Visualization and Animation of Protective Relay Operation from DFR Data

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Abstract: DRF data are useful for post mortem analysis of system disturbances. Central to this problem is the response of relays to disturbances. This paper presents an improved method for post-mortem analysis of relay response to disturbances from DFR data. Specifically, a visualization application for the operation of protective relays using digital fault recorder data is presented. The visualization is implemented with animated display objects attached on a general purpose DFR data display and analysis package (XFM). The visualization objects illustrate the evolution of relay variables that are used to determine the tripping logic. Two examples of protective relay types are presented: (a) a modified mho relay and (b) a transformer differential relay. This tool is extremely valuable for educational purposes. Another potential application is digital relay testing. Actual digital relay algorithms can be interfaced to the visualization objects, yielding a flexible testing tool for the plethora of relays and relay manufacturers.

Introduction

Relaying has always played a very important role in the security and reliability of electric power systems. Many events of outages and blackouts can be attributed to the misoperation of relaying schemes or inappropriate relaying settings. Traditionally, a two-step procedure is applied to minimize the possibility of such events. First, in the design phase, comprehensive analyses are utilized to determine the best relaying schemes and settings. Second, if such an event occurs, an exhaustive post mortem analysis is performed to reveal the root cause of the event and what "was missed" in the design phase. The post mortem analysis of these events is facilitated with disturbance recorders.

In this paper we propose a new approach to this old and perpetual problem. The proposed approach is driven by two factors: (a) recent developments in software engineering and computer graphics and (b) the new generation of power system digital-object oriented relays. Specifically, it is possible to integrate relay animated visualization objects within a general purpose DFR data display and analysis package. The relay visualization objects may contain a generic algorithm for a specific relay class, or alternatively, be interfaced to a specific digital relay algorithm. Using this approach, actual recorded fault data can be used to study relay response, under any desired relay setting. This new approach has been implemented on the XFM program, a general purpose power system waveform display and analysis tool.

The paper presents a brief description of the XFM program, followed by detailed descriptions of two specific relay visualization examples: (a) differential relays and (b) distance (impedance) relays. Note that the presentation of the paper will be augmented with live demonstration of these examples.

Description of the XFM Program Organization

The XFM program is a MS-Windows application for the display and analysis of DFR data. The main program window is illustrated in Figure 1.

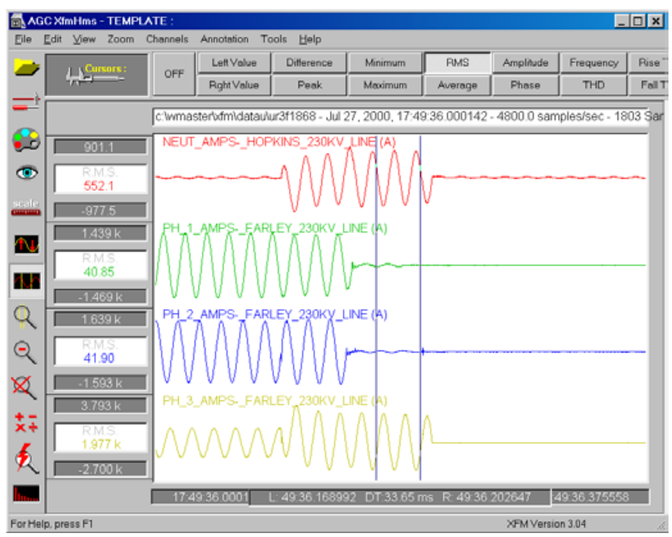

Figure 1. The XFM Program Main Window

The program accepts DFR data in COMTRADE format. The program includes many tools that aid in the analysts of disturbance data. For example, the waveform calculator (illustrated in Figure 2) allows the user to synthesize and display new waveforms as functions of any combination of existing waveforms.

An instrument transformer library is included which allows computation of waveforms at the high voltage side of the transformer from the low voltage side data. Other tools include: fault location, harmonic analysis, phasor display, numerous cursor based computational functions, etc.

