ADVANCED RELAY TESTING AND SIGNAL PROCESSING SOFTWARE FOR TWO-TERMINAL DIGITAL SIMULATOR

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INTRODUCTION

Current utility practice for relay testing is to use portable test-sets capable of generating steady-state test waveforms. Recent studies, however, have indicated that steady-state tests are not sufficient if the full behavior of a relay is to be evaluated [1]. Digital simulator concept is one of the most desirable solutions to this problem. It includes hardware and software that allow both phasor and transient testing of protective relays [2], [3].

This paper describes relay testing and signal processing software for a newly developed two-terminal digital simulator. The simulator development was initiated in late 1989 and has resulted in several modeling and simulation studies, as well as simulation hardware and software designs [4]-[7]. The software discussed in this paper was installed for beta-site testing at the Department of Energy—Western Area Power Administration (WAPA) in the summer of 1995. It has also been extensively evaluated at Texas A&M University, with the close cooperation of Houston Light and Power Company (HLP). This software is capable of performing data conversion, signal processing, signal analysis, relay testing, and test result analysis using various transient data formats such as COMTRADE (IEEE Computer Format for TRAnsmitted Data Exchange) [8], electromagnetic transient program (EMTP) [9], and digital fault recorder (DFR) [10].

In this paper, the digital simulator hardware configuration is presented first. The software requirements and software configuration are discussed next. Next, the new software developments are described. Examples of the software applications are also outlined.

HARDWARE ARCHITECTURE

The two terminal simulator architecture is shown in Fig. 1. The host computer (IBM RISC System/6000, Model 417) generates the transient data file to be replayed to the device under test. When the user requests a file replay, the file is transferred to the DSPs via the Micron bus - DSP System Interface Board (inside the RISC) and the DSP - Micro Channel Communication Board (inside the DSP chassis).

The DSP subsystem contains two TMS 320C40 DSPs. DSP1 is responsible for communicating with the RISC, and replaying waveforms on I/O Terminal 1 (Master Terminal). DSP2 is responsible for replaying waveforms on I/O Terminal 2 (Slave Terminal). Digital replay byte streams are converted to serial data and transferred to the I/O subsystem by the DSP-to-Terminals Communication Board. The I/O subsystem and the amplifier subsystem are packaged into a custom designed cabinet called the I/O Terminal.

The I/O subsystem is divided into a communication interface to receive/send serial data from/to the DSP subsystem, a D/A subsystem for reconstructing the analog signals, a digital I/O subsystem to monitor contact status, and a hardware mechanism for clock synchronization between the Master and Slave I/O terminals. Clock synchronization between the two terminals is achieved by using Phase Locked Loop ICs, which tie the Slave Terminal clock to the Master Terminal clock.

SOFTWARE REQUIREMENTS

The relay testing and signal processing software (RTSFS) package provides an effective interface between the user and the system. The RTSFS is capable of performing data conversion, signal processing, signal analysis, relay testing as well as graphic user interface functions. Table 1 gives a breakdown of the requirements of the RTSFS.

Data conversion is needed for both Digital Fault Recorder (DFR) and EMTP files. DFR files from different type of recorders usually have different data formats. A similar situation is present with EMTP output files where they may be either binary or ASCII and may have a unique format. In RTSFS, COMTRADE format is chosen as the
TABLE I
REQUIREMENTS FOR RTSFS

<table>
<thead>
<tr>
<th>Requirement Category</th>
<th>Requirement Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data Conversion</td>
<td>Conversion of data recorded in different DFR formats into IEEE COMTRADE format. Conversion of EMTP output files into IEEE COMTRADE format.</td>
</tr>
<tr>
<td>Signal Processing</td>
<td>Signal Filtering, Context State Modification, Pre- and Post-Waveform Extension, Sampling Rate Change, Signal Polarity Change, Change Scaling Factor, Channel Select, Signal Length Editing, Masking Phase Reconstruction</td>
</tr>
<tr>
<td>Signal Analysis</td>
<td>Spectrum Analysis, Waterfall 3-D Presentation</td>
</tr>
<tr>
<td>Operator Interface</td>
<td>GUI for Function Access, Database Interface, Waveform Viewing, Instantaneous Value Display, Signal Graph Management (Zoom in/out, Autoscale On/Off, Grid on/off)</td>
</tr>
</tbody>
</table>

