A Novel Digital Relay Model Based on SIMULINK and Its Validation Based on Expert System

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***Abstract*—This paper presents the development of a novel digital relay model and its validation by a digital relay data analysis application. The model is developed as a SIMULINK S-function block. MATLAB file I/O functions are employed to generate an oscillography file and an event report. The expert system based digital relay data analysis application validates the relay model and generates diagnosis information for refining the model. An example is used to demonstrate the procedure of simulation, validation, and refining.**

***Index Terms*—relay model, SIMULINK, relay file, expert system, validation**

I. Introduction

SOFTWARE models, in the form of equations representing the operating characteristics of relays, have long been used by academics, manufacturers, and consultants for designing relays and checking their performance [1]. In recent years, they are further employed to study multi-terminal, coordinated relaying schemes, model substations, and generate data for some intelligent applications [2], [3].

Most existing relay models reflect their behavior by graphic outputs such as plots of impedance trajectory, trip signals, and contact signals. This feature is rather useful for manual analysis of internal dynamics of the relay models and validation of their operations. It is more desirable to have the relay models generate files for detailed oscillographing and event reporting so that several benefits can be further achieved. First, the behavior of the relay model will be more explicitly reflected with the oscillography file indicating what the relay model exactly "sees" and the event report providing details of the status and timing of every active protection element. Second, if several relay models are in a multi-terminal scenario, the relay operations can be globally analyzed by correlating the data and information in their relay files. Third, relay files actually act as the information media which can be accessed by other computer programs. With these advantages gained from relay files, it is feasible to realize detailed automated validation of relay models using new computer applications.

Reference [4] introduces an expert system based digital protective relay data analysis application (DPRDA). It is originally developed for validation and diagnosis of real digital relays by analyzing relay files and reports. With modification and expansion of its knowledge base, the application can also be used for validation of relay models since digital relays and its computer models inherently have lots of similarities.

This paper presents the development of a digital relay model and its validation by the DPRDA application. The relay model is developed as a SIMULINK S-function block. It can interact with the power system network model created by MATLAB Power System Blockset to achieve closed-loop simulation. MATLAB file I/O functions are used to generate an oscilloraphy file and an event report for the relay model. Taking the relay files as inputs, the DPRDA application validates the prototype of the relay model, and identifies design deficiencies and incorrect relay settings. With the diagnosis information, refining of the relay model and adjusting of the relay settings can be more easily achieved. Fig. 1 illustrates the development cycle of prototyping, validation, and refining for fast and accurate relay modeling.

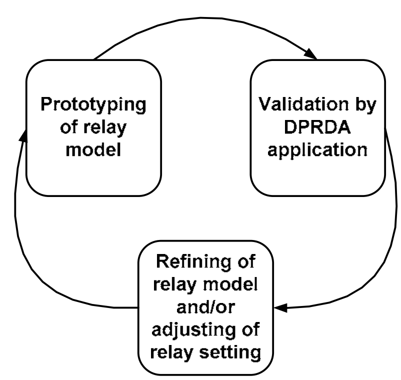

Fig. 1. The development cycle of relay modeling

Section II of this paper introduces the digital relay model based on SIMULINK S-function. Section III presents the strategy of relay model validation by the DPRDA application. Section IV uses an example to demonstrate the process of simulation, validation, and refining. Conclusions are drawn in Section V.

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II. Relay Model Based on SIMULINK S-Function

A. Advantages of SIMULINK S-Function for Relay Modeling

An S-function is a computer language description of a SIMULINK block written in MATLAB, C, C++, Ada, or Fortran [5], [6]. Its most common use is to create a custom block which can dynamically interact with other blocks in a SIMULINK environment. The users can use an S-function for a variety of applications such as describing a system as a set of mathematical equations, incorporating existing C/C++ code into a simulation, and adding a block that represent a hardware device driver. There are several advantages to using an S-function to model a digital protective relay. First, MATLAB provides Power System Blockset to model power system networks in a SIMULINK environment [7]. If the relay model is developed using an SIMULINK S-function, the interfacing between the power system network model and the relay model can be easily achieved. Second, an S-function relay model can fully utilize MATLAB functions to realize sampling, signal processing, and protection algorithm implementation. Third, an S-function can work with the newly developed Real-Time Workshop for SIMULINK, which automatically generates, packages, and compiles sources code from SIMULINK models to create real-time software targeting embedded systems [8]. So by using an S-function to model a digital relay, it is possible to utilize the direct and rapid path from system design to implementation built by the Real-Time Workshop.

