A NOVEL APPROACH FOR INTERACTIVE PROTECTION SYSTEM SIMULATION

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ABSTRACT: This paper presents a new approach for interactive protection system simulation. In the new approach, power system transients are simulated using an Electromagnetic Transients Program(EMTP), while protective relays can be modeled using any high level language or commercially available software package, such as MATLAB. The interactions between power systems and relays are implemented by using an "interaction buffer". Using this technique, the EMTP can be run in single-step, multiple-step, or mixed mode. This new approach makes the protection system simulation quite efficient, flexible and accurate.

KEYWORDS: Power System, Protection System, Simulation, Relay Modeling, EMTP, ATP.

I. INTRODUCTION

A comprehensive evaluation of a protection system can be carried out using sophisticated test equipment such as digital simulators [1], [2], [3]. Although relay testing using digital simulators is the most attractive laboratory method to test individual relays, it still has certain constraints such as the limited number of relays which can be tested simultaneously, extended length of time required to carry out tests, and the need for costly amplifiers and interfacing equipment.

Combined computer simulation of power systems and protective relays, on the other hand, provides a good supplement to the relay performance evaluation. Protection system simulation can be used as a valuable preliminary step for overall relay design performance testing. This approach allows complex, multi-terminal, coordinated relaying system simulations.

In the relay simulation, power system modeling and relay modeling are two very important tasks. The use of the electromagnetic transients programs for power system fault modeling has been known for a long time [4]. Protective relay simulation has also been of great interest to researchers for more than a decade [5]- [11]. It has been used for relay algorithm study and performance evaluation by researchers and application engineers.

Another important issue is the interfacing scheme adopted for simulating interactions between the power system models and relay models. This issue has been explored in the past to assess the alternatives and potential benefits as they related to the performance of the relay simulation study. This paper is aimed at outlining an advanced approach to a powerful interactive simulation scheme. As a result, protective relay modeling can be implemented independently from the network modeling. This provides additional flexibility in selecting the most appropriate simulation tools resulting in improved accuracy of the relay model. The final benefit of the new simulation approach presented in this paper is that both the interactive simulation and improved relay model representation are possible making the overall protection system simulation more powerful.

In section II, an overview of the existing protective relay simulation approaches is given and the pros and cons of these approaches are discussed. Section III is devoted to the new interactive simulation approach. Examples of relay modeling and simulation study using the new interactive approach and improved simulation tools are given in sections IV and V respectively. The conclusions are given at the end.

II. AN OVERVIEW OF PRESENT PROTECTIVE RELAY SIMULATION APPROACHES

Several relay simulation implementations have been introduced in the past decades. Based on the interaction scheme employed, relay simulation can be classified into the closed-loop or open-loop simulation. In the closed-loop simulation, the relay trip signal is fed back to control the circuit breaker of the power system model. In the open-loop approach, the feedback is not taken into account.

A. Open-Loop Relay Simulation Approach

The open-loop (also called play-back) simulation may use any electromagnetic transients program (EMTP) as a signal generator which creates power system voltage and current transient waveforms [12], [13]. The relay model is a stand alone model which is implemented normally in high level language, such as C, FORTRAN, BASIC etc. Because these high level languages are straight forward to use, relay model realization is easy. The transient waveforms generated by EMTP are generally stored in files. Those files are then converted to certain format, loaded into computer, and fed into relay models to perform simulation. However, this approach does not allow the modeled relays to operate switches in the EMTP since there is no appropriate feedback implemented. The interaction between the relay trip signal and the circuit-breaker of the power system under studies can not be simulated, thus consequences of some important subsequent events such as the auto-reclosing can not be studied properly [7].

B. Closed-Loop Simulation approaches

There were several closed-loop (also called real-time) simulation schemes introduced in the past. These closed-loop simulation approaches have greatly enhanced the accuracy of the computer simulation of the relaying system behavior, and made it possible to simulate the dy-

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namic interactions between power systems and protection systems. Unfortunately, the existing closed-loop simulation approaches require relay models to be embedded into EMTP executables or EMTP input data cases. These restrictions make relay modeling inflexible.

