characterization flowchart

3.2 Identifying the causes

Prompt and accurate location of the disturbance source is often an important step in solving the related problems. The work mentioned here focuses on locating the fault that caused the sag disturbance. It is assumed that recorded data coming from sparsely located recording devices are available. 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 [6]. 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 allowing the best match between the simulated and recorded waveforms. The matching is made at the phasor level presently. PSS/E software is utilized to carry out the short circuit studies [7].

The fault location estimation has been mathematically formulated as an optimization problem of which the fault location and fault resistances are unknown variables. An efficient GA based searching scheme is developed for obtaining the globally optimal solution [8].

3.3 Utilizing both simulated and recorded data

To automate the analysis of power quality events, the ability to utilize recorded data from different recording devices is required. A "Data File Library" has been built as shown in Fig. 3, which consists of modules for reading Digital Fault Recorder (DFR) files, IEEE COMTRADE files [9], PQDIF files [10]. It can also retrieve waveforms saved in relational databases using Matlab Database toolbox.

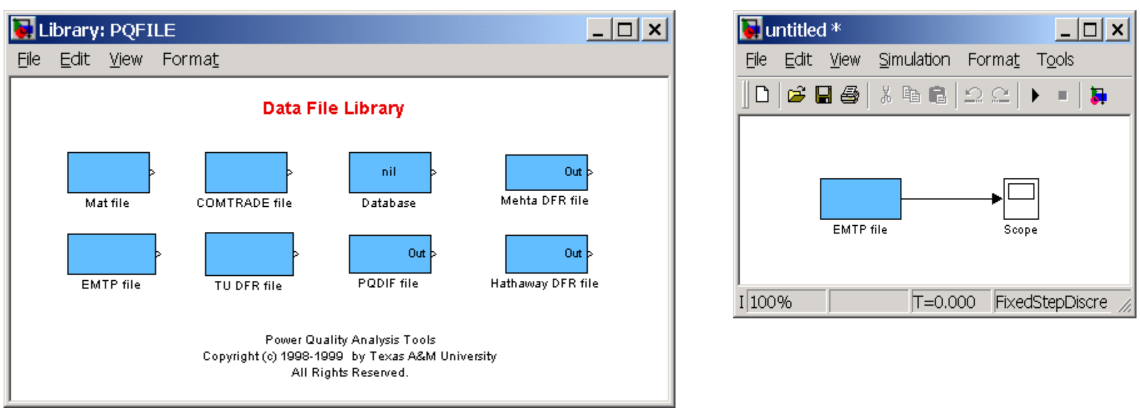

Fig. 3. Data file library

Field recorded data are usually difficult to obtain without cooperation of utilities. Also, certain types of events do not happen very often and may not be available as recorded data. Therefore, for tuning and testing the performance of the automated analysis system, waveforms obtained from simulations have been extensively used. The simulation is done using either Matlab Powerlib blockset [3] or EMTP. As shown in Fig. 3, a module for reading EMTP PL4 files has been provided in the library. When Powerlib blockset is used for simulation, the results will be in Matlab native format, which the library can read directly.

The usage of the library is pretty simple. As shown to the right of Fig. 3, a “scope” is connected with an EMTP file module. After selecting the EMTP PL4 file to be played back and pressing the "run" button, the “scope” will show the waveforms. Other types of data files can also be played back in this manner.

In automated event analysis, the typical usage of the modules in the Data File Library is to connect them with modules from the Characterization library or the Classification library. The only difference is that the waveforms are now played against the characterization or classification modules rather than “scopes”.

4. MODELING THE SOURCES OF PQ DISTURBANCES AND SIMULATING RELATED IMPACTS

Modeling of the various disturbances and devices involved in the power quality events is crucial for the power quality assessment. This section illustrates how the advanced modeling in the time domain using Electromagnetic Transients Program can be used to pursue such a study.

4.1 Modeling arc furnaces

Historically, there have been two general approaches to the problem of arc furnace modeling: stochastic and chaotic. In most of the previous studies, stochastic ideas are used to capture the a-periodic, non-linear, and time varying behavior of arc furnaces [11, 12]. It is a fact that, frequency modulation of the supply voltage of less than 0.5 % can cause voltage flicker if the frequency of the modulating signal lies within the 6-10 Hz range[13]. Starting from this fact, generating white noise within the mentioned frequency range and modulating it with arc voltage to resemble the behavior of an arc furnace voltage has been a common approach in these models [14]. Arc voltage has been obtained either from the simplified v-i characteristics of the arc furnace load, or from the empirical formulas related to arcing process.