B. Main Features of the Relay Model

The developed relay model may be used in a variety of simulation studies. Besides the features which satisfy the common functional requirements for components, interface, and protection functions, the relay model is also capable of generating relay files, which provide access to the relay data and information for other computer programs. Table I lists the main features of the relay model.

TABLE I: Main Features of the Relay Model

Requirements	Features
Components	• analog filter • A/D converter • implementation of signal processing and protection algorithms
Interface	• up to 4 channels of node voltages inputs and 8 channels of branch currents inputs • up to 2 channels of circuit breaker status contact inputs • up to 2 channels of trip signal outputs
Protection Functions	• phase distance • ground distance • phase instantaneous over-current • ground instantaneous over-current • autoreclosing
Others	• setting file reading • generation of oscillography files, fault reports and event reports

C. Implementation of the Relay Model

Although it is possible to realize all the functions of the relay model in one S-function block, we adopt a hybrid approach to realize the relay functions in both SIMULINK blocks and S-functions because some SIMULINK blocks have unique features which facilitate modeling of some components of the relay. Analog signal filtering is realized by an S-function block which contains Butterworth filtering function of MATLAB. The A/D conversion is implemented by a Zero-Order Hold block of SIMULINK. All other functions of the relay model are realized in another S-function.

1) Analog Filtering and A/D Conversion

In order to meet the sampling theory, the sampling rate of the relay model should be twice the maximum frequency in the input analog signals. Sampling with a lower sampling rate will result in errors due to the aliasing effect in the discrete time signals. The anti-aliasing filters, which in practice are analog filters, should be used to minimize such aliasing effect as well as to attenuate the high frequency components. In the relay model, analog second order Butterworth low-pass filters are employed. They are realized by Butterworth filtering function of MATLAB called from an S-function block. The sample and hold circuit of A/D converter of the relay model is realized by a Zero-Order Hold block of SIMULINK. This will actually perform the sampling on the original simulation time steps and hold the sampled value at each sampling interval.

2) Protection Algorithms

All the protection algorithms are implemented in another S-function. Fourier Transform is used to extract the fundamental frequency phasors for phase voltages and currents, line voltages and currents, and zero sequence currents. The phasors of phase currents and the phasors of zero sequence currents are used for comparison with the pickup thresholds of the Phase IOC Element and the Ground IOC Element respectively. The phasors for line voltages and currents are used to calculate the line impedances for comparison with the MHO characteristic of the Phase Distance Elements. The phasors for phase voltages and currents are used to calculate the phase impedances for comparison with the quadrilateral characteristic of the Ground Distance Elements. Timers are simulated to ensure the required time coordination between the pickup and the operation of protection elements.

3) Relay File Generation

In the relay model, the analog signals of input voltages and currents, and digital signals representing current supervision, pickup and operation of protection elements are stored in the arrays for oscillography use. The status changes of digital signals are detected and used for event report generation. At the end of the simulation, the file I/O functions of MATLAB are called to generate the event report and the oscillography files in COMTRADE format [9].

III. STRATEGY OF RELAY MODEL VALIDATION

When the prototype of the relay model is finished, interactive simulation of the relay model and the power system network model will be performed in the SIMULINK environment. Then validation of the behavior of the relay model during the simulation will be realized in the DPRDA application [4]. Fig. 2 illustrates the conceptual strategy of the simulation and validation.

A. *Interactive Simulation in SIMULINK*

Before the simulation, the fault information including fault type, fault location, fault inception time, and fault disappearance time should be specified in the power system network model. This can be easily achieved by setting parameters in the dialogs for components of the power system network model. In the mean time, the fault information needs to be saved in a fault information file for the use of DPRDA application. Relay settings also should be specified in the relay setting file before simulation to set operating parameters of each protection element. During the simulation, the relay model responds to faults and sends out control signals to its associated circuit breaker. At the end of the simulation, the relay model generates an oscillography file and an event report which contain detailed information about the external and internal behavior of the relay model during the entire simulation.