B.1 TACS/MODELS-Based Relay Simulation

The transient analysis of control systems(TACS) module in the EMTP was designed as a simulation tool that functions in ways similar to analog computers, differential analyzers, and algebraic and logical processors combined. The TACS signals and EMTP electrical-network variables can be interfaced, to form a hybrid EMTP-TACS interactive configuration [12]. The MODELS feature, which is currently only available in the alternative transients program (ATP) version of EMTP, is an enhancement to the TACS [13], [14]. It provides more flexibility and programmability over the TACS, when relay modeling is being considered. Both TACS and MODELS can be used to implement relay models for interactive relay simulation study. However, relay model implementation is difficult because there is limited capability to add FORTRAN code to the TACS/MODELS at present [7].

B.2 Built-in FORTRAN Relay Simulation

To solve the problem of the limited capability to add FORTRAN code to the EMTP, a built-in FORTRAN relay model approach was introduced [7], [10]. In this approach, relay models can be implemented using a full FORTRAN capability. The relay models are then recompiled and relinked to the EMTP. Thus, several modifications to the EMTP source codes are required and some additional new subroutines to interface the FORTRAN relay models are needed. Moreover, every time when a new FORTRAN relay model is built, the user needs to recompile and re-link the whole EMTP program. Another major limitation is that the users normally do not have access to the source codes. And if they have, they may not be allowed to modify the source codes because of the copyright reason.

The advantages and disadvantages of different approaches are summarized in Table I.

TABLE I
Comparison of Various Relay Modeling and Simulation Approaches

Item	**Open Loop**	**Closed-Loop**		
		S1	**S2**	**S3**
Interactive simulation available?	No	Yes	Yes	Yes
Optimal interactive simulation?	No	No	No	Yes
Relay model being implemented in any language?	Yes	Limited FORTRAN Capability	Full FORTRAN Capability	Yes
Relay simulation using data other than EMTP?	Yes	No	No	Yes
Friendly user interface?	Yes	No	No	Yes
EMTP code modification needed to setup interaction?	No	No	Yes	Yes
EMTP code modification needed to setup new relay model?	No	No	Yes	No

S1: TACS/MODELS-based relay simulation [6], [9]
S2: EMTP built-in FORTRAN relay simulation [7], [10]
S3: New EMTP interfaced relay simulation [discussed in this paper]

C. Limitations of the Existing Approaches

In order to study protective relaying system performance accurately, a real-time closed-loop simulation approach is highly desirable. Unfortunately, the existing closed-loop simulation approaches require all the relay models to be embedded in the EMTP. This restricts the application of the closed-loop simulation. Another fact is that most of the existing relay models (for example relay algorithms implemented for actual relays) were implemented in high level languages other than FORTRAN. Therefore it will be more efficient if closed-loop relay simulation can use relay models implemented in any language. The new closed-loop interactive relay simulation approach presented in the next section solves these problems.

III. A NOVEL CLOSED-LOOP INTERACTIVE RELAY SIMULATION METHODOLOGY

This novel closed-loop interactive relay simulation methodology combines the advantages of both the closed-loop and open-loop approaches. Fig. 1 shows the new closed-loop protection system simulation structure, where a relaying scheme for a transmission line is modeled.