In this paper, arc voltage is simulated by solving the corresponding differential equation which yields a dynamic and multi-valued v-i characteristics of the arc furnace load. On the other hand, a low frequency chaotic signal is generated via simulation of Chua's well known chaotic circuit shown in Fig. 4. These two signals are modulated to represent the flicker effect in arc furnace voltage. Fig. 5 shows the simulated arc current signal using the developed model. Model details can be found in [15].

4.2. Validating the modeling of Induction Machine Starting

The model development is not complete without its validation against recorded transients. This is done by comparing simulated and recorded waveforms for an induction motor switching event, which is recorded by a utility company in Texas.

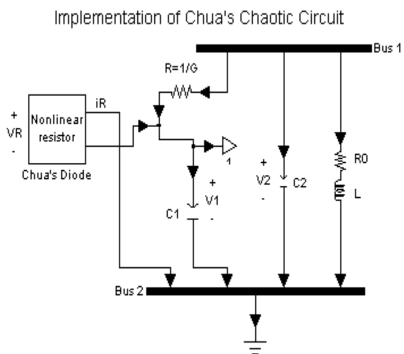

Fig. 4. Implementation of Chua's circuit

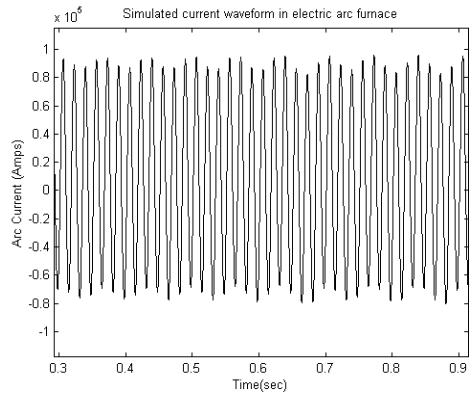

Fig. 5. Arc current obtained by simulation

The event data include voltage and current waveforms monitored at the bus where two induction motors (used to drive sewer lift pumps) are connected. The recorder was connected at the incoming main electrical switchgear. The motors are 3-Phase, 88 HP (at 60 Hz), 460 Volts, and manufactured by Flypt. It should be noted that, motor 2 is started after motor 1 and reached its steady state operating point. The one-line diagram of the corresponding power system is given in Fig. 6.

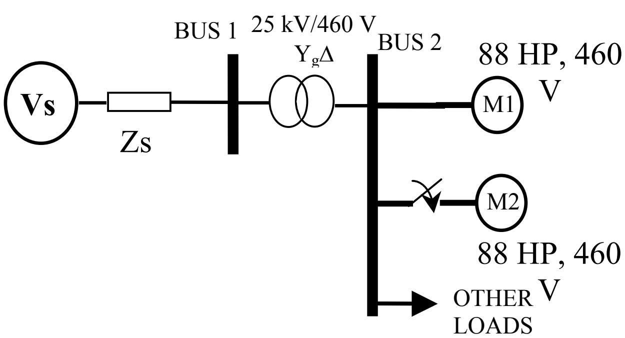

Fig. 6. One-line diagram of the studied power system

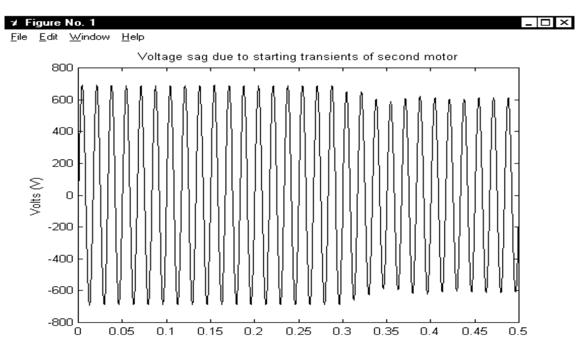

Fig. 7. Simulated voltage waveform

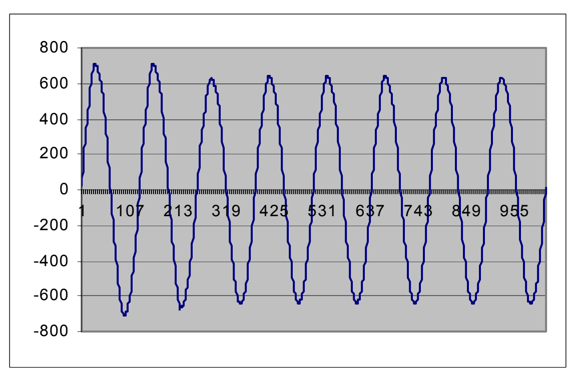

Fig. 8. Actual recorded voltage waveform

Fig. 7 shows the voltage sag at bus 2 due to the starting transients of the second motor, while actual recorded voltage waveform is shown in Fig. 8. The simulated and recorded waveforms appear in close agreement.

