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 simulator 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(HL&P). 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 COMmon format for TRAnsient 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 requirement and software configuration are discussed then. 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 41T) 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 Micro Channel - 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 files from DSPs 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 changes of the device under test 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(RTSPS) package provides an effective interface between the user and the system. The RTSPS is capable of performing data conversion, signal processing, signal analysis, relay testing as well as graphic user interface functions. Table I gives a breakdown of the requirements of the RTSPS.

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 RTSPS, COMTRADE format is chosen as the

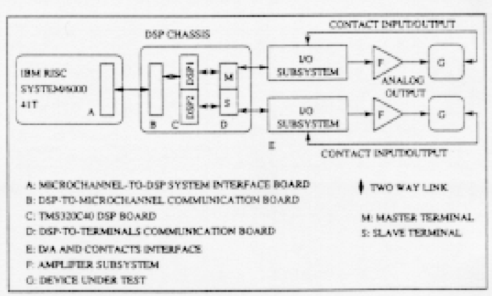

Fig. 1. Hardware Architecture

TABLE I
REQUIREMENTS FOR RTSPS

Requirement Category	Requirement Description
Data Conversion	• Conversion of files recorded in different DFR formats into IEEE COMTRADE format. • Conversion of EMTP output files into IEEE COMTRADE format.
Signal Processing	• Signal Filtering • Contact State Modification • Pre-fault Waveform Extension • Sampling Rate Change • Signal Polarity Change • Change Scaling Factor • Channel Selection • Signal Length Editing • Missing Phase Reconstruction
Signal Analysis	• Spectrum Analysis • Waterfall 3-D Presentation
Operator Interface	• GUI for Function Access • Database Interface • Waveform Viewing • Instantaneous Value Display • Signal Graph Management(Zoom in/out, Axes On/Off, Grid on/Off)
Relay Testing	• Single Case Mode Relay Testing • Batch Mode Relay Testing • Test Result Viewing • R-X Diagram Plotting

common data format for signal manipulating. All the transient data with other formats is first converted to COMTRADE.

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 RTSPS 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.

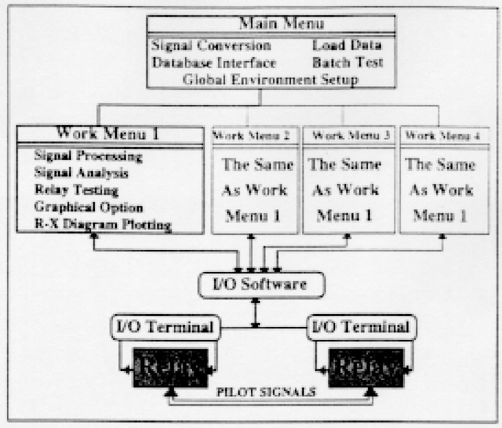

Fig. 2. Relay Testing and Signal Processing Software Organization

SOFTWARE ARCHITECTURE

The RTSPS is developed on an IBM RS/6000 workstation, and designed to operate in 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 RTSPS 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 RTSPS 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 RTSPS 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 RTSPS, 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 RTSPS, Rochester, Hathway and Mehta DFR files can be converted to COMTRADE data by ROCHCONV, HATHCONV and MEHCONV 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 needed 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.
- Create / Modify Contact State Function is used to create /modify digital signals used to represent the digital contact outputs of the simulator.

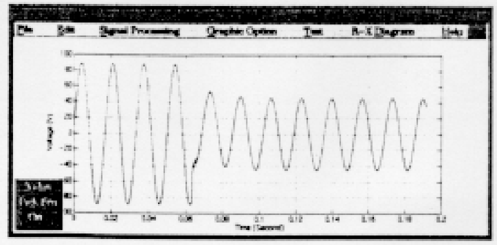

Fig. 3. Waveforms Before Prefault Extension

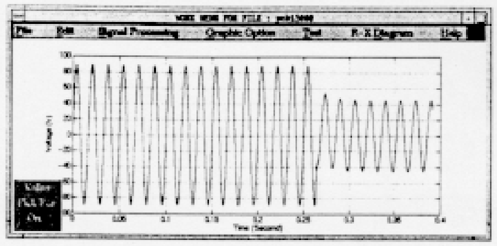

Fig. 4. Waveforms After Prefault Extension of 0.2s

- Missing Phase Reconstruction Function is designed to reconstruct a missing signal out of 3 known signals in the three phase power systems. 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 parameter 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 affects relay performance. Hence, it is important to view the harmonic content of the signals to aid relay engineers in identifying