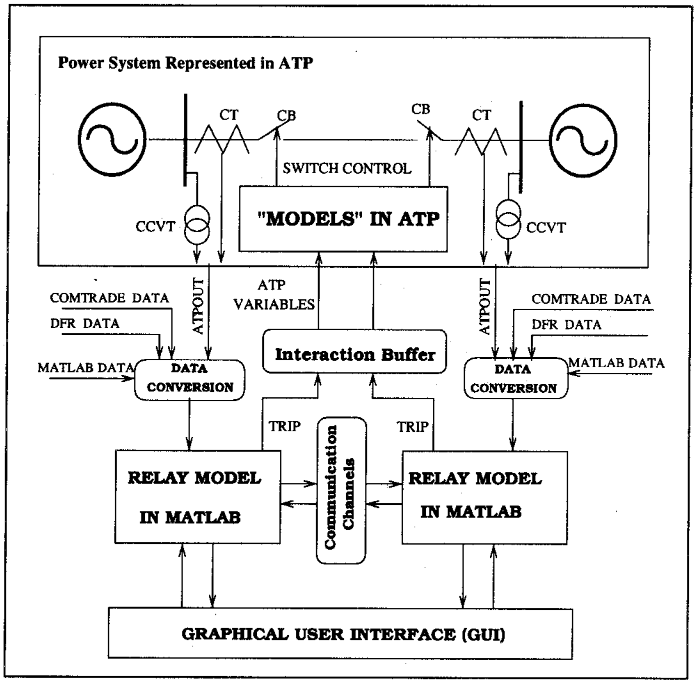

Fig. 1. Proposed New Interactive Protection System Simulation Structure

In the new approach, the power system model is represented in ATP [13]. The relay models can be realized using any high language or powerful software package such as MATLAB [15]. Unlike the open-loop approaches, the new simulation scheme provides a "feedback" path. Thus the relay trip or re-closing signals can be employed to open or close the circuit breakers in the ATP power system network model. The interaction between the power system transients and the responses of the modeled relays is achieved through an "interaction buffer". The "interaction buffer" could be implemented by a block of reserved shared computer memory. In order to achieve the interaction, both the ATP power system model and relay models should be able to read from and/or write to the " interaction buffer".

To accomplish this, a minor modification of the ATP program is needed. Two "foreign models" are added by modifying the file *mod001.f* of the ATP source codes [13]. One of the "foreign models" (called *CHECK_STATUS*) is used to check the *continuation* flag, and read in the *fault_detected* and *fault_cleared* flags from the "interaction buffer". If the *continuation* flag is set, the ATP simulation will continue. If the *fault_detected* flag is set, the ATP simulation mode will be changed to the single step mode. On the other hand, if the *fault_cleared* flag is set, the simulation mode will be changed back to the multiple step mode. The other foreign model (called *READ_TRIP_SIGNAL*) is used to read in the *trip signal* which is used to control switches.

In the single-step mode, the two "foreign models" are invoked every single step, thus any change in the trip signal will be fed back to the power system simulation immediately. However, more simulation time is required. In multiple-step mode, the "foreign models" are invoked once every N steps (N can be defined by the user). The change of any status is checked once every N steps. In this mode, the simulation time is reduced.

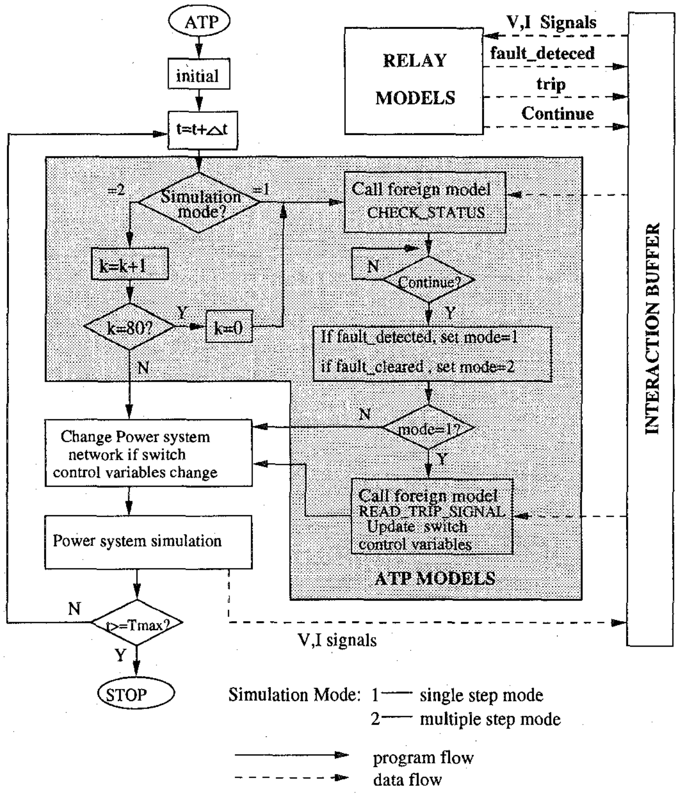

Fig. 2. Interactive Simulation Flow Chart

Fig. 2 shows details of the interactive simulation. In the MODELS section of the ATP input data case, the "foreign models" can be called as needed in either single time step or multiple time steps. Thus, the power system simulation can be run in single-step, multiple-step, or mixed mode (i.e. sometimes in single-step mode, sometimes in multiple-step mode) based on the information read from the "interaction buffer".

On the other hand, the relay models can read in the ATP simulated power system transient waveforms, sample by sample, immediately after they are available. Those samples are then filtered and utilized to update the relay response signals. If the trip or auto-reclosing signals are issued by the relay, the relay models will update this change in the "interaction buffer" immediately.

The relay response signals which are stored at the "interaction buffer" are checked by the "foreign models" of the ATP immediately to see if the circuit breaker status modification is required. If the modification is needed, after ATP MODELS card reads in the signals, the switch control variable in the ATP is changed, thus the switch (which represent the circuit breaker) status will be changed accordingly. After the modification, the ATP simulation will continue and new power system network configuration will be simulated.