Signal Processing is required if test signal properties have to be altered or various parameters have to be determined. A typical need for signal processing appears when the sensitivity of relays to various signal characteristics is to be tested. Signal filtering, change of signal length, and various scaling operations are examples of the useful signal processing operations.

Signal Analysis in the time and frequency domains is essential since fault transients may have significant frequency content across the spectrum. Since relay designs may be sensitive to a given signal component, it is important to have means of analyzing the signal in order to determine its properties.

Operator Interface provides the user a GUI to access all the RTSFS functions and invoke the database management system.

Relay Testing is one of the most important requirements since it includes functions for performing relay test (one and two terminal single case mode relay testing, one and two terminal batch mode testing), test result viewing, and R-X diagram plotting. The R-X diagram software module calculates and plots, in the case of distance relay testing, the impedance trajectory using transient waveforms of voltages and currents. The R-X plane is used to represent the calculated trajectory versus relay settings to estimate relay performance.

SOFTWARE ARCHITECTURE

The RTSFS is developed on an IBM RS/6000 workstation, and designed to operate in an X-Windows environment with friendly GUI. MATLAB [11] and OSF/Motif [12] are the main tools used to implement the software. All the functions required are grouped in several GUI menus, and can be readily accessed via pull down menus or push buttons. The RTSFS menus can be divided into several levels. Fig. 2 shows the software organization.

As illustrated in Fig. 2, most of the functions required are integrated in one of the two GUI Menus: main menu or work menu. Once the RTSFS is invoked, the main menu will automatically appear. However, the work menu is activated only after a signal data file is loaded. The maximum number of files loaded is four, so up to four work menus can be activated at the same time.

Main Menu GUI: The main menu GUI is an integrated environment to access the following functions: test data loading and conversion, software global environment setup, database interface and batch relay test functions.

Work Menu GUI: A new work menu is activated every time when a test case is loaded. Most of the signal processing, signal analysis and relay testing functions are accessed from the work menu GUI.

SOFTWARE CHARACTERISTICS

As illustrated in Table I and Fig. 2, the RTSFS has been organized into five main parts. Each part contains routines to perform specific functions. The following sections describe the various functions with examples.
Data Conversion

The COMTRADE data format is selected as the common data format for the software. Three files are defined by this standard: header file (*.hdr), configuration file (*.CFG) and data file (*.DAT). The header file contains supplementary information in a narrative manner for the user to better understand the nature of the transient data. The configuration file contains information needed by a computer program to properly interpret the transient data. This configuration file includes items such as sample rates, number of channels, channel information, etc. The data file contains samples from each input channel signal. In the RTSFS, all types of transient data are first converted to COMTRADE format.

EMTP Files are transient data generated by simulating the power system faults using the Electromagnetic Transients Program. These files are converted to COMTRADE format by using EMTPCONV, a data conversion program written in C. DFR files are actual recordings of power system faults. Currently, in RTSFS, Rochester, Hathaway and Mehta DFR files can be converted to COMTRADE data by ROCBCONV, RATHCONV and MEHC.Conv software.