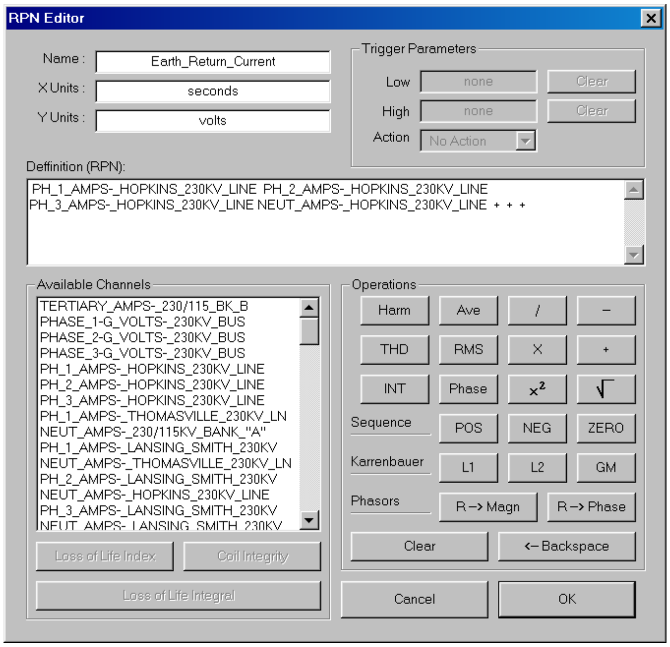

Figure 2. The Waveform Calculator Tool

Relay visualization objects were added as tools within the XFM program. The system provides the capability to animate the internal workings of the relay, and to display internal relay variables. For example these variables can be the impedance "seen" by the relay, the operating or restraining coil current, the force on a relay switch etc. These variables can be displayed in any desirable form: (a) oscilloscopic views, (b) 3-D visualization of relay mechanical parts, (c) visualization of logic flow, etc. The following section presents two specific application examples:

1. Distance and Mho relay operation.
2. Transformer Differential Relay.

We present the basic animation and visualization modules for these relays and a number of possible applications.

Protective Relaying Example 1: Distance and Mho Relay Operation

This example illustrates the visualization of the operation of the modified impedance relay (Mho Relay). The operation of this relay is based on the apparent impedance that the relay 'sees' and the trajectory of this impedance. The data for this case were recorded on the system illustrated in Figure 3. The system consists of a generator, a transmission line, a step-down transformer, a passive electric load, and an induction motor driving a fan. The data used in the relay visualization were recorded during two events:

(a) An induction motor start-up followed by a single-phase to ground fault on the Delta side bus of the transformer.

(b) An induction motor start-up followed by a three-phase fault on the Wye side bus of the transformer.

The recorded data for each case include the transmission line three phase voltages and currents at the generator end of the transmission line.

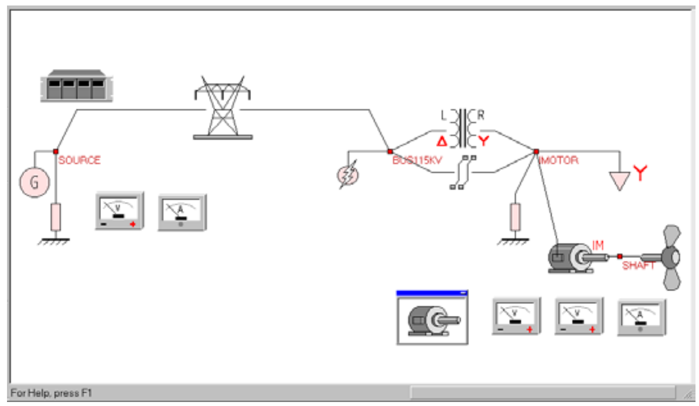

Figure 3. System from which DFR data were obtained For Mho Relay Visualization

The relay visualization object (illustrated in Figures 4 and 5) accesses the three phase voltage and current waveforms from the XFM program. Subsequently, it computes the phasors of the voltages and currents as well as the sequence components of these voltages and currents. From this information, the apparent impedance seen by the relay is computed and displayed.

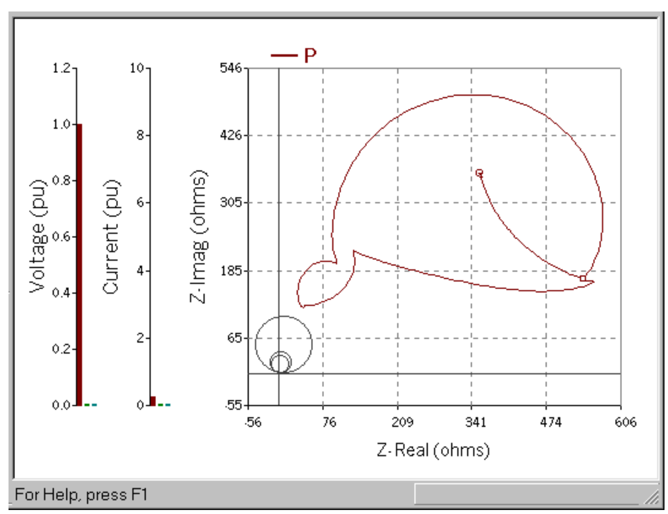

Figure 4. Mho Relay Visualization Window for a Single Line to Ground Fault on the 115 kV Bus