Compared with the existing closed-loop simulation approaches, where only the single-step interaction mode is available, one of the main advantages of the new approach is that the interactive simulation is optimized since the simulation runs automatically in either multiple or single step mode according to the stage of the power system simulation. Thus the simulation will be more efficient. In addition, powerful software packages such as MATLAB can be used to model relay [15]. Therefore, relay model implementation will become easier and more efficient. Another advantage is that, compared with the built-in FORTRAN relay model approach, which requires the EMTP executables to be rebuilt when a new relay model is added, this approach only requires that ATP is recompiled and re-linked once to setup the interface. Once the interface is built, both EMTP power system model and relay models can "talk" to the "interaction buffer".

From Fig. 1 it can be noticed that the pilot schemes between different relays could be simulated easily. This can be simply done by setting up a communication channel in each relay model and taking it into account in the relay trip logic unit in the modeling.

In addition to the closed-loop interactive simulation ability, the new structure allows open-loop simulation using various kinds of input data as well. This can be achieved by disabling the "interaction buffer". The data formats that can be used in the open-loop simulation include digital fault recorder(DFR), common format for transient data exchange (COMTRADE) [16], MATLAB [15], or EMTP output data. Those data are normally pre-generated and stored in files.

Another feature is a friendly graphical user interface(GUI) that can be readily integrated. It is very important for an application software to have a friendly user interface. In the relay simulation applications, the GUI may be used to monitor the waveforms at different functional blocks inside the relay model. Further more, the GUI can be utilized to "re-design" relays (by selecting algorithms, hardware models), change relay settings, control the simulation, view simulation results, etc.

IV. MICROPROCESSOR-BASED RELAY MODELING

Because the new simulation approach allows relay model to be implemented in any high level language or software package, relay model realization could be more flexible and more detailed.

As an example, a methodology for modeling a microprocessor-based distance relay (MDR) is presented in this section [17]. To illustrate the advantages of having the flexibility to choose the most appropriate tools for relay modeling, multiple software packages and simulation approaches to obtain best results in modeling digital relay hardware and software are used. Fig. 3 shows the simplified block diagram of the main modules of the MDR. It consists of several functional modules representing hardware and software, such as analog signal path, output channels and protection algorithms. In order to simulate the relay performances precisely, it is essential to model all modules correctly. The data needed for relay modeling can be obtained from the manufacturer or the designer.

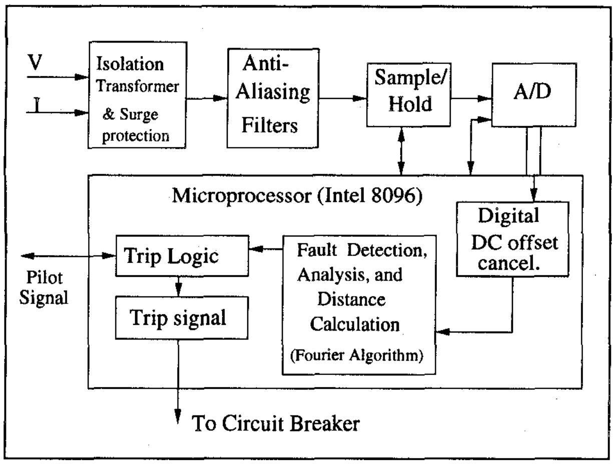

Fig. 3. Simplified MDR Relay Block Diagram

A. Analog Signal Path Modeling

As shown in Figure 3, the analog signal path includes modules such as isolation transformers, anti-aliasing filters, sample and hold, programmable gain amplifiers, and analog-to-digital converter (ADC). The analog signal path is the most difficult section to model. This is because these modules and the original signals in the physical relay are analog in nature, while the models and signals in the relay simulation need to be represented in digital formats. In order to model the characteristic of the analog signal path accurately, the Simulation Program with Integrated Circuit Emphasis (SPICE) is used to perform circuit simulation and the circuit parameters extraction when needed. SPICE is a powerful, general-purpose circuit analysis program extensively used to simulate analog circuits [18].