4.3 Implementing optimal placement of capacitors

An important issue in distribution system operation is to maintain an even voltage profile. This is accomplished by placing capacitors at strategic locations. Historically, optimal capacitor placement has been defined as the decision on location, size and types of the capacitors to be placed in the power distribution systems to minimize both the power loss and the capacitor costs. However, optimal capacitor placement problem will be further complicated if harmonic concerns are brought into the problem formulation. This is the case when the system contains nonlinear loads that inject harmonic currents, which in turn may cause unwanted harmonic over-voltages at capacitor locations.

A simple yet effective algorithm is developed for the solution of this problem. The algorithm uses discrete unit capacitor sizes in sizing the capacitors, takes into account the cost of individual units, total harmonic distortion (THD) limits on bus voltages, rms bus voltage and line flow limits. Harmonic sources are represented as equivalent bus injections, and all bus loads are modeled as constant impedance type loads. At each step of the solution algorithm a fast power flow is solved to determine the location of the next unit capacitor to be placed. The objective function, used in deciding on the location of the next unit of capacitor, will include not only the network losses but also the total harmonic distortion of the bus voltages. In order to calculate this value a fast harmonic solution for selected harmonic components is also developed. The resulting algorithm yields the best locations and sizes of capacitors to be placed in the system so that both the network losses and the voltage THDs are minimized. Details of the algorithm development and simulation results can be found in [16].

5. REPLAYING RECORDED AND SIMULATED WAVEFORMS

This section describes the elements of the new simulator design [17]. Only the main aspects of the hardware and software architecture are elaborated on. In addition, the provision for replaying simulated or recorded waveforms into the models representing actual devices is also discussed.

5.1. Replaying recorded waveforms

The major hardware building blocks of the simulator architecture can be represented as given in Fig. 9.

Due to the fact that the simulator hardware specifications are defined by the intended applications, custom I/O hardware may offer the best replaying characteristics. Data acquisition manufacturers offer a great number of digital-analog conversion boards. Some of these boards fit very well the waveform replaying requirements. Even 16-bit D/A cards with a sophisticated signal reconstruction are available at an affordable price.

When used with commercial power amplifiers, they offer an opportunity for building powerful and inexpensive simulator hardware.

The simulator software architecture is shown in Fig 10. The main elements of the architecture are described below.

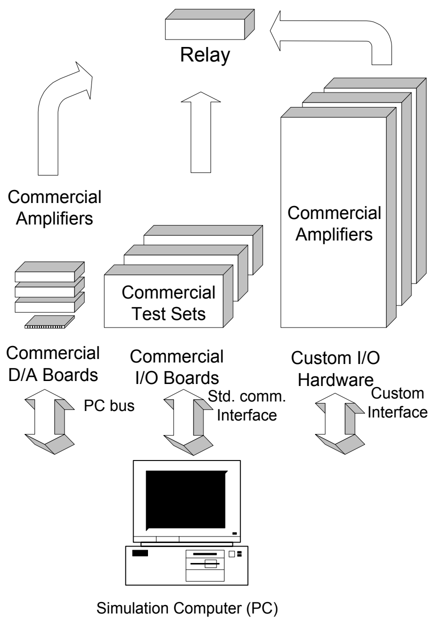

Fig. 9. The hardware architecture of the simulator

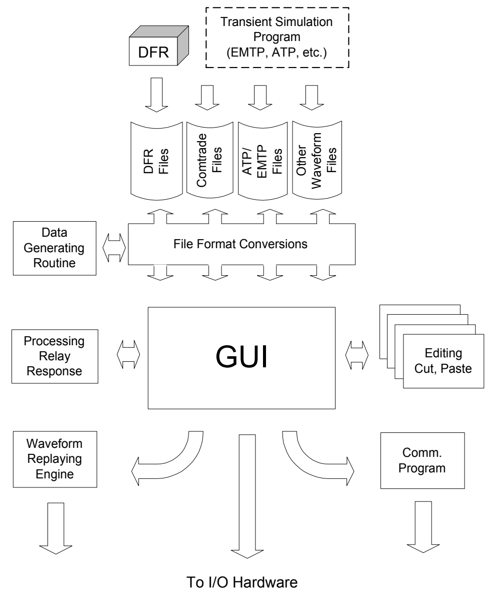

Fig. 10. The software architecture of the simulator

The waveform files used for replaying usually originate either from PQ meters or from transient simulation programs. A great variety of file formats may be used and the simulator software must include a file format conversion layer to facilitate the use of the most commonly found file formats. In any case, the COMTRADE and PQDIF formats should be a standard feature. Other formats that need to be supported are ATP/EMTP, native DFR formats, MATLAB and ASCII.

