New Software Framework for Automated Analysis of Power System Transients

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Abstract - **This paper presents new software framework aimed at automating the analysis of power system transients. The transients of interest are those caused by faults and power quality disturbances. Various intelligent electronic devices can record these transients so that their impacts on the equipment and system operation can be studied. Today, such analysis is done manually and requires significant effort and expertise. Innovative approaches and tools are required to attain greater efficiency. The paper presents an approach where the expertise in analysis and simulation area is embedded in the software modules that can be executed automatically. The paper also shows that parallel use of analysis and simulation techniques lead to enhanced methods and improved results.**

Keywords: Transient Analysis, Transient Simulation, Modeling, Intelligent Techniques, Automated Analysis.

I. INTRODUCTION

Electromagnetic transients are caused by sudden changes in system topology or parameters. Depending on the cause, various categories of transients can be defined. For instance, short-circuit faults are one of common causes of transients. Similarly, power system switching causes transients. Transients associated with power quality events and those associated with faults are the focus of this paper.

Protection systems play a vital role in maintaining stability of electric power systems. Their role is to detect presence of the fault and to assist in isolating it from the healthy part of the system. Protection engineering is mature, but still dynamic profession. Current research is often related to assessing impacts that electromagnetic transient have on protection systems [1].

Power quality has established itself as a distinct area of the power engineering in the nineties [2]. The factors that contributed to that were vulnerability of modern electronic devices and competitiveness of deregulated electric power markets. Great effort has been put into developing devices, methods and standards related to power quality. Studying electromagnetic transients in this context is crucial.

This paper presents a new software framework that facilitates electromagnetic transient simulation, recording and analysis as the part of research and development efforts in protective systems and power quality engineering. Following the description of the framework, several software tools developed to fit into it are also presented.

The paper discusses several new systems developed for automated detection and classification of power system events. The systems use waveform data captured by various recording devices. Depending on the type of the event, a decision is made about the subsequent analysis step. If the fault transients are detected, the type of fault is determined and a fault location is computed. In addition, the analysis of the relaying equipment operation is performed [3]. If the transients are caused by the power quality disturbance, the disturbance is classified and the impact is characterized [4]. The analysis sometimes requires that transient simulations are performed using models of the network sections of interest and the results are compared with the recorded waveforms. Recorded or simulated transients can be used to make relay evaluation more realistic. A solution that offers such capabilities is also discussed [5]. When the evaluation of actual relays is not possible, relay models can be evaluated. Software tools that make this approach possible must possess quite advanced features [6].

The techniques used in listed applications are advanced signal processing, expert systems, fuzzy logic, neural nets, and genetic algorithms. They are incorporated in software modules performing tasks such as waveform analysis, fault location, waveform matching, disturbance detection, disturbance classification, disturbance characterization, etc. The paper describes the used algorithms and outlines the implementation characteristics of the software framework. Some practical results obtained by utilizing various software modules are also given.

II. ENGINEERING TASKS AND TOOLS

As mentioned in the introduction, this paper is focused on electromagnetic transients associated with short-circuit faults and power system disturbances. Related to these events, protection and power quality engineers need to perform specific tasks. Similarly, they must use appropriate engineering tools. These tasks and tools are briefly introduced in this section.

A. Engineering Tasks

Short-circuit faults have various causes, but all cause change in the system voltages and currents. Analysis of the voltage and current phasor quantities can be used in detecting the fault presence as well as in determining its type and location. Transition between normal pre-fault-state of the system and abnormal fault-state of the system is characterized by the presence of electromagnetic transients. Similar to phasors, analysis of electromagnetic transients can be used to make decision on the fault type and location. Common tasks performed by the protection engineers in the fault analysis are listed in Table I.

TABLE I Protection engineering tasks

Task
Troubleshooting misoperations and failures
Evaluating new relay designs
Tuning the relay settings
Analysis of relay operation
Application testing
Design testing

Various power quality events have different nature and characteristics. Any analysis technique must take these characteristics into account. According to one classification that suits the topic of this paper very well, two classes of power quality disturbances can be observed: a) voltage and current variations and b) system events. In this context, system events are especially interesting. Tasks related to their analysis are listed in Table II.

TABLE II Power quality engineer tasks

Task
Classification of events
Characterization of events
Equipment sensitivity studies
Mitigation studies
Worst-case scenario evaluation
Location of system disturbances

B. Fault Analysis Tools

The fault analysis is of interest to electric power utilities for several reasons. First, such analysis facilitates assessment of the fault event and enables timely protection action. Second, restorative measures in the system can be undertaken sooner after the fault event. Third, fault analysis can help in improving maintenance actions by determining points of weakened insulation.

