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A Simulation and Testing Laboratory for Addressing Power Quality Issues in Power Systems

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Abstract – A simulation and testing laboratory for electric power quality studies is described in this paper. The functions of the laboratory as a medium of instruction and as a research environment are presented. Examples of utilizing the laboratory for this dual purpose are given. Software and hardware tools that are integrated into this laboratory environment are discussed and their utilization in the context of power quality related studies are shown.

Keywords: Education, laboratories, power quality, transients, instrumentation, measurements, protective relaying.

1 Introduction

The composition of electric utility systems' elements have gone through a gradual change from being largely linear to partially or dominantly nonlinear in the past decade. Some examples include high voltage d.c. converters, flexible a.c. transmission (FACTS) devices, arc furnaces, uninterruptable power supplies and variable speed motor drives. As a result of this change, utility system planning and operation issues have acquired an additional dimension which is commonly referred to as *electric power quality*. The term itself is widely and vaguely defined perhaps due to the broad class of topics it touches upon at the transmission, distribution and generation end of the power system operation spectrum.

A wide range of possible research directions have been identified in the general area of power quality [1]. These include issues such as direct calculation of time domain steady state solutions for systems containing nonlinearities and electronically switched loads [2, 3], error analysis of numerical integration methods used in time domain simulations, efficient and accurate state estimation techniques for power quality applications, modeling of nonlinear loads, and design of grounding systems.

On the measurement side, the measurement of harmonics, voltage sags and swells, flicker, surges, energy usage, and changes in the frequency can be listed. Burke et al. [4] present existing power quality problems from two perspectives, one looking at the disturbances generated at the utility side but affecting the customers, and the other looking at the customer caused disturbances that also affect the utility side.

While the acceptance of the revenue meter location as the boundary between the customer and the utility is well established, this may not be the most natural boundary with respect to the power quality considerations. Fault clearance times that lead to voltage sags unacceptable to the customers, and time varying loads like arc furnaces or variable speed drives that pollute the utility feeder with unwanted harmonics, are two such cases. In both cases, poor power quality penetrates beyond the revenue metering point into the other party's zone.

The results of system studies can be utilized to develop strategies for assesment of the customer power quality problems in particular if the customer problems are caused by the utility system operation [5]. In some instances, both the utility and the customer may have to work together to find the best solution for the overall problem. This may quite possibly involve cost sharing for the implementation of a mutually agreed solution even when it is implemented only by one side or in the operating zone of only one of the involved parties.

Most temporary faults, switching of power factor correction capacitor banks, large motor starting transients, or the use of static var compensators may lead to power quality problems due to voltage sags, swells, flickers, surges and interruptions that are initiated by these events. Coney summarizes the causes and the effects of voltage sags and interruptions as well as the possible ways of characterizing such events in a quantitative manner [6]. He also mentions an artificial neural network based intelligent auto-reclosing scheme by which unsuccessful auto-reclosings can be reduced to a minimum. Characterizing voltage flicker has been a concern since its recognition as one of the common power quality problems. Halpin and Burch have described a simulation based method for analyzing and evaluating some mitigation strategies for the voltage flicker problems [7]. Other issues pertain to the mitigation of harmonics, modeling of harmonics sources, and assessment of the distortion of voltage and current signals at critical points in the system via a harmonics study [8]. An important portion of the power quality research is devoted to the processing of the measured or recorded signals in order to assess the quality of power [5, 9, 10, 11, 12].

In an attempt to respond to the growing need of the power quality studies with the above described versatility, a simulation and testing laboratory has been established at Texas A&M University through the sponsorship of the National Science Foundation. The laboratory is designed in such a way as to accomodate

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a wide range of teaching and research activities. In this paper, we will describe the utilization of this laboratory for the study of power quality issues caused or affected by the utility system operation. We will describe the computer and instrumentation infrastructure first. Essential idea behind the presented set up is to facilitate flexible waveform generation through simulation or replaying field recorded data. A digital simulator can be used to generate inputs either to the actual hardware or its model. This set up allows processing of simulated or recorded data, where an interaction between the power system and related controllers is combined in one coherent framework. It provides an environment in which various power quality studies involving steady state as well as transient modes of system operation can be carried out with equal ease. Some examples of utilizing this environment for a variety of power quality related system studies are given in the following sections.