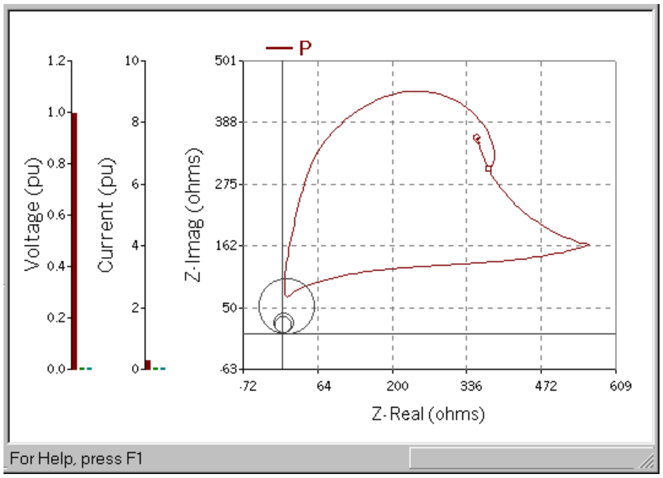

Figure 5. Mho Relay Visualization Window for a Three Phase Fault on the 13.8 kV Bus

The voltage and current phasor magnitudes are displayed as bar graphs on the left side of the visualization object window. The impedance trajectory is displayed over a complex impedance plot, (real/imaginary components), which also includes the relay setting zones (gray circles, see Figure 4).

Figure 4 shows the relay operation for event **a** (induction motor start-up and high side single-phase to ground fault). In this case the impedance trajectory does not visit the trip "region" of the relay. Figure 5 shows the relay operation for event **b** (induction motor start-up and low side three-phase fault). In this case the impedance trajectory visits the trip "region" of the relay.

Note that the voltage and current phasors displayed in the relay visualization window correspond to the cursor location on the XFM waveform display window. Furthermore, the red square marker on the impedance trajectory plot corresponds to the time instant indicated by the XFM waveform display window cursor. Thus moving the waveform display cursor allows inspection of the evolution of the relay internal variables over time.

It is important to note that the user may select what phasors to display, i.e. phase voltages or currents or any of the sequence components of the voltages or currents. In this example, the positive sequence phasors of the voltage and current as well as the positive sequence of the apparent impedance is displayed. Figure 6 shows the visualization object parameter setup window, which allows the user to select relay parameters, display options, as well as assign the recorded waveforms to the appropriate relay inputs.

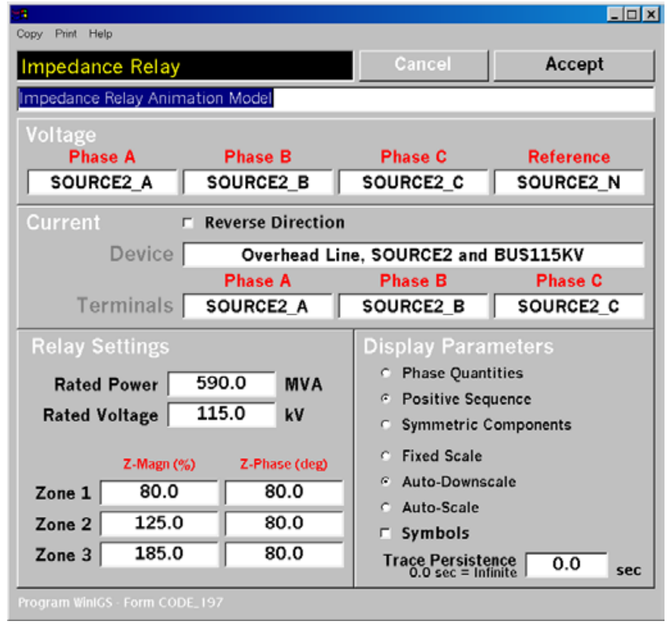

Figure 6. Mho Relay Setup Window

Protective Relaying Example 2: Transformer Differential Relay

Another important protective relaying example is the differential relay. In this example we present the visualization of a differential relay scheme for a delta-wye connected transformer with tap changing under load. The system may operate under steady state, or under transient conditions. The effects of tap changing on the operation of the relay can be demonstrated. The system from which the example waveform data were obtained is shown in Figure 7. It consists of an equivalent source, a transmission line, a 30 MVA delta-wye connected transformer, a distribution line and an electric load. The transformer terminal currents were stored in a COMTRADE file for use in the relay visualization example.