Automated fault analysis can facilitate assessment of fault events. Such solutions could also provide a system-wide analysis within seconds following occurrence of an event. Attempts have been made since mid-eighties to automate fault analysis. A number of solutions have been proposed, but a fully integrated and automated solution does not exist yet. Thanks to expanding use of Intelligent Electronic Devices (IEDs) and high-speed data communications such systems are becoming feasible today.

Streamlining archival of data and dissemination of the reports is one of the main objectives of integrated fault analysis systems. A centralized database is necessary for that purpose. Centralized data storage makes it possible to perform a system-wide event analysis as well. Incoming event files and reports from various substations can be correlated based on their time stamps and samples that are taken using the GPS receivers for synchronization.

C. Power Quality Assessment Tools

The process of power quality assessment is aimed at detecting, classifying and characterizing various power system phenomena affecting power quality. The information obtained in this process can be used for better understanding of power quality problems and in mitigating the effect of such phenomena on the user equipment. Electromagnetic transients (e.g. those caused by faults and capacitor switching) are examples of events of interest.

Knowing how and to what extent power quality problems impact sensitive equipment is the most important for users. Assessing the nature and extent of these impacts is the goal of power quality sensitivity studies. These studies attempt to correlate the equipment behavior to the specific disturbance features. Their findings can be used to fine-tune the system operation and to improve the equipment design as well as equipment selection.

Power quality assessment is complex subject and may require very diverse knowledge and skills. Due to that and the novelty of the subject, there is a shortage of both experienced engineers and advanced tools. Electric power utilities are in great need of the methods and tools that can be used to enhance power quality studies.

Roughly, power quality assessment may be viewed as consisting of the following activities: monitoring, analysis, and mitigation. Power quality analysis is of specific interest in this paper. Main elements of the power quality analysis are detection, classification and characterization. Part of this process can be the modeling and simulation of the power system, power quality events as well as various devices. Automating this process is the ultimate goal.

D. Relay Evaluation Tools

Operation of modern power systems highly depends on the performance of installed protective devices. In order to ensure best possible operating performance, users regularly test their protective devices. Indicators such as security, dependability and availability are used to express the quality of the performance. As with any testing, to a high degree, the results depend on the methods and tools used.

Modern, microprocessor relays are complex devices. Many different modules and technologies operate together to fulfill design requirements. This makes it difficult for evaluation, especially from user perspective. For users, evaluating the performance of a given relay component (relay algorithms, operating principles, internal settings, etc.) is not feasible, since the information about the components is typically unavailable. Usually, an overall relay performance is assessed through testing.

At present, most users utilize phasor-based methods for verifying the operating characteristic and calibrating relay settings. It has been known for a long time that such testing may fail to provide comprehensive assessment of the relay performance. It has been concluded that extensive testing with transient signals is the best way for assessing relay performance under actual fault conditions. Thereby, the need for better test tools is recognized.

III. FRAMEWORK

This section provides discussion of the engineering tool framework. The most important elements of the framework are indicated in. Fig 1.

The building blocks of the framework are: a) models of the user equipment and system elements as well as b) tools for engineering analysis and simulations. Most of these blocks are original developments, but integration with third-party blocks is possible and encouraged.

Transients can be recorded in the field using various devices. Most of these devices comply with COMTRADE standard [7] and our framework does to. In addition, our framework has a provision for reading files given in the native format of popular Digital Fault Recorders (DFRs).

Depending on their nature, recorded transients can be analyzed using various tools. For fault-related events, one can use a tool that assesses fault nature and location as well as operation of the protection system. For power quality-related events, one can use tools for classification, location and characterization.

The results of the analysis can be used in three ways. First, an assessment of the operation of the installed equipment can be made. Second, one can use recorded and processed signals for testing the actual devices or their models. Third, one can use the results to verify the custom-made models of the equipment, events, components, as well as the entire system.

Simulation of the transients is performed by third-party tools (Alternative Transient Program-ATP, Matlab). Customized user interfaces and libraries of special components have been added, however, to enhance simulations. The libraries include models of power system elements, relay components, power quality events and user equipment.

Advanced tools for testing are important in making the equipment evaluation as efficient and as reliable as possible. These tools rely heavily on the mentioned system models and analysis tools. In addition, they are focused on streamlining the process by using the advanced graphical user interface, automated test result processing, embedded result report generators, etc.