2 Computer and Instrumentation Infrastructure

2.1 Functional Requirements

The laboratory has been designed to allow for a number of application studies related to power system faults and power quality (PQ) disturbances to be carried out for different purposes and various levels of details such as:

- Power System Modeling. Multi-phase detailed modeling of power system elements, various control and protection systems, switching equipment and various nonlinearities are accomplished using the electromagnetic transients program. Data module feature of the program is exploited in creating a library of models for commonly used devices. Availability of such a collection of device models greatly facilitates the integration of simulation tools into the teaching and research process.
- Digital Simulation. A workstation based digital simulator configuration is implemented providing multiterminal I/O interfaces for connecting external devices. The simulator is equipped with software and hardware enabling study of power system transients and behavior of related control and protection equipment both at the simulation level and through testing of actual devices.
- Programmable Signal Sources. Several high and low power signal sources are acquired. They allow generation of the power quality disturbance signals with a mixed frequency content. Also, generation of 3–phase phasors with varying amplitude and phase characteristics for relay testing is possible.
- Data Recording and Monitoring. A suite of digital instruments for recording and monitoring power system disturbances is acquired. The instruments include PQ monitors, variety of high performance oscilloscopes and several types of digital multimeters.
- Signal Processing and Analysis. A number of custom software packages that support analysis of data from specific digital recording instrumentation as well as general purpose signal processing tools are available on both the PCs and work–stations.

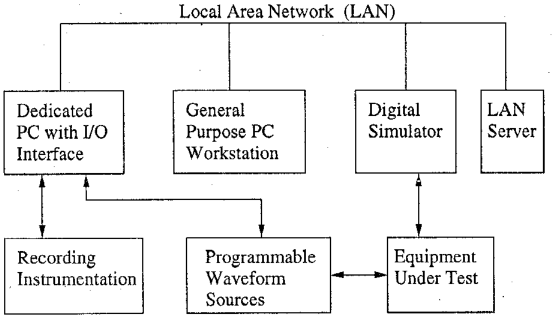


Figure 1: Arrangement of the Equipment in the Lab.

2.2 Equipment Arrangement

The equipment arrangement is shown in Figure 1. The equipment is organized around certain types of computer and/or instrumentation study environments interconnected via a dedicated local area network (LAN).

The following is a brief description of the digital simulator capabilities as a part of the overall equipment arrangement.

- Waveform Generation [13]. This function allows for generation of waveforms associated with fault and other disturbances either through importing recorded data files or simulating appropriate power system events. Data conversion routines are made available to convert data files coming from various recording instruments, such as Digital Fault Recorders (DFRs). A standard COMTRADE format is also used [14]. Data files available on the computer facilities anywhere in the laboratory can be downloaded to the simulator workstation.
- Evaluations Using Simulator Environment [15]. This feature enables evaluation of various applications at the level of an algorithm or device behavior using digital models. For example, an entire relaying system and its performance in a given power system application can be evaluated by simulating faults. Interactions between the power system and relaying system can be simulated as well.
- Testing Using Digital Simulator [16]. This option allows for connection of various control and monitoring devices, such as relays and different types of advanced transient waveform monitors, to the simulator. A variety of test waveforms can be generated within the simulator and replayed to the devices under test. For special cases, the simulator computer may be used to control programmable signal sources to generate test waveforms with very particular power level and/or waveshape characteristics.

3 Laboratory Uses

3.1 PQ Lab as a Research Facility

3.1.1 Development and Validation of Models

As described in the above section, the laboratory set up allows the use of a simulator to generate signals which can then be applied to actual devices to be modeled. Most of the device models are intended for use in simulating operation of systems containing harmonics and / or transients. Therefore, development of models that remain valid over a wide band of frequencies is required.