The isolation (auxiliary) transformers are used to provide the electrical isolation of the input circuit, as well as suitable low voltages and currents for the electronic components of the relay. In some electromechanical and solid state relays, the auxiliary transformers are designed by using gaped iron core in order to remove the DC offset of the input current. However, in the microprocessor-based relays, the auxiliary transformers do not have to be of non-gaped type, and the DC offset may be removed using digital filtering algorithms. Therefore, the auxiliary transformers can be modeled as ideal transformers which are implemented by scaling down the input signals according to the turn ratios of the transformers. Band-pass filters may be used to remove some of the DC component.

The MDR includes seven active low-pass Butterworth anti-aliasing filters (for 3 phase voltages and currents), which are used to band-limit the analog input signal prior

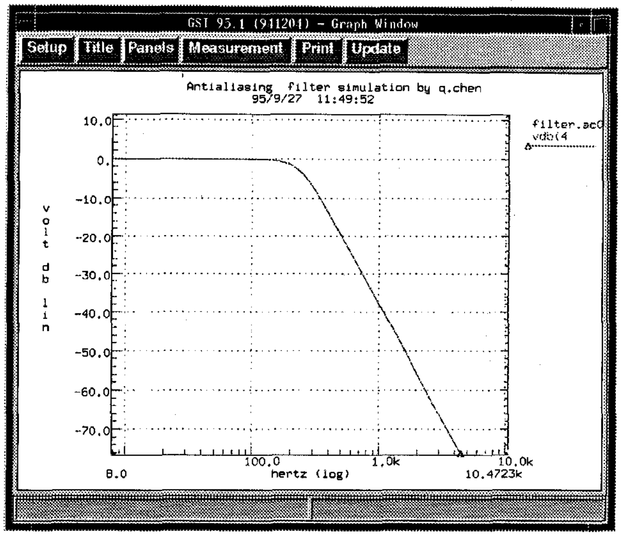

Fig. 4. SPICE Simulation Result of the Anti-aliasing Filter

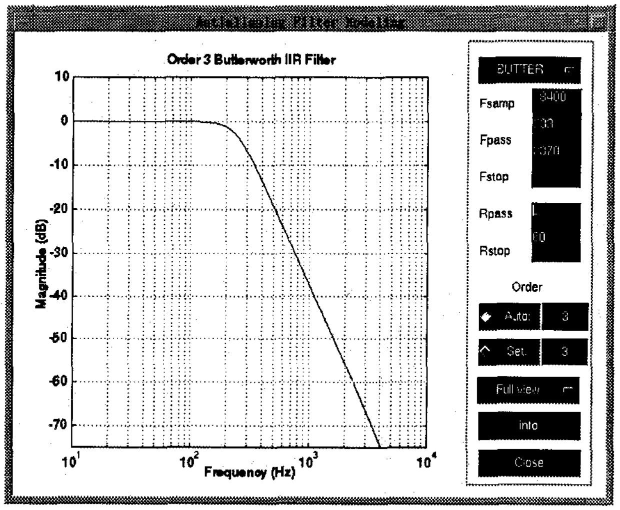

Fig. 5. Characteristic of the MATLAB Anti-aliasing Filter Model

to sampling and quantization. The filters are simulated in SPICE first using the circuit structure and component parameters provided by the manufacturer. The SPICE simulation result is shown in Fig. 4. From the figure, the characteristic of the anti-aliasing filter is extracted:

- Cutoff frequency(passband edge frequency): 232.97Hz at $-3db$
- Stopband edge frequency: 2370Hz at $-60db$
- Filter order: third-order filter, since the gain of the filter is attenuated at $-60db/dec$ which corresponds to 3rd order filter.

Based on the parameters extracted from the SPICE simulation results, the MATLAB anti-aliasing filter model can be easily designed. Fig. 5 shows the characteristic of a MATLAB implementation of a third-order Butterworth low-pass IIR (Infinite Impulse Response) filter model. Comparing Fig. 5 with Fig. 4, it is noticeable that the MATLAB model simulation result matches the one from the SPICE quite well.

The sample and hold circuit can be easily represented in MATLAB using interpolation and decimation operations. To model analog to digital converter(ADC), its main characteristics, such as resolution, conversion speed, and quantization error, should be taken into account if possible. The resolution of ADC can be modeled by using *FIX* or *ROUND* operation to map the input samples to digitized output. The ADC conversion speed can be modeled by adding time delay to the samples. The quantization error of the ADC is modeled by adding a random error in the range of $\pm\frac{1}{2}LSB$.