Signal Processing

Transient signal may be edited before performing testing to obtain desired waveforms. The following signal processing functions are provided:

- Channel Selection Function is used to allow selection of the relevant channels for relay testing. Normally DFR records many channels in case of power system fault. Only a few may be relevant to the fault.
- Signal Length Selection Function allows the user to truncate the length of a signal by selecting the starting and ending point of the waveform in case the transient signal has too many sample points.
- Change Scaling Factor Function allows the user to change the channel conversion factor to scale the signal to a desired amplitude.
- Change Signal Polarity Function is needed when wrong connections are used in DFR. The signal with wrong polarity can be flipped to obtain the correct power system signal.
- Prefault Length Extension Function is useful when the prefault steady-state waveform has insufficient length to test certain relay. Prefault extension is done for a user specified length by estimating the steady-state parameters of the limited prefault portion already present in the signal. At least three zero crossings of the prefault signal are needed for such a calculation.

Fig. 3 shows the actual waveform before performing prefault extension. Fig. 4 shows the waveform with 0.2 second of prefault added to the original signal.

- Missing Phase Reconstruction Function is designed to reconstruct a missing signal out of 3 known signals in the three phase power system. This function is useful in case that for various reasons, only signals for two phase and neutral may be recorded in DFR’s. This function is quite dependent on the calibration of the DFRs, and its applicability has to be evaluated on a case-by-case basis.
- Change Sampling Rate Function is needed when the sampling frequency of the transient output waveform is out of the frequency range specified by the digital simulator. The techniques employed for changing sampling rate are the interpolation and decimation operations.
- Filtering Function is very useful in identifying the relay sensitivity to a particular set of harmonics in the input signals. The user is allowed to select the filter (Butterworth filter, Chebyshev filter or Yulewalk filter); choose filter type (Lowpass, Highpass, Bandpass or Bandstop) and specify filter characteristic parameters such as cutoff frequency and the order of the filter. Fig. 5 gives an example of the filtering effects on a voltage signal. This figure shows the filter response, the unfiltered and filtered signal in both frequency and time domain in one plot.

Signal Analysis

The presence of transients may greatly affect relay performance. Hence, it is important to view the harmonic content of the signals to aid relay engineers in identifying
the magnitudes of the harmonics and filtering some of them out using signal processing tools.

- **Spectral Analysis Function** is a major tool in analyzing signal frequency content. It is implemented by using fast Fourier transform (FFT). The user is allowed to specify the following parameters: channels selected from the transient data file; length of signal on which the analysis is to be performed; type of windowing function to be used for reducing the influence of the side lobes and improving resolution (Hanning, Hamming, Bartlett and Rectangular).

- **Waterfall Display Function** is helpful in analyzing signal frequency contents in a 3D plot. It is implemented by using the overlapped FFT transforms of the windowed portion of input signal. The analysis result is displayed in a three dimensional "waterfall" waveform in which the relationships of time versus frequency versus magnitude for a spectrum are illustrated.

**Operator Interface**

The software provides a friendly environment with extensive graphical user interface (GUI) features. From the GUI, the user can readily invoke all the functions through menus and/or push-buttons. The software global variables, such as: The number of hardware terminals (cabinets), the ratios of current transformer (CT) and capacitor coupled voltage transformer (CCVT), and the numbers of current and voltage channels, can be defined through the GUI too.

**Relay Testing**

The relay testing functions allow user to perform various transient relay testing procedures, view test results and the R-X diagram is case that the relays under test are distance relays. The relay testing functions might be specified as either single case or batch test mode for both one and two terminal transient relay testing.

- **Single Case Mode Relay Test Function** is designed for relay testing in a one-test-per-run application. Test file which contains transient or steady state signals is loaded into workspace first. The user might perform certain signal processing if needed. After the testing function is initiated, the signals will be checked for validation (sampling frequency check, the number of current/voltage channels check, and peak value check). If the signals pass those checks, a test file will be created and sent (replayed) to the relays. After the relay testing is finished, a capture file is created, which includes the information on the relay trip signals and sequence timing data.