Since the devices need not be physically built, but instead can be integrated into the time-domain simulators by their discrete-time equivalent circuit models, they provide a very flexible yet effective medium for testing, simulation and model validation. A general approach to development of multiport frequency dependent network equivalents was presented in [17, 18]. This method can be employed to generate frequency dependent discrete-time equivalent circuit models for various devices as long as these devices can be subjected to multisine [18] signals and their time responses are properly recorded in the laboratory.

Examples of such models include capacitor coupled voltage transformer models (CCVT), high frequency power transformer models, and models for cables. These are all linear device models and therefore any nonlinearities associated with parts of these devices need to be modeled as an external component [19].

Nonlinear devices are modeled either by the approximate piecewise linear characteristics or by using switches that emulate the time-dependent topology changes of the device model [20, 21].

3.1.2 System Study of PQ Related Phenomena

Utility systems containing sensitive loads, sources of harmonics, large industrial plants with static var compensators or shunt capacitors, may have to be simulated as a whole in order to identify sources and penetration mechanisms of other PQ disturbances and harmonics in the system. Such simulations can be carried out in the time domain by using an electromagnetic transients program. Assuming that proper device models exist or have been developed per the discussion above, system behavior can be simulated under desired operating conditions. Events involving switching of a device or component with the intention of its permanent removal from the circuit, can be simulated as a transient. The objective of such simulations is to study the behavior of certain nonlinear loads, e.g. variable speed drives, during the transient event. If the nonlinear load under consideration, has difficulty riding through the transient without tripping or loss of synchronization, then various remedies can be designed and immediately tested using the same simulation set up.

3.1.3 Examples

Two cases of research studies related to voltage sags and swells, will now be briefly described. The disturbances that lead to power quality problems in both of these cases, are utility system faults. The cases are simulated by using an electromagnetic transients program [22].

Case 1: Voltage Sag Study

Consider the system whose reduced one-line diagram is shown in Fig. 2. The rest of the system to the left of bus 2 is represented by a short circuit equivalent. A single phase to ground fault occurs at bus 5 in phase A. The fault is cleared by the sending end relay on line 2-5 and the line is disconnected. The system recovers from this transient, however, the remaining 13.8 KV buses experience a temporary voltage sag, as shown for bus 4 in Fig. 3. If the loads at buses 3 or 4 are voltage sensitive, then they may be disconnected from the system during such a transient.

Case 2: Voltage Swell Study

Fig. 4 shows the one-line diagram of a system where two feeders are powered from the same substation, behind which a short circuit equivalent is attached to model the rest of the system. A three phase fault occurs at the remote end of the second feeder at bus 4. The feeder is disconnected by the operation of the circuit breakers at the sending end bus 3. The receiving end voltage at bus 6 of the unfaulted feeder shows a swell during this transient event, as represented in Figure 5. The p.f. correction capacitor installed at bus 3 is partially responsible for this temporary overvoltage.