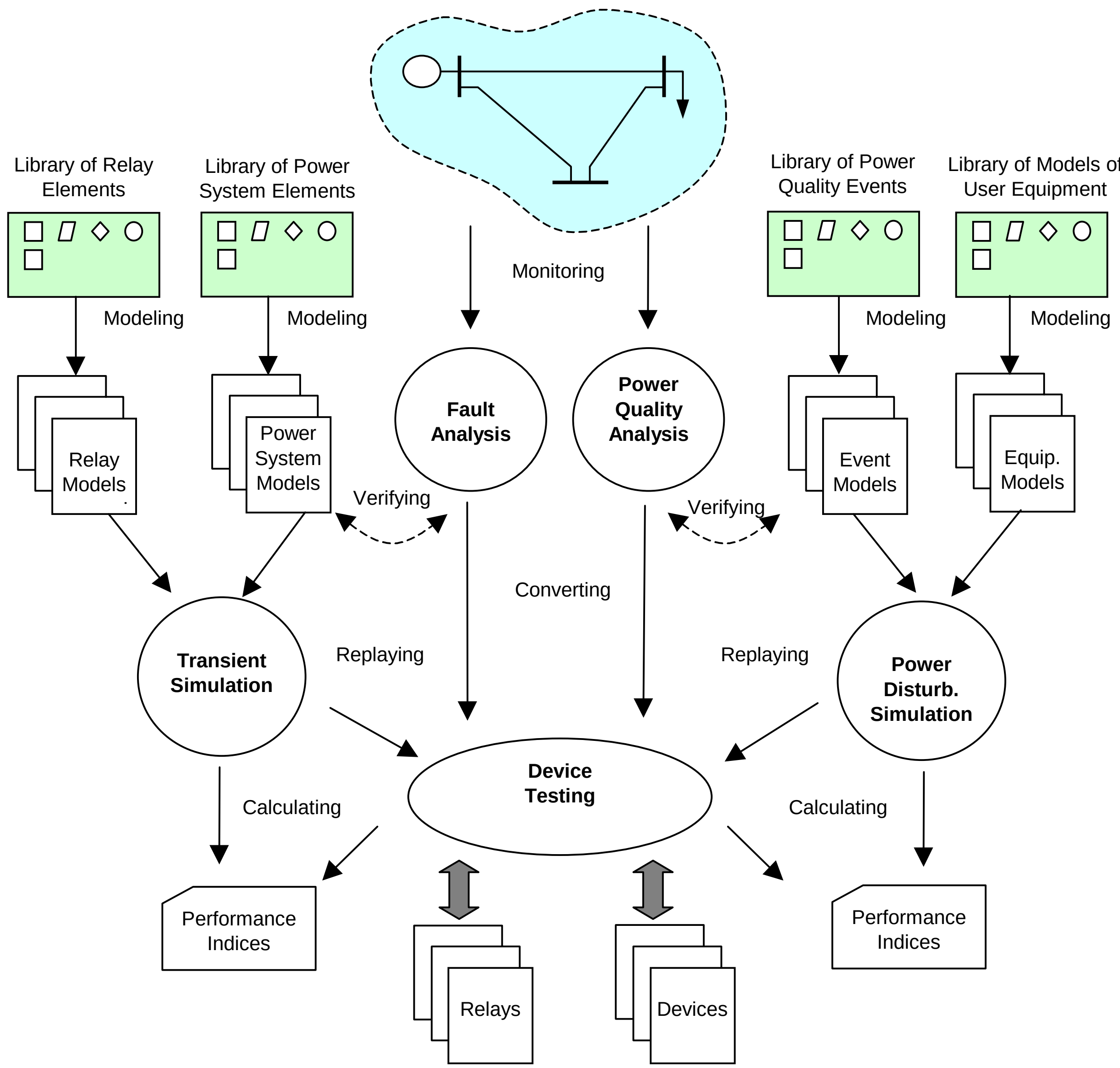

Fig. 1: The software framework

IV. APPLICATIONS

This section discusses the characteristics of the main elements of the presented framework. To facilitate the discussion, several characteristic examples are used.

A. Automated Fault Analysis

Various systems for automated fault analysis were proposed in the last decade. The system presented here is first to offer fully automated operation [3]. Its architecture uses client/server paradigm (Fig. 2) with three distinct and independent layers: Application Layer, Data Management Layer and Data Presentation Layer. Clients (Fig. 3) and Server may reside in different locations. Following are main system characteristics.