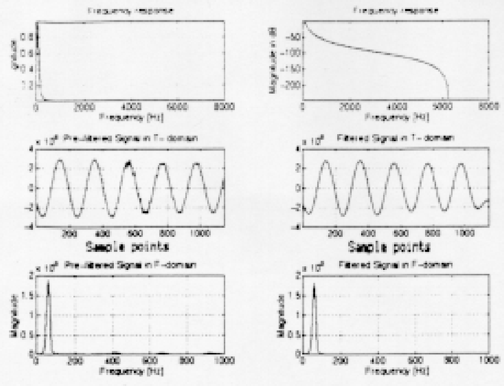

Fig. 5. Signal Filtering

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 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 'ot the R-X diagram in case that the relays under test e 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 relay(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 be 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:

$$Z = \frac{\frac{E_a - E_b}{I_a - I_b} + \frac{E_a - E_c}{I_a - I_c} + \frac{E_b - E_c}{I_b - I_c}}{3}$$

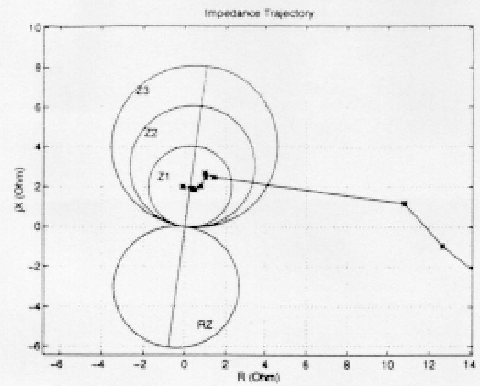

Fig. 6. R-X Diagram

– SLG fault (A-G fault):

$$Z = \frac{Ea}{I_a + KI_0}$$

Where

$$K = \frac{z_0}{z_1} - 1$$

z_0: transmission line zero sequence impedance
z_1: transmission line positive sequence impedance
and

$$I_0 = \frac{I_a + I_b + I_c}{3}$$

Similar expressions can be obtained for B-G and C-G faults.

Figure 6 gives an example of the R-X diagram.

SIMULATOR APPLICATIONS

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

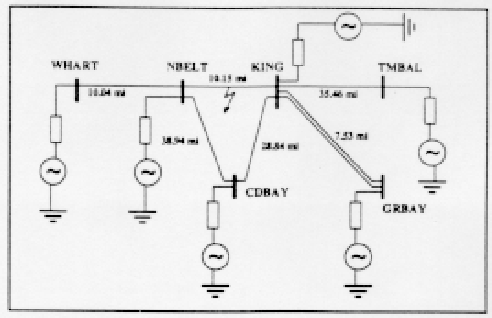

Fig. 7. One-line Diagram of the Reduced HL&P System

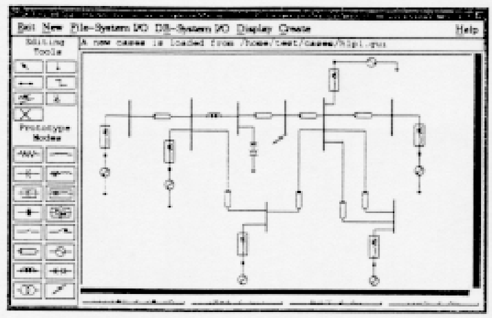

Fig. 8. EMTP GUI Representation of the HL&P System

specified as either single case or batch test mode. Using the above mentioned method, hundreds of cases have been perform to test relays for the HL&P system using the digital simulator.

Fig. 9 gives an example of the two terminal (single case mode) relay test results. In the figure, the 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 lowest plot on the left-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 (NBELT terminal). The fault simulated is a 3 phase fault which is located on NBELT-KING line and is 75 % away form 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 NBELT terminal.

CONCLUSIONS

Conventional 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

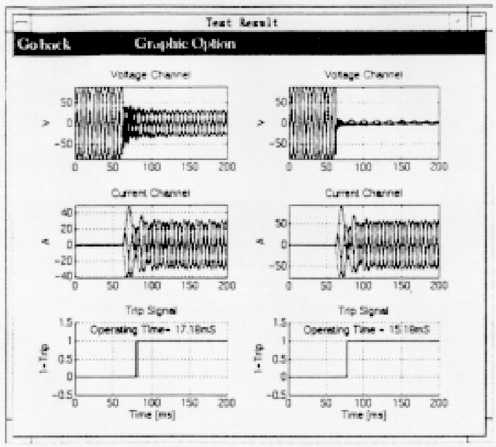

Fig. 9. Two-Terminal Transient Relay Test Results

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 integrated in the software ease the relay testing burden.

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