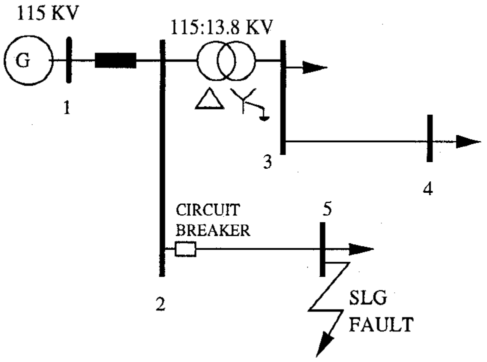


Figure 2: Case 1: Test system one-line diagram

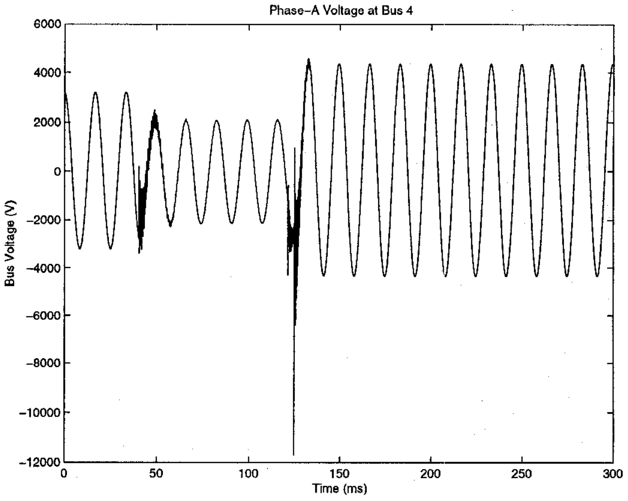


Figure 3: Voltage sag at bus 4.

3.2 PQ Lab as a Teaching Facility

3.2.1 Tools for Simulation and Modeling

The laboratory is equipped with 8 personal computers that are networked together and all loaded with simulation and signal processing software. ATP [22] along with its input processor ATPDRAW [23] are used as the essential part of the simulator. While models for most of the traditional utility system elements such as power transformers and transmission lines are readily available in ATP, new models for devices such as instrument transformers, phase shifters, converters, series capacitors with MOV protection, etc. need to be implemented. The data base module feature of ATP is used for this purpose. These modules can provide a set of default values in addition to avoiding the need of putting together a circuit model each time one of these elements is to be modeled. One example of such a module is the 6 pulse diode bridge rectifier. A data base module for this

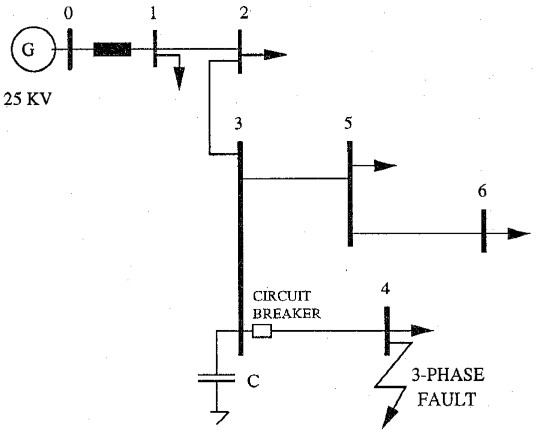


Figure 4: Case 2: Test system one-line diagram

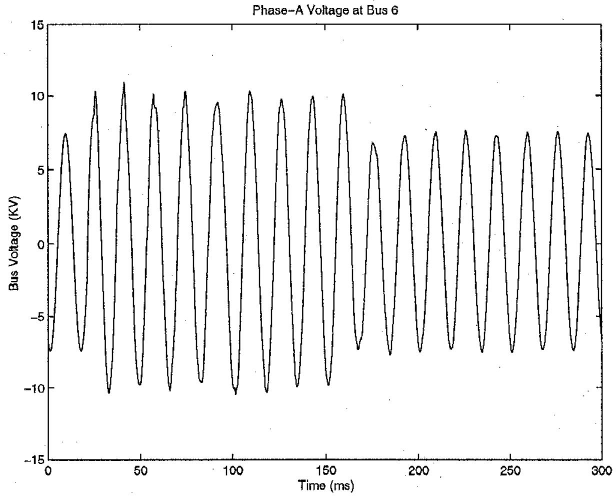
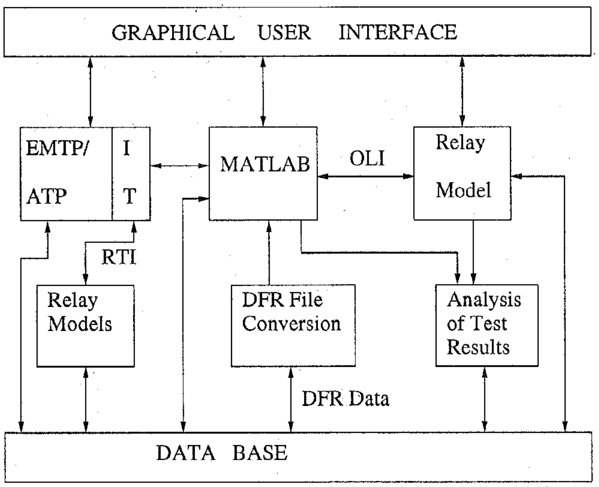


Figure 5: Voltage swell at bus 6.