B. Relay Program Modeling

The relay program may be straight-forwardly modeled by transferring the relay program to the simulation environment. The relay program is stored in the EPROM, which is executed by the microprocessor to perform DC offset correction, phasor calculation, fault detection, fault analysis, distance calculation and zone checking. The algorithm to perform DC offset correction is based on [19]. In the program, an exponential decayed DC offset model is used. Thus, the DC offset can be removed by using the following expression:

$$I_c(K) = I(K) - \frac{I(K) + I(K - N/2)}{1 + exp(\pi/\tan\phi)}$$

Where:

I(K): present current sample
I(K-N/2): current sample taken half cycle earlier
N: number of samples per cycle
$I_c(K)$: the corrected value for I(K)
ϕ: line angle

The full cycle Fourier algorithm with a data window of 8 points is employed to calculate the phasors [20].

After the phasors are obtained, the fault detection and fault classification are performed. The apparent impedance of the relay is then calculated. The zone checking program will then compare the apparent impedance with the MHO settings and make the trip decision. The relay's MHO characteristics are implemented using a self-polarized voltage.

C. Relay Trip Logic

The MDR relay trip logic circuit is designed and implemented by using **AND, OR** and **NOT** logic gates. This digital circuit can be modeled well using **AND, OR** and **NOT** logic operation statements in any high level language.

D. Relay Model Validation

The relay model validation is required in order to perform further studies. The relay model can be verified by comparing the modeling results to the physical relay testing results [7], [9]. The parameters to be checked include the relay trip time and reach accuracy. Table II lists the response times and reach accuracy (zone 1) of both the relay testing [1], [2] and relay model simulation results.

In 12 out of 12 cases, the modeled relay has the same trip or no-trip response as the physical relay. The MDR model acts faster than the actual relay. One possible reason is the relay trip logic is modeled as ideal logic operation without taking into account the circuit delay. Another reason is that the relay algorithm in the actual relay is performed by INTEL8096 microprocessor while the algorithm simulation is done using SUN SPARC1000 workstation; and the later is much faster that the former. Taking these into account, if a 2.0ms delay is added, the response times agree better.

TABLE II
RELAY RESPONSE (MODEL VERSUS PHYSICAL RELAY)

Case Name	Fault Location	Fault Type	Actual Time (ms)	Model Time (ms)
sta50	50 %	AG	20.39	18.7
stb50	50 %	BC	20.75	19.1
stc50	50 %	ABC	22.78	19.7
std50	50 %	BCG	20.56	18.9
sta75	75 %	AG	28.47	25.7
stb75	75 %	BC	28.05	26.3
stc80	80 %	ABC	27.78	25.5
std80	80 %	BCG	28.34	26.7
sta90	90 %	AG	No Trip	No Trip
stb90	90 %	BC	No Trip	No Trip
stb95	95 %	BC	No Trip	No Trip
std95	95 %	BCG	No Trip	No Trip

V. THE SIMULATION STUDY EXAMPLE

This section illustrates how the combined benefit of having the interactive simulation feature and improved relay models can allow for quite an elaborate simulation study of relay performance.

A relay controlled power system simulation has been performed using the new simulation approach. A typical 345KV power system section is modeled in ATP. Fig. 6 gives the one-line diagram of the system. The line section of interest runs from STP substation to SKY substation.

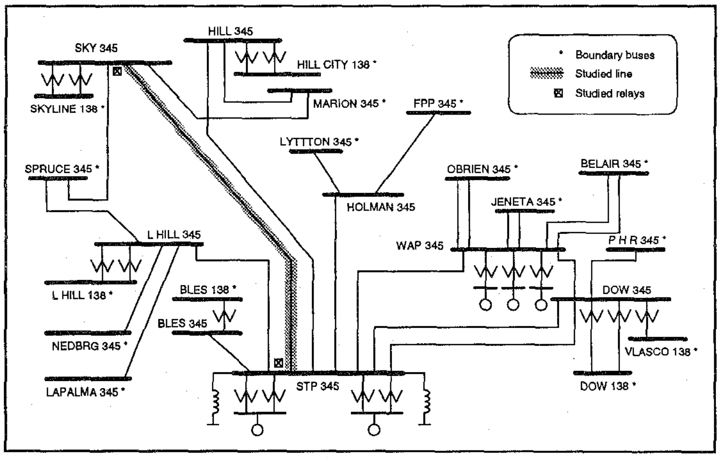

Fig. 6. Power System One-line Diagram

In order to investigate the influence of instrument transformers on signal distortion, the actual CTs and CCVT located at STP and SKY substations are modeled. EMTP-based CT and CCVT models developed at TAMU earlier [21], [22] are used in this study. The power system model was verified using both the steady state and transient state results.