B. *Validation Process of DPRDA Application*

Validation analysis of the DPRDA Application is fundamentally based on comparison of expected protection operation and actual protection operation in terms of status and timing of predefined logic operands. If the expected and actual status and timing of a logic operand is consistent, the correctness of the status and timing of that operand is validated. If not, certain failure or missoperation is identified and diagnosis will be initiated to trace the reasons by logic and cause-effect chain.

The expected protection operation is predicted by an expert system module which simulates relay operation logic using forward chaining rules. Inputs to this module are fault information and performance specification. The fault information is read from the fault information file saved at the simulation stage. The performance specification, which specifies the timing criteria for the operation of each protection element, is available from a dialog.

The records of actual protection operation are obtained from the oscillography file and the event report. A signal processing module is used to process the analog current data in the oscillography file to detect current interruption after the circuit breaker opening, current reappearance after the circuit breaker reclosing, and current reinterruption after the circuit breaker reopening if it happens to reclose onto a permanent fault.

With the information of both the expected and actual protection operation available, an expert system module will perform validation based on hypothesis-fact matching and diagnosis based on cause-effect chain. Finally a report on the results of validation and diagnosis will be generated. This report will assist the relay model designers in refining the relay model and adjusting the relay settings.

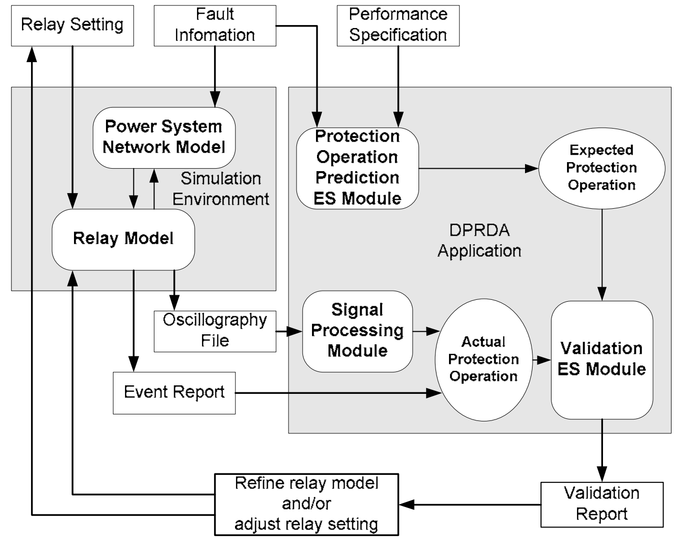

Fig. 2. Conceptual strategy of the simulation and validation.

IV. EXAMPLE

In this section, an example is used to demonstrate the procedure of simulation, validation, and refining of a relay model.

A. *Simulation Environment*

Fig. 3 shows simulation environment using the SIMULINK platform. A 9-bus power system network model is created by the Power System Blockset and a relay model DR01 is developed as an S-function block. The relay takes voltage and current measurements from circuit breaker CB01 as inputs and its output controls opening and reclosing of the circuit breaker. Such a configuration enables the relay to protect the transmission line LINE45 in its Zone 1 and Zone 2 and transmission LINE57 in its Zone 2 and Zone 3.

B. *Relay Setting*

Four protection elements together with 1-shot autoreclosing logic are enabled in the relay model. Table II lists the major relay setting.

TABLE II: MAJOR RELAY SETTING

Elements		**Range (% of the length of LINE45)**	**Coordination Time Delay (Second)**
Phase Distance	**Zone 1**	75	0.0
	Zone 2	150	0.2
	Zone 3	230	1.0
Ground Distance	**Zone 1**	75	0.0
	Zone 2	150	0.2
	Zone 3	230	1.0
Phase IOC		N/A	0.3
Ground IOC		N/A	0.3
Autoreclosing		N/A	0.4

C. *Fault Scenario*

A permanent fault is assumed to occur on the transmission line LINE45. TABLE III lists the fault information.