OLI : Open Loop Interaction; RTI : Real-Time Interaction
IT : Instrument Transformers

Figure 6: Protective Relay Simulation Environment

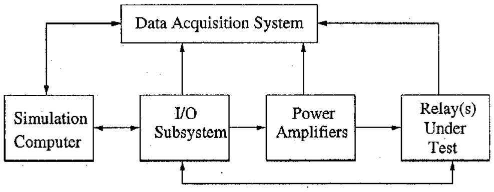


Figure 7: Simulation Hardware Architecture

device and its associated icon are created. The module has three a.c. terminals for the three phase a.c. input signals, and two d.c. terminals to be connected to the load, which may be an inverter driving an a.c. motor. Details of building data base modules and creating icons can be found in the ATPDRAW manuals [23]. Having a library of devices commonly used in power quality studies, allows the instructor to focus on the analysis rather than the mechanics of obtaining simulation results. In addition, while creating these data modules, built-in default values for the device parameters are used in order to facilitate the job of the novice user of the transients simulator. The user is however free to modify the set of default parameters when building the desired circuit.

The simulation results can be stored and converted into proper format to be accepted by commonly used programs such as MATLAB [24]. In particular, analysis of harmonics, fast Fourier transform, Wavelet transform, sampling, filtering etc. of the simulated signal can be easily implemented this way.

3.2.2 Means for Device Modeling and Evaluation

The laboratory is equipped with a new digital simulator developed at Texas A&M University [16]. This simulator enables extensive study of a variety of control and measurement devices. For example, protective relays and relaying systems at both the simulation and actual device level can be evaluated. The students can develop new relay models or use the existing ones to enhance their understanding of the relay designs. After that, the relay models can be utilized to study power quality phenomena affecting, or caused by, the relaying system. The entire study can be done at the simulation level where the models of the power system, instrument transformer, and relays are used in the simulation environment shown in Figure 6 [15].

Yet another approach may be to connect actual relays to the simulator and perform a variety of studies associated with evaluation of the performance of the relays and relaying systems under different fault and power quality disturbances. The simulator hardware used in this external device testing mode is shown in Figure 7 [25].

3.2.3 Examples

Two cases related to the use of the simulator in demonstrating how the relays may affect the generation of the power quality disturbances as well as how the power quality disturbances may affect relays are discussed.

Case 1: Study of the interaction between the power system and relaying system.

This study is carried out using the simulation environment shown in Figure 6. The fault transients are generated using a detailed model of an actual power system section from the 345KV system of Houston Lighting and Power (HL&P) Company shown in Figure 8 [16]. This level of detail gives a unique opportunity for students to learn peculiar features of the protective relay