- The same architecture can be configured for variety of applications and installations.
- The system is capable of importing data from different IEDs (digital fault recorders, relays, meters, etc.).
- Analysis is focused on fault characteristics, protection system operation and fault location.
- Fault event analysis modules are universal, intelligent, expandable and interchangeable.
- The archival and retrieval of fault data and reports is centralized, flexible and automated.

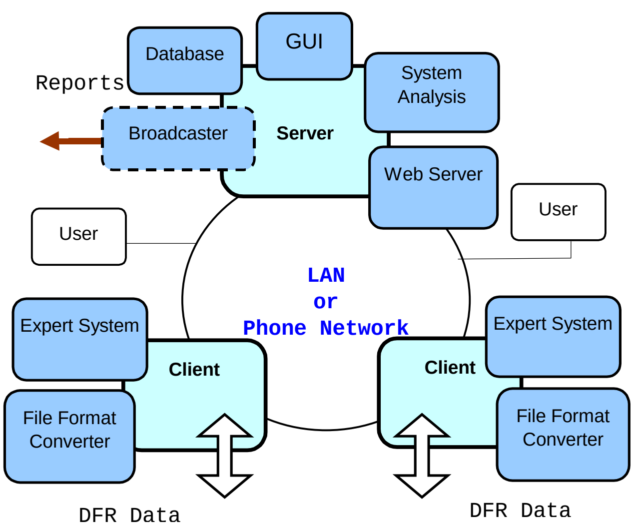

Fig. 2: The architecture of the new system

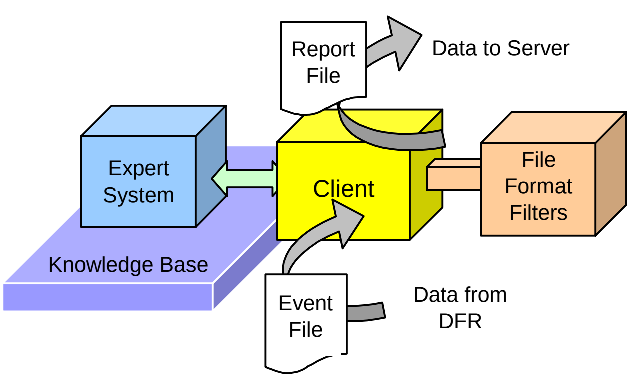

Figure 3: The architecture of Client

Following scenario describes the operations performed by the system.

- Client queries DFR for new events. When a new event is detected, Client uploads and converts it.
- Various signal-processing modules are employed to extract representative event parameters.
- Expert system classifies the event. If the event is a fault, its location is calculated.
- Event report and associated COMTRADE event file are sent to Server for further processing.
- After being detected by Server, new event report is parsed and data saved into the system database.
- Broadcaster alerts system users that new event has occurred via e-mail, fax and pager.
- Web Server responds to on-line queries by sending requested data to user's Web browser client.

Centralized data database enables further advancement of intelligent event analysis through use of other framework elements. Using this idea, a system for system-wide fault location based on sparse monitoring has been implemented. The method entails repetitive network simulations to obtain signal waveforms for assumed fault parameters. Simulated waveforms are compared with recorded ones in an iterative procedure. In this procedure, pattern matching and genetic algorithm-based search are used to estimate actual fault location. As other algorithms usually fail due to scarcity of data, benefits of the integrated framework are obvious [8].

B. Transient Relay Testing

Closed-loop power system simulators enable real-time transient testing. However, most users prefer cheaper open-loop simulators that use transient waveforms calculated or recorded in advance. A solution offering a balance between the cost and the functionality is shown in Fig. 4. Its design follows these requirements.

- Modules for test creation enable: reading various waveform files (COMTRADE, ATP, Matlab, native DFR) and creating arbitrary test waveforms.
- Modules for waveform massaging (cut/paste, copy, insert, rescale, resample, invert, extend pre-fault, etc.).
- GUI modules (displaying waveforms, reviewing test results, editing test reports, signal massaging, etc.).
- Modules for waveform replaying that include drivers for various supported I/O hardware

The software framework not only enables integration of various software tools, but also promotes integration with third-party software and hardware products. For example, the simulator has been recently used in extensive transient testing of four relays. In this testing, ATP and ATPDraw were used for system modeling and electromagnetic transient simulation. Specially developed system element models were used for network modeling. Test software [5] has enabled efficient varying of the fault parameters. A commercial test set has been used for waveform replaying.