The relays of interest are installed at two terminals of the STP—SKY line section. Fig. 7 shows the two terminal relay controlled power system simulation structure.

As an example, the power system ATP model, and the MATLAB relay models are implemented together. An AG fault located at 50 % of the STP-SKY line is simulated. Figures 8-10 show the simulation results for relay model #1(at STP terminal). Similar figures for relay model # 2 (at SKY terminal) can also be obtained.

Fig. 8 shows the simulated relay input voltage and cur-

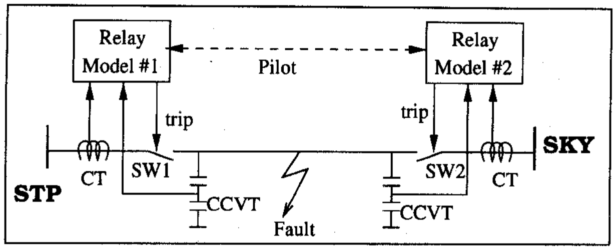

Fig. 7. Two Terminal Protection System Simulation Set-up

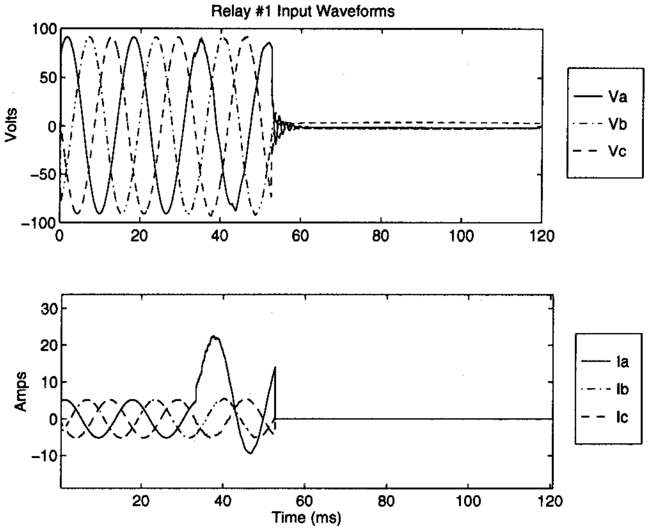

Fig. 8. Relay Model #1 Input Signals

rent waveforms. The fault occurred at the time of T=33.3 ms. Fig. 9 illustrates the internal waveforms of the relays. The relay picks up at T=52ms, thus the relay operating time is 18.7ms. Right after the trip signal was issued, it was stored in the interaction buffer and used to open the switch (Type 13) to clear the fault. It was also sent to the relay model #2 as a permissive underreach transfer trip signal.

Fig. 10 plots a R-X diagram of the impedance to the fault as seen by the relay #1. The trajectory is plotted only up to the point when the trip signal is issued. The relay settings are also shown. The zone 1 is set at 85 % of the line. Zone 2 is 150 % and zone 3 is 200%. A reverse zone is set at -150 %. From the R-X diagram, the trajectory of the fault impedance seen by the relay is clearly visualized. The fault location can also be roughly estimated from the figure.