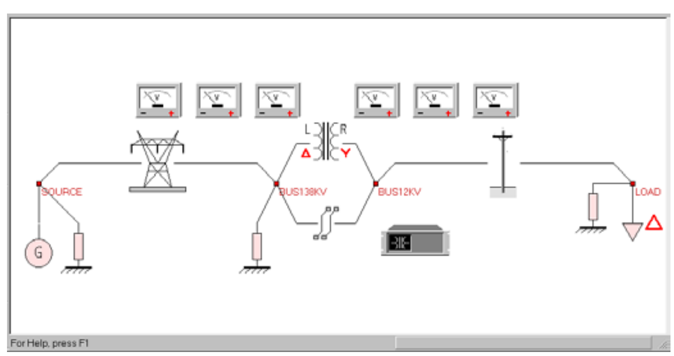

Figure 7. Example Test System For Transformer Differential Relay Animation

The differential relay visualization object window is illustrated in Figure 8. It is based on the electromechanical equivalent of a differential relay. It contains RMS bar-graph and phasor displays of the differential relay restrain and operating coils, as well as a bar-graph of the net force applied on the relay trip switch arm. Restrain coil current displays are in red, operating coil current displays are in green, and the switch force display is in blue color.

All displayed quantities provide the state of the relay at a time instant corresponding to the cursor location on the XFM waveform display window. When the waveform cursor is repositioned, the relay visualization window is dynamically updated providing an animation effect.

The importance of this visualization object is that one can study the effects of various parameters and phenomena on the operation of the relay. Relays can be tested for various sets of recorder or simulated waveforms. For example, a relay can be tested for various tap settings of the monitored transformer in order to determine the optimal level of percent restraint for the relay. An other example is testing the relay operation during transformer energization. Using recorded or simulated inrush currents for various types of breaker closing schemes, the optimal relay settigs can be determined by observing the relay operation. Note that the user can select the relay restrain and trip settings, the ratios of the CT's feeding the relay as well as the CT connection (Wye/Delta) using the parameter setup window illustrated in Figure 9.