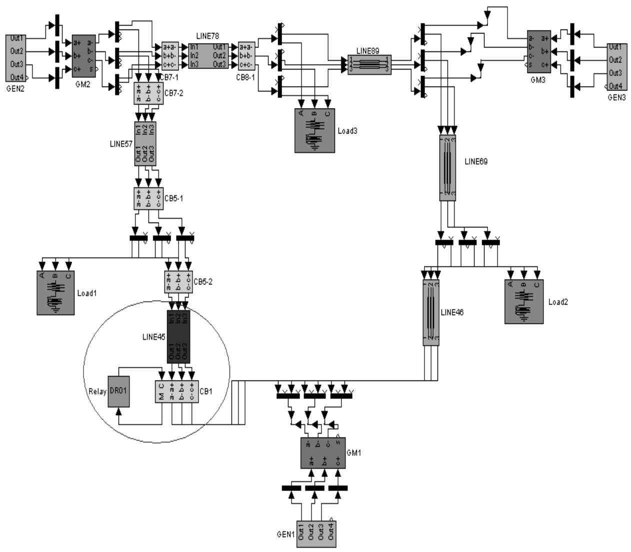

Fig. 3. Simulation Environment

TABLE III: FAULT INFORMATION

Fault Type	B-C
Fault Location (% of the line length)	80 (Zone 2)
Fault Inception Time (Second)	0.100
Fault Disappearance Time (Second)	N/A

D. Oscillography File and Event Report

After a simulation lasting for 1.0 second, the relay model generates an oscillography file and an event report. Fig. 4 shows the oscillography file and the event report displayed in the GUI of the DPRDA application.

E. Performance Specification

In order to validate the operation of the relay model during the simulation, its performance specification is obtained through a dialog in the DPRDA application shown in Fig. 5.