The waveform files generated by the transient simulation programs or recorded (by DFRs or PQ meters) usually require certain processing in order to be actually used for replaying. The signal editing and processing functions such as cut, paste, insert, resample, rescale, invert, and filter are examples of the functions that need to be supported.

The graphical user interface (GUI) is the single most important element of the overall simulator design. Its functions for waveform replaying and handling as well as signal processing and displaying affect the productivity of the simulator user tremendously. In addition, GUI provides the required software/hardware transparency.

5.2. Replaying simulated waveforms

This section presents examples illustrating the applications of the developed methodology and related tool for replaying simulated waveforms. A short circuit fault has caused the voltage waveforms as shown in Fig. 10. The waveforms were recorded at a substation using a DFR. 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 Table 1.

TABLE 1. CHARACTERIZATION RESULTS OF THE SAG WAVEFORMS

Sag Parameter	Phase A	Phase B	Phase C
Minimum rms value (p.u.)	0.981	0.929	0.932
Maximum rms value (p.u.)	1.0	1.001	1.0
Average rms value (p.u.)	0.991	0.972	0.973
Final rms magnitude (p.u.)	1.418	1.411	1.430
Peak value (p.u.)	1.418	1.411	1.430
Sag starting time (ms)	0	47.0	51.2
Sag duration (ms)	0	100.1	100.1
Sag initial angle (degrees)	0	53.1	48.9
Sag initial angle (degrees)	0	335.1	303.7
Sag initial phase angle shift (degrees)	0	-1.67	2.21
Sag initial phase angle shift rate (degrees/sec.)	0	-87.51	127.51
Sag initial phase angle shift (degrees)	0	28.13	270.0
Sag end phase angle shift rate (degrees/sec.)	0	74.2	-87.5
Total harmonic distortion	0.015	0.027	0.044
Rms magnitude unbalance ratio	0.064		
Three-phase phase angle difference deviation (degrees)	3.92		

TABLE 2. CHANGES OF VSD PARAMETERS DUE TO RESULTS OF 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

A variable speed drive modeled in MATLAB as shown in Fig. 11 is subjected to the recorded waveforms and its operating characteristics can be obtained as listed in Table 2 . In Fig. 11, 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 virtual "scopes" are used for examining quantities of interest. It is seen from Table 2 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.

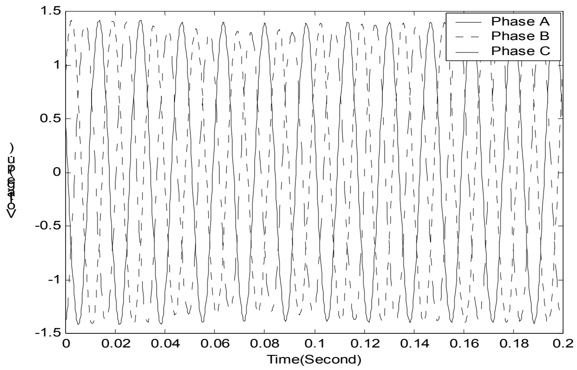

Fig. 10. A recorded sag waveform

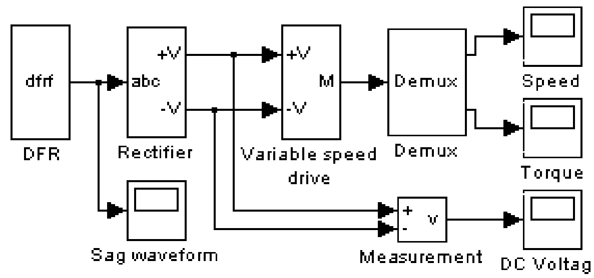

Fig.11. The testing diagram for the VSD

6. CONCLUSIONS

Several important conclusions can be reached based on the results presented in this paper:

- Power quality has been analyzed in the past by observing the events and performing simple simulations
- The importance of power quality in gaining a competitive edge in deregulated and restructured markets requires closer look at the power quality
- To have a closer look, power quality assessment has to be made using advanced tools for the analysis
- Detailed time-domain modeling and simulation as well as extensive field recording and processing are the basis for needing the new analysis tools
- The engineering tools for generating and analyzing simulated and recorded waveforms, implementing detailed models of the system components and replaying the waveforms are very instrumental in performing power quality assessment in the competitive markets

7. ACKNOWLEDGEMENTS

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