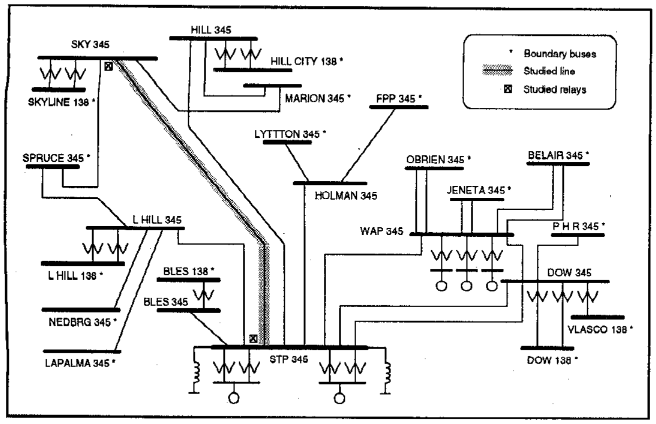


Figure 8: Model of the HL&P System Section

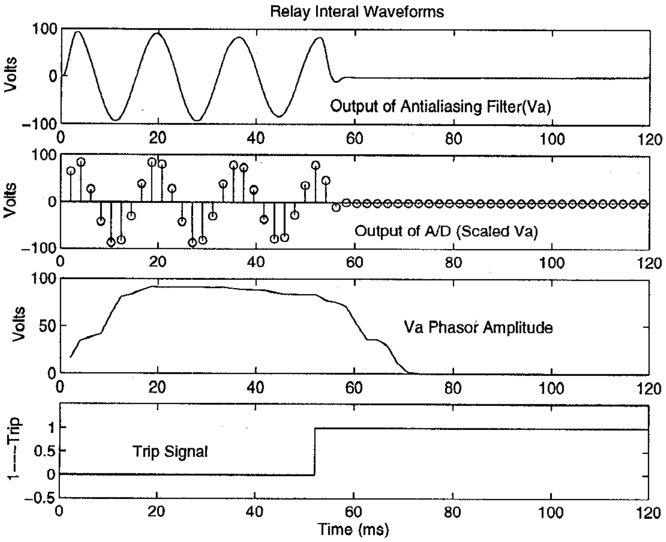


Figure 9: Internal Waveforms from a Relay Model

behavior affecting power quality disturbances. Detailed models of instrument transformers and relays are also developed and connected to the power system model [13]. A two terminal transmission line relaying system behavior is studied by using the fault simulations and recordings of both the fault transients generated by the transient program and relay responses generated by the relay models. Typical results showing the relay internal waveforms are shown in Figure 9.

Case 2: Study of the protective relay behavior under transient conditions.

This study is demonstrated using the testing hardware shown in Figure 7. The transient conditions, that may include fault transients or harmonics, are generated by the simulation programs using the power system model of the HL&P system section mentioned before. Several commercial relays can be connected to evaluate their performance under transient conditions of interest. One typical assessment made during such a study is the relay operating time delay under different transient conditions. An example that illustrates operating time behavior of several different relays is shown in Figure 10.

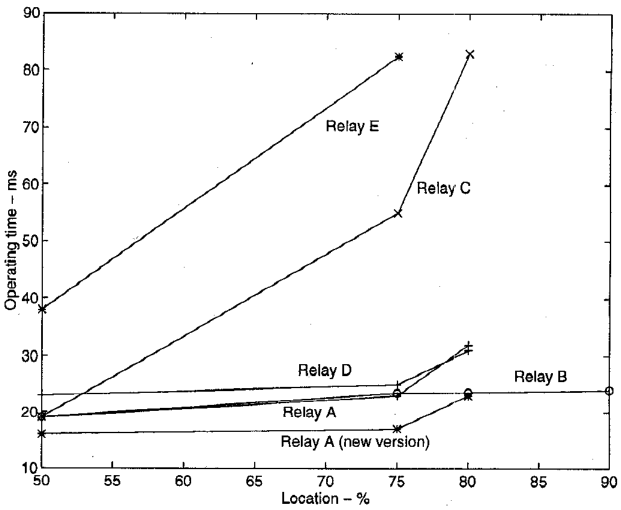


Figure 10: Zone I Operation Time of Different Relays

4 Conclusions

In this paper, a laboratory set-up along with related examples are described for electric power quality research and education. The laboratory is designed to accomodate both simulation and experimental testing as well as model verification of actual devices' operation during transient and steady-state conditions. A dedicated local area network interconnects a set of eight personal computers (PC) along with a digital simulator. In addition, a variety of instruments commonly used for data acquisition and analysis of PQ disturbances are connected to the same set-up. Device to be tested can be connected directly to the simulator or to a waveform generator that is programmable by a personal computer with an input/output interface. All PC's can run the time domain simulation program ATP which can simulate transient, sinusoidal and non-sinusoidal steady state operation. Special features of its input processor ATPDRAW is utilized in order to generate a customized library of models with associated objects in order to facilitate creation of new simulation cases. The laboratory provides a flexible and effective environment to carry out both teaching and research in the area of electric power quality by utilizing simulations and actual field data.

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