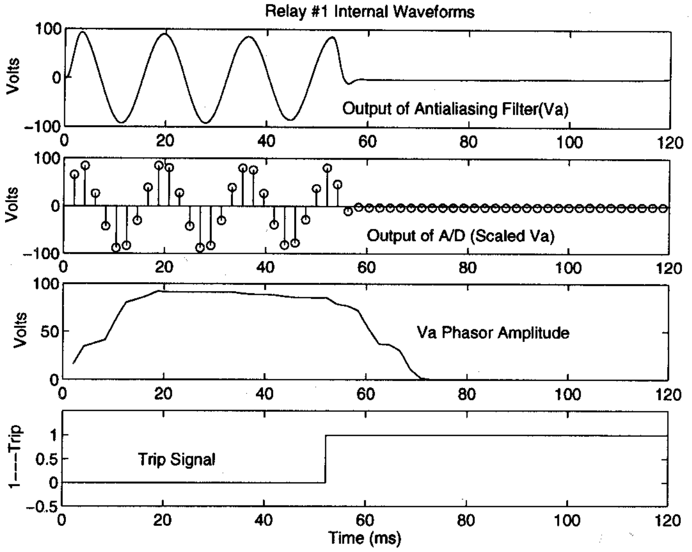

Fig. 9. Relay Model #1 Internal Waveforms

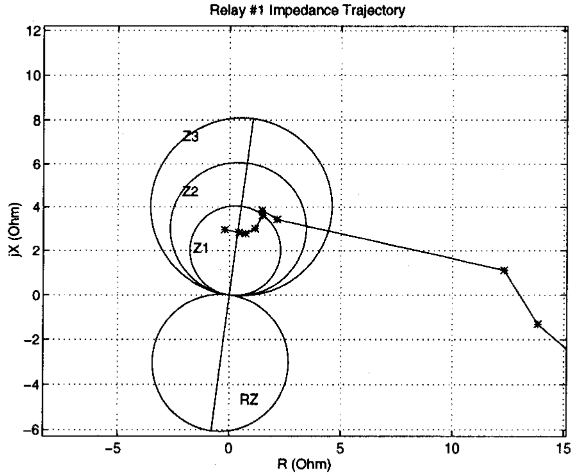

Fig. 10. Relay Model #1 R-X Diagram

The interaction between the power system model and the relay models was efficiently and accurately simulated in the study. The ATP simulation time step was $\Delta t = 0.02604ms$, which is corresponding to a sampling rate of 38400Hz for the relay input signals. The AG fault was applied at T=33.3 ms. When simulation was initiated, the ATP program was invoked to perform power system simulation at multiple-step mode. This was accomplished by invoking the *CHECK_STATUS* "foreign model" once every 80 time steps (2.0832ms). The power system simulation iterations were carried out in full speed for 80 time steps. During this period, the relay models read in the voltage and current waveforms and the fault detection program was used to detect the inception of fault. When the *CHECK_STATUS* model was called, the *continuation* flag and *fault_detected* flag was checked. If the *fault_detected* flag was set, the simulation mode would be changed to single-step mode until *fault_cleared* flag was set by the relays. In the single-step mode, the *CHECK_STATUS* and *READ_TRIP_SIGNAL* "foreign models" were invoked every single time step. These two "foreign models" would check and read in the *fault_cleared flag* and the relay trip signal when they were available. If relay had tripped, the trip signal would be used to control TYPE 13 switches to update the power system network.

Fig. 11 shows the simulation modes being used in the course of the simulation interaction. In the first stage, when no fault was detected by the relay, the multiple-step simulation mode was used. In this period of time, the interaction was activated every $80\Delta t$ (the number 80 can be defined by the user). Thus, less time was spent for the interaction in this stage. In the second stage, when there was a fault, the single-step interaction mode was used. Thus the relay trip signal can be examined every Δt. This optimal interaction scheme can save the overall simulation time.

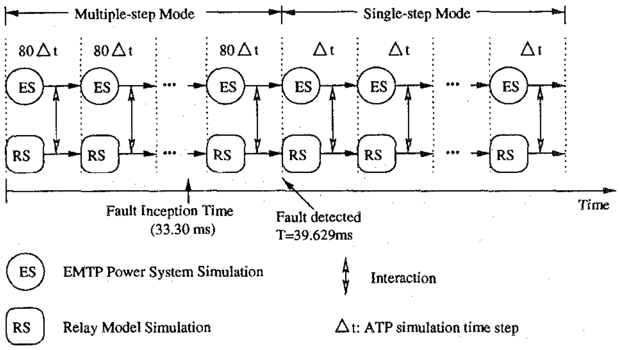

Fig. 11. Simulation Modes Used in the Interactive Simulation

From this example it can be seen that a relay controlled power system model can be readily implemented and simulated. The interaction between the relays and the power system as well as the coordination between different relays can be efficiently represented and studied.

VI. CONCLUSIONS

A new protection system simulation approach has been introduced in this paper. It combines the advantages of the existing closed-loop and open-loop simulation approaches. The new simulation structure uses an "interaction buffer" to simulate the interaction between power system and relays. The new simulation structure allows optimal interactive simulation in that it automatically selects either multiple or single step simulation mode according to the stage of the power system simulation. It also allows the relay model to be implemented in any high level language. Having the improved interactive simulation and ability to select the most appropriate simulation tools make the relay modeling and simulation more flexible, efficient and accurate.

VII. ACKNOWLEDGMENTS

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