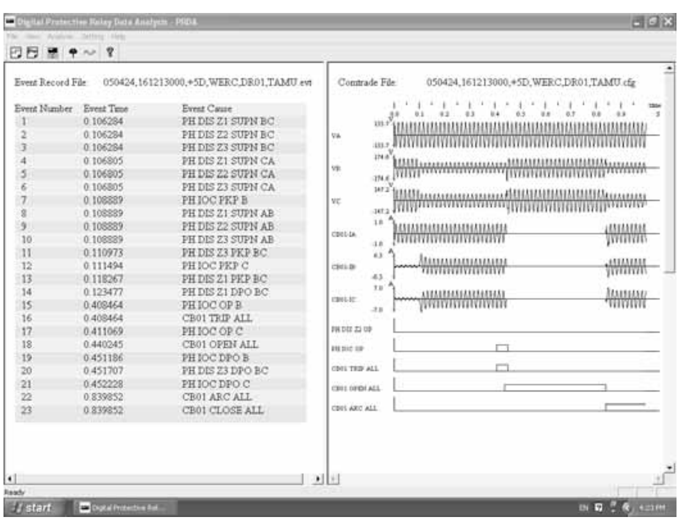

Fig. 4. Oscillography file and event report

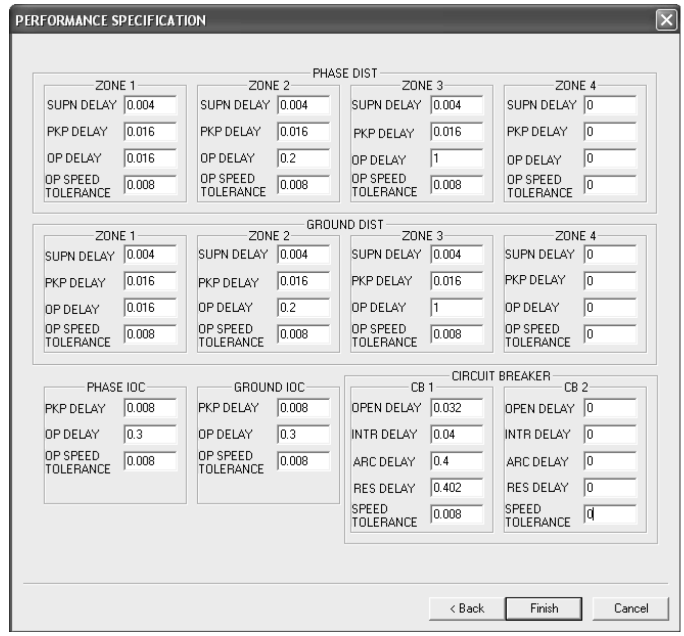

Fig. 5. Performance specification dialog

F. Validation Report

The validation report generated by the DPRDA application is shown in Fig. 6. As we can see from the "Summary of Protection Operation" section, the Phase Distance Zone 2 Element is expected to operate to make the relay trip at 0.3160 second. After opening and reclosing, the circuit breaker is expected to reopen to interrupt the currents at 0.7640 second since the fault is a permanent one. However, the actual protection operation is quite different from the expected operation. The Phase IOC Element operated to make the relay trip at 0.4085 second and the circuit breaker did not reopen after its reclosing. The "Diagnosis Information" section gives the detailed explanation of the difference between the expected and actual protection operation. The reason for the fact that the Phase IOC Element operated instead of the Phase Distance Zone 2 Element was because the Phase Distance Zone 2 BC Phase Element failed to pickup due to incorrect characteristic setting of the Phase Distance Zone 2 Element. The reason for the failure of reopening of the circuit breaker after it reclosed onto the permanent fault is that the fault detection function of the autoreclosing logic is not correctly designed.

G. *Refining of the Relay Model*

The validation report generated by the DPRDA application identifies the design deficiency of the relay model and incorrect relay setting, which helps to quickly pinpoint the problem domains during the relay modeling. After debugging the algorithm for fault detection function of autoreclosing logic and adjusting the characteristic setting for the Phase Distance Zone 2 Element, the second validation process does not identify any major problem. Fig. 7 and Fig. 8 show the relay files generated by the refined relay model and the validation report generated by the DPRDA application.