- **Batch Mode Relay Test Function** is designed for automatic relay testing in a multiple-test-per-run application. Hundreds of pre-generated test cases could be selected to form a group (called batch) to test the relays(s). Once the function is activated, all cases in the test batch will automatically be checked for validation, and sent to the relay one by one until all of the test runs are done. At the same time, a capture file is generated whenever a case is replayed to the relay. In this manner, hundreds of cases may be run without user's interaction.

- **Test Result Viewing** can be used to view the relay test results by examining corresponding capture file. Capture file contains information on the time of changes of simulator input contacts connected to relay trip signals. Test result viewing function draws and indicates any changes in the digital channels.

- **R-X Diagram Plotting Function** calculates and plots, in the case of distance relay testing, the impedance trajectory using the voltage and current transient waveforms. The R-X plane is used to represent the calculated trajectory versus relay settings to estimate the performance of the relay under test. The transient data (such as EMTP output file) are first re-sampled to 720 Hz and processed to obtain the phasor quantities at each time step (using Fourier algorithm). After this step, the fault detector is invoked to decide if fault has occurred or not. If a fault has been seen, the fault is then classified and corresponding algorithm is chosen to compute the impedance. The impedance calculations are performed as follows:

  - **Phase to phase fault:**
    \[ Z = \frac{E_{a} - E_{b}}{I_{a} - I_{b}} \]
    for A-B fault.

  - **3 phases fault:**
    \[ Z = \frac{E_{a} - E_{b} + E_{b} - E_{c} + E_{c} - E_{a}}{I_{a} - I_{b} - I_{b} - I_{c} - I_{c} - I_{a}} \]
SIMULATOR APPLICATIONS

A typical 345kV system section has been chosen for simulator application study. Fig. 7 shows the one-line diagram of the reduced IL&P system. The line section from A to B is selected for relay testing studies [2]. The modeling of this system involves two major steps: (1) obtaining Thévenin equivalent circuits for all the boundary buses; (2) detailed modeling of the components which are close to the A-B-C line section.

EMTP simulation of the system is performed by first drawing one-line diagram of the system using EMTP GUI software developed by TAMU [7]. Then EMTP input data is generated by invoking EMTP GUI tools. This solution avoids tedious EMTP input data preparation. Fig. 8 gives the GUI representation of the system under study. The EMTP simulation can be readily invoked through the GUI.

After the EMTP simulations are completed, the RTSPS is invoked to perform relay testing, and/or signal processing and analysis if needed. The relay testing procedure is specified as either single case or batch test mode. Using the above mentioned method, hundreds of cases have been performed to test relays for the IL&P system using the digital simulator.

Fig. 9 gives an example of the two terminal (single case mode) relay test results. In the figure, EMTP generated waveform and relay responses are shown. The upper two plots on the left-hand side are the voltage and current waveforms which are replayed at the “master” terminal. The lower plot on the right-hand side is the trip signal of the relay at “master” terminal (KING terminal). The 3 plots on the right-hand side are the corresponding signals for the “slave” terminal (NLBEET terminal). The fault simulated is a single phase fault which is located on NLBEET-KING line and is 75% away from the KING terminal. In the test, both relays trip. The operating time of the relay at KING terminal is 17.18 ms, and it is 15.18 ms for the relay at NLBEET terminal.

CONCLUSIONS

Conventionally commercial relay testing equipment, in general, is not capable of performing full scale transient testing. However, the digital simulator have both hardware and software capabilities to support transient testing.
of protective relays. The transient relay testing and signal
processing software presented in this paper is an important
application software for digital simulator. The software is
capable of performing both one and two terminal transient
testing, as well as various data conversion, signal processing
and signal analysis functions which are necessary in certain
circumstances. The automatic relay testing functions inte-
grated in the software ease the relay testing burden.

ACKNOWLEDGMENTS

This project was funded by the Electric Power Research
Institute (EPRI), Pacific Gas and Electric, Houston Lighting
and Power Company, FPL Company, Western Area
Power Administration and Texas A&M University under
EPRI project No. RP 3192-01.

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