If fault recordings are available, they can also be replayed. Similarly, they can be used to “calibrate” models used for simulating the faults. The model can then be used to generate a variety of test waveforms.

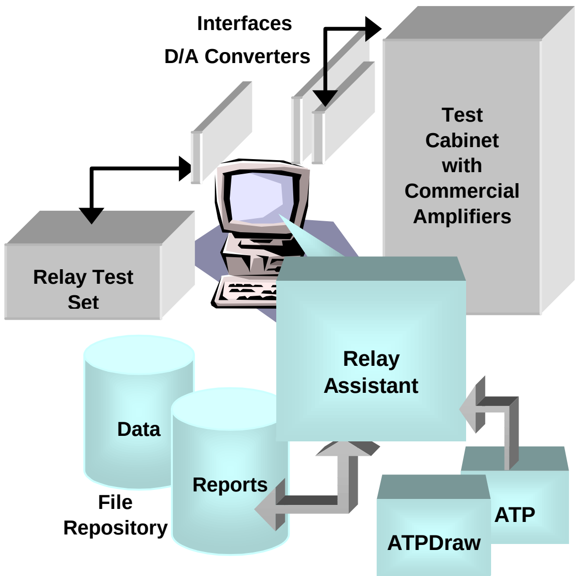

Fig. 4: The architecture of the simulator

C. Relay Modeling and Simulation

The evaluation of a relay is usually performed through testing. In some cases, however, it may be possible to evaluate relay models instead actual relays. Such an approach calls for software tools capable of modeling both the relays and surrounding power system. The following are main requirements for such tools.

- Relay Elements: generic relay components must enable one to create various digital relay models
- Relays: usual protective relay models (overcurrent, impedance and differential) must be available
- Protection Systems: modeling complete protection terminals and/or schemes must be possible
- Input Signals: specialized signal generators and file converters must be available

Developed package uses Matlab and SIMULINK to provide such capabilities [6]. For example, Relay Element library (Fig. 5) among others contains these elements: data acquisition board, digital filter, digital Fourier transform, impedance measurement, universal and zone comparator, triggering element and bias characteristic.

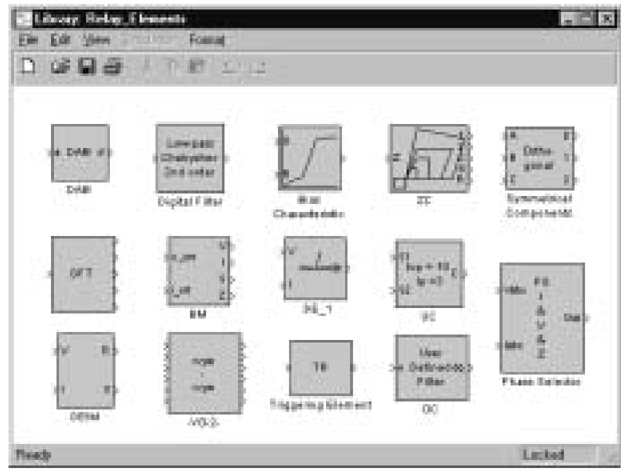

Fig. 5: The library of relay elements

By using elements from Relay Library, one can quickly model a given relay. Developed models can be made part of existing or new libraries. Models of protective relays or systems developed using the libraries can be tested with the input signals from one of the following sources:

- Signal generators of the Input Signals library
- Power System Blockset of MATLAB
- ATP output files via the developed file converter
- Transient data files via the developed file converter

The results of testing can be seen using waveform display or saved into a file of appropriate format.

D. Power Quality Analysis

As mentioned earlier, discussion of power quality assessment in this paper is limited to power quality analysis [4]. Detailed discussion of power quality monitoring and mitigation is out of scope of this paper.

a. Disturbance Detection and Classification

First step in the analysis of various power quality disturbances is their detection. In practice, detection needs to be an automated procedure as manual detection is time-consuming due to huge amount of data. Detection of power quality disturbances usually can be seen to consist of two steps (Fig. 7): a) feature extraction and b) classification.

Feature extraction recognizes and quantifies distinct and dominant features of a given disturbance. From the pattern recognition area it is known that transferring problem in the lower dimensional space some information may be lost, but classification usually becomes simpler. Two feature extractors were developed: Fourier Transform (FT) based and Wavelet Transform (WT) based.

