실시간 전력계통 시뮬레이터를 이용한 보호계전모델 개발

論文
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Implementation and Verification of Distance Relay Models for Real Time Digital Simulator

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Abstract - This paper discusses how to implement and verify a software model of the digital relay that can be added to real time digital simulator(RTDS) model library and is then subjected to the same outputs as the actual relay. The software model is stand-alone and can be used with real relays. It is also possible to conduct interactive real-time tests when the system effects of the relay action need to be investigated. The characteristics of mho type and the quadrilateral type, which is commonly used in recently developed relays, are modeled in this paper. Single circuit line and double circuit line system are used for model verification. The transmission lines are each 100 km in length and are modeled as distributed parameter lines but not frequency dependent. The transmission lines in the single circuit system are modeled as ideally transposed line. The mutual coupling data with the parallel line was taken account in the transmission lines for the double circuit system. The main CTs and PTs are included and operated in their linear region during the tests. For the purpose of testing the relay model accuracy the faults have been applied at various points on the protected line. Its accuracy is assessed against theoretical values.

Key Words : Digital relays, Distance relay model, Real Time Digital Simulator, Capacitive Voltage Transformer

1. INTRODUCTION

In recent years, strong interest in applying protective relaying system to power system simulation has been appeared on the scene fromnumerous technical articles[1] because the need to increase the transmission capability of existing and new electrical networks is forcing the relay engineer to examine the performance of present and future relays than has been the case in the past. Especially the need to observe the transient response of the power system network adopting the high-speed relays is imminent.

The use of simulation software such as EMTP, EMTDC, PSS/E and EUROSTAG,which is commonly used to observe the response of a power system network, would be a satisfactory way to simulate a power system network if only the action of primary protection is considered. But if the system stability or the subsequent action of other relays on a parallel line is considered, then the effect of the primary relay trip must be fed back into the simulation. This requires other devices that are not widely available. Therefore it is desirable to have a model of the relay that can be included in the simulation. The simulation software mentioned above contains a group of relay models in its model library for its users[2-3]. Those models are intended to represent the general principles of relays and are not intended to exactly represent any particular product of any relay manufacturer. Rather, they can model the effects of actual relays given properly specified data and proper interpretation by the engineer. Many utilities already have complete EMTP models of their power system that have been verified against actual field data[4]. These models have been used for performance testing of new and existing protection schemes, studies on high impedance fault(HIF) in transmission line, the effects of DC-Offset and harmonics, optimal zone setting and so on.

However RTDS has no relay models in its model library becauseRTDS is originally invented for the test of the actual relay[5-7]. Therefore the need of relay models gradually increases among the users.

This paper describes the development and testing method for a software model of the digital relay that can be run on RTDS.

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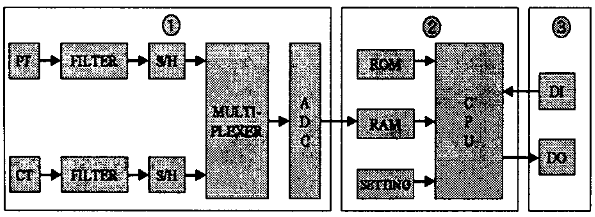
2. DEVELOPMENT OF RELAY MODEL

Most of protective relays were the electromechanical type or solid-state type, and these are still in wide use, but digital type designs are now in common. Although this trend continues, it may be a long time before all devices are completely replaced. In developing a software model for the electromechanical type relay and the solid-state type relay, it is very difficult to construct an accurate model. The primary reason is the lack of design data on which the model to be based. The second reason is the difficulty involved in fitting a digital model to a non-linear analogue device. On the contrary, in case of the digital relay, it is relatively easy to develop an accurate model because the protective relaying algorithms remain basically the same in spite of varying with different manufacturers and constantly changing. According to the trend and the above-mentioned reasons, digital type relays have been developed by user defined component(UDC) method for RTDS. The UDC method provides a tool that allows end users to develop theirown component models and run them on the RTDS just as another components. All the details related to linking them to the existing RTDS software are handled automatically by RTDS compiler. The software model of the relay developed by UDC method can be used interactively with the simulation running on after the relay action takes place.