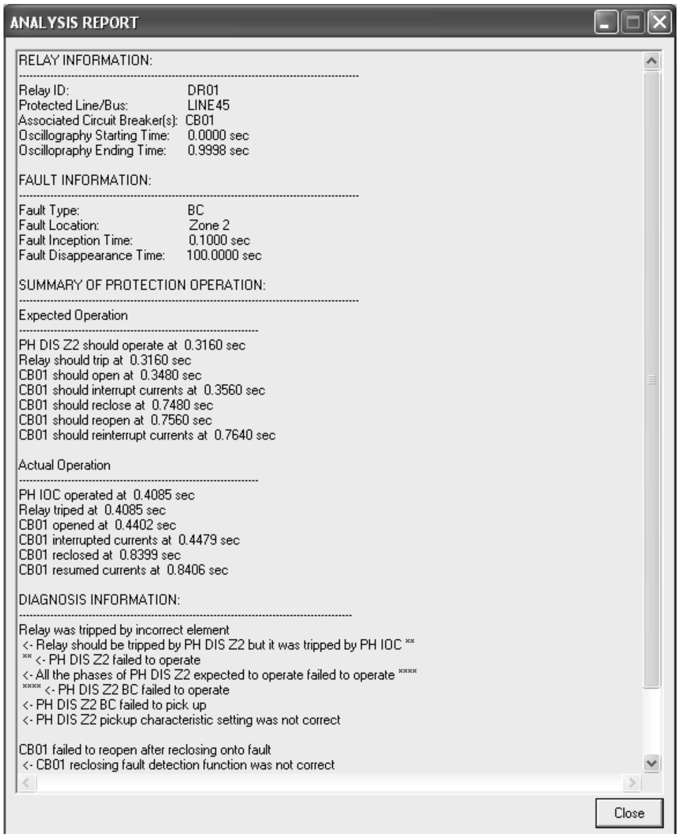

Fig. 6. Validation report

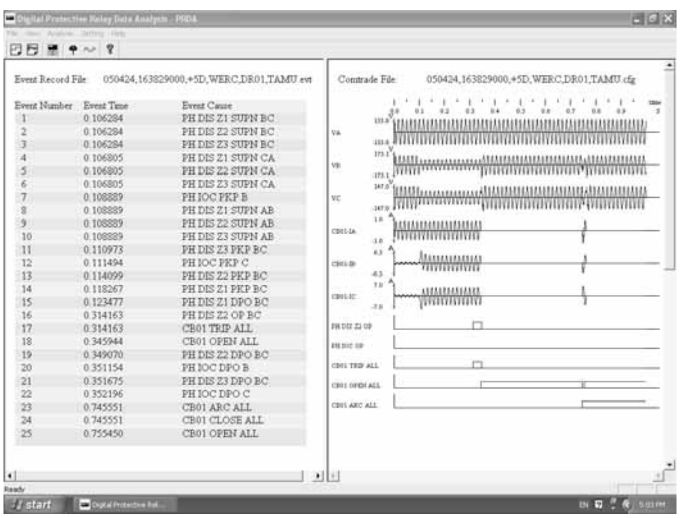

Fig. 7. Oscillography file and event report after refining the relay model and adjusting the relay setting

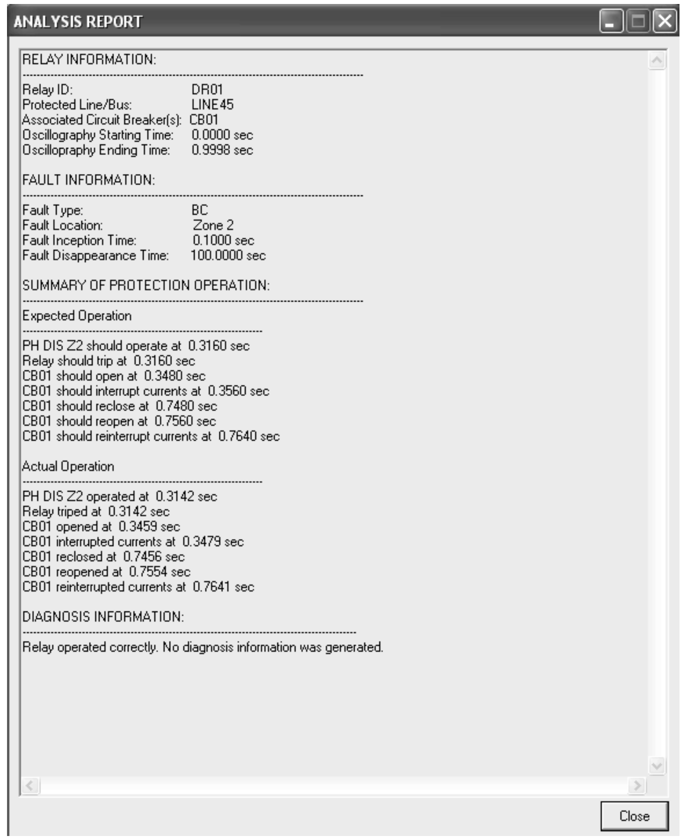

Fig. 8. Validation report after refining the relay model and adjusting the relay setting

V. CONCLUSIONS

Based on the discussion in this paper, conclusions are drawn as follows:

- There are many advantages to using SIMULINK S-functions to model a digital protective relay which can significantly facilitate the modeling process.
- The oscillography file and the event report generated by a relay model provide direct access to the relay data and information for other computer programs.
- Relay data analysis application can be used to validate the prototype of a relay model during the modeling process. The validation results provide guides to the designers to refine the relay model and adjust the relay settings.

VI. REFERENCES

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VII. Biographies

Xu Luo (S'05) received his B.E. and M.E. degrees from Xi'an Jiaotong University, Xi'an, China, both in electrical engineering in 1999 and 2002 respectively. He has been with Texas A&M University pursuing his Ph.D. degree since Aug. 2002. His research interests are power system protection, substation automation, and artificial intelligence applications in power system monitoring, control, and protection.

Mladen Kezunovic (S'77, M'80, SM'85, F'99) received his Dipl. Ing. Degree from the University of Sarajevo, the M.S. and Ph.D. degrees from the University of Kansas, all in electrical engineering, in 1974, 1977 and 1980, respectively. He has been with Texas A&M University since 1987 where he is the Eugene E. Webb Professor and Director of Electric Power and Power Electronics Institute. His main research interests are digital simulators and simulation methods for equipment evaluation and testing as well as application of intelligent methods to control, protection and power quality monitoring. Dr. Kezunovic is a registered professional engineer in Texas, and a Fellow of the IEEE.