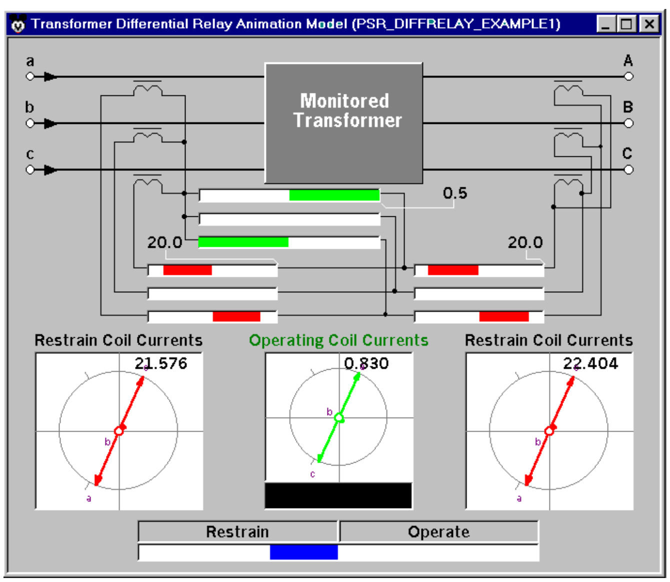

Figure 8. Transformer Differential Relay Visualization Object Window

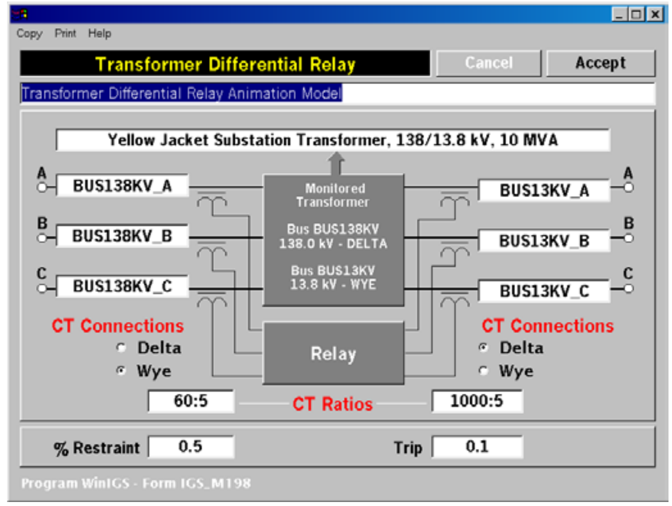

Figure 9. Transformer Differential Relay Parameter Setup Window

Interfacing With Digital Relays

The XFM program uses a flexible open architecture. Plug-In tools such as the presented relay visualization examples can be easily added. These tools can be directly linked with the program or attached in run-time as "Dynamic Link Libraries". We propose that the natural extension of the work reported in this paper is to use this feature to interface with commercially available digital "relays". The word "relay" is in quotation marks to indicate that the relay is simply a digital program that takes inputs of voltages and currents, performs an analysis of this data, applies logic and issues a decision. This program can be packaged into a Dynamic Link Library.

If this DLL is "linked" with the virtual test bed, in the sense that the inputs come from the virtual test bed, then the specific relay can be evaluated within the virtual test bed environment. The paper proposes an interfacing procedure. This procedure consists of modeling in the virtual test bed the instrumentation channel (i.e. instrument transformers, control cable, attenuators, etc.) and the output of the instrumentation channel is input to the relay object (or DLL). Note that the relay object is the manufacturers software and therefore the response of this relay will be identical with the actual relay in the field. The paper proposes a specific standard for this interfacing. Assuming acceptance of this standard by the relay manufacturers, the virtual test bed could be used to evaluate any commercially available relay that meets this standard. This tool will be invaluable in two respects: (a) to test commercial relays within the virtual laboratory, an inexpensive testing procedure, and (b) to train students and young engineers in the art of protective relaying.

Conclusions

This paper has discussed and presented protective relaying visualization objects implemented as tools of a general purpose DFR data display and analysis package (XFM). We have discussed our recent work towards the development of visualization objects of various protective relays. Two examples of protective relay visualization objects have been presented: (a) a distance relay and (b) a transformer differential relay. From these examples, it is clear that this approach can be quite beneficial from the educational point of view as they can provide insight of the system under study that are impossible in a physical laboratory. In addition, the relay visualization objects are valuable for testing commercially available digital relays assuming that they can be encapsulated within a standard MS-Windows-DLL. The presentation of the paper includes a live demonstration of these examples. It is important to note that much more work remains to develop a comprehensive library of relay visualization objects for the plethora of existing power system relaying devices.

Acknowledgments

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References

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Biographies

A. P. Sakis Meliopoulos (M '76, SM '83, F '93) was born in Katerini, Greece, in 1949. He received the M.E. and E.E. diploma from the National Technical University of Athens, Greece, in 1972; the M.S.E.E. and Ph.D. degrees from the Georgia Institute of Technology in 1974 and 1976, respectively. In 1971, he worked for Western Electric in Atlanta, Georgia. In 1976, he joined the Faculty of Electrical Engineering, Georgia Institute of Technology, where he is presently a professor. He is active in teaching and research in the general areas of modeling, analysis, and control of power systems. He has made significant contributions to power system grounding, harmonics, and reliability assessment of power systems. He is the author of the books, *Power Systems Grounding and Transients*, Marcel Dekker, June 1988, *Ligthning and Overvoltage Protection*, Section 27, Standard Handbook for Electrical Engineers, McGraw Hill, 1993, and the monograph, *Numerical Solution Methods of Algebraic Equations*, EPRI monograph series. Dr. Meliopoulos is a member of the Hellenic Society of Professional Engineering and the Sigma Xi.

George Cokkinides (M '85) was born in Athens, Greece, in 1955. He obtained the B.S., M.S., and Ph.D. degrees at the Georgia Institute of Technology in 1978, 1980, and 1985, respectively. From 1983 to 1985, he was a research engineer at the Georgia Tech Research Institute. Since 1985, he has been with the University of South Carolina where he is presently an Associate Professor of Electrical Engineering. His research interests include power system modeling and simulation, power electronics applications, power system harmonics, and measurement instrumentation. Dr. Cokkinides is a member of the IEEE/PES.