The typicalarchitecture of digital relays is shown in Fig, 1. Generally, Digital relays are made up with three stages as follows.

① Analog-digital converting stage
② Calculation and decision stage
③Digital inputs and outputs stage



S/H : sampling holder　　ADC : analog-digital converter
SETTING : setting interface　　CPU : central processing unit
DI : digital input interface　　DO : digital output interface

Fig. 1 Typical architecture of digital relays

On the stage of analog-digital conversion(①) in Fig.1, The sampling holders, multi-plexer and A/D converter have not been modeled because all the input signals are already in digital. The auxiliary PTs and CTs have been regarded as operate in their linear region. The voltages and currents are taken through a low pass filter and a DC-Offset removal filter, then are processed in Discrete Fourier Transformation(DFT) to give the fundamental components in terms of sin and cosine components for passing on to next stage. The calculation and decision stage(②) in Fig.1 plays the most important role in the software model for the relay. This stage can be divided into two parts. The first part is responsible for the calculation of the impedance from the relay to the fault point using the fundamental components of voltages and currents. In order to correctly calculate the impedance to the fault point, the current input to the earth fault calculating elements is compensated by the residual current(3Io) of the protected line in the case of a single circuit and by the residual current of the protected line and residual current of the parallel line in the case of a double circuit line. The equations for ground fault are as follows[8].

$$Ior = Iar + Ibr + Icr \tag{1}$$
$$Ioi = Iai + Ibi + Ici \tag{2}$$
$$Iomr = Ia2r + Ib2r + Ic2r \tag{3}$$
$$Iomi = Ia2i + Ib2i + Ic2i \tag{4}$$
$$Kr' = \frac{Kr}{3} = \frac{Z0 - Z1}{3Z1} \tag{5}$$
$$Km' = \frac{Km}{3} = \frac{Zm}{3Z1} \tag{6}$$
$$Iar' = Iar + Kr'*Ior + Km'*Iomr \tag{7}$$
$$Iai' = Iai + Kr'*Ioi + Km'*Iomi \tag{8}$$
$$Da = Iar'^2 + Iai'^2 \tag{9}$$
$$Ra = \frac{Var*Iar' + Vai*Iai'}{Da} \tag{10}$$
$$Xa = \frac{Vai*Iar' - Var*Iai'}{Da} \tag{11}$$
$$Za = \frac{Va}{Ia + Kr'*Io + Km'*Iom} \tag{12}$$

where,
Va : phase 'a' voltage
Ia, Ib, Ic : phase currents of the protected line
$Ia2, Ib2, Ic2$: phase currents of the parallel line
Io : zero-sequence current of the protected line
Iom : zero-sequence curent of the parallel line
Kr, Kr', Km, Km' : compensation factor
$*r$: real part
$*i$: imaginary part
Z0 : zero-sequence impedance
Z1 : positive-sequence impedance
Zm : mutual impedance

Zb and Zc are calculated in the exactly same way.

The following equations[8] are used for impedance calculation of phase-phase fault.

$$Vabr = Var - Vbr \tag{13}$$
$$Vabi = Vai - Vbi \tag{14}$$
$$Dab = Iabr^2 + Iabi^2 \tag{15}$$
$$Rab = \frac{Vabr*Iabr + Vabi*Iabi}{Dab} \tag{16}$$
$$Xab = \frac{Vabi*Iabr - Vabr*Iabi}{Dab} \tag{17}$$

$$Zab = Rab + jXab = \frac{Vab}{Ia - Ib} \qquad (18)$$

where,

Vab : line-line voltage between phase 'a' and 'b'
Iab : line-line current between phase 'a' and 'b'