Disturbance classification is final step of the detection and it is implemented through some form of decision-based system. Conventional approach is to use rule-based expert systems. More recent approach is to utilize non-linear mapping capability of artificial neural networks. In this system, both approaches were applied, but expert system has been implemented using fuzzy reasoning.

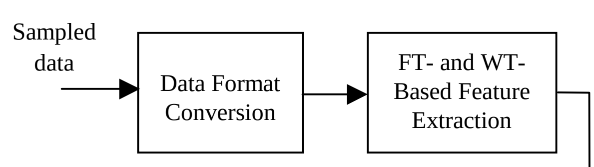

Fig. 7: Power quality disturbance classification

The system was tested using disturbances simulated by Matlab and Alternative Transient Program (ATP). The results are given in Table III.

TABLE III Disturbance classification test results

Type of Disturbance	Total number	FES error rate (%)	ANN error rate (%)
Sag	100	2	3
Swell	100	0	4
Interruption	100	0	2
Harmonic	100	0	4
Switching	100	2	5
Impulse	100	0	3
Flicker	100	3	1
Notch	100	9	3

b. Power Quality Disturbance Characterization

Similar to feature extraction, power quality disturbance characterization is concerned with extracting distinctive and pertinent event parameters. However, the goal here is not only classification, but also complete description. Therefore, the procedure has two steps: classification and characterization. Second step concentrates on calculating distinct event parameters more precisely. Fig. 8 illustrates the characterization procedure.

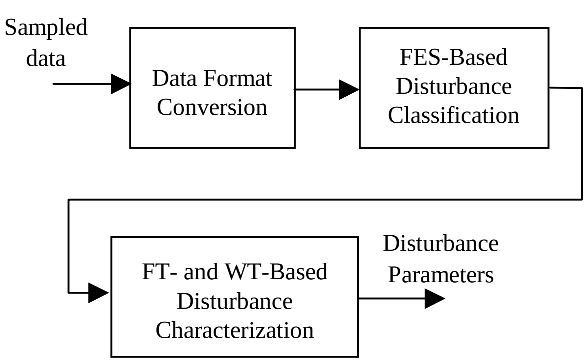

Fig. 8: Power quality disturbance characterization

Fig. 9 shows a switching transient captured in field using other elements of the framework [3]. This transient has been characterized through an automated procedure [4] by parameters shown in Table IV.

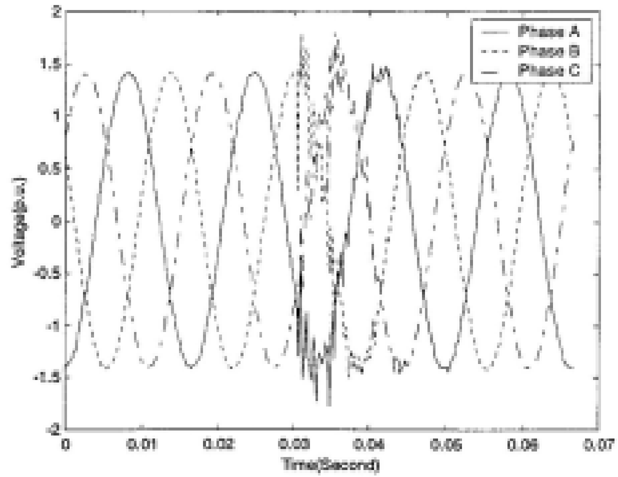

Fig. 8: Switching transient disturbance

TABLE IV Switching transient paramters

Parameter	Phase A	Phase B	Phase C
Magnitude of fundamental component (p.u.)	1.0	1.0	1.0
Peak value (p.u.)	1.78	1.76	1.79
Switching starting time (ms)	23.05	30.73	30.73
Transient end time (ms)	45.97	59.77	44.79
Transient duration (ms)	22.92	29.04	14.06
Magnitude of oscillatory components (p.u.)	0.027 0.026	0.050 0.040	0.038 0.029
Frequency of oscillatory components (Hz)	1320 420	1260 480	1260 1800
Decaying time constant of oscillatory components (ms)	15.49 9.53	3.90 5.70	4.16 7.09

V. CONCLUSIONS

This paper has presented a software framework for automated analysis of power system transients. After discussing some typical tasks performed by protection and power quality engineers, characteristics and elements of the framework were described. It has been demonstrated that analysis that is usually carried out manually can be automated. Four characteristic examples of the framework application were briefly described. These examples clearly demonstrate benefits of an environment that integrates tools for analysis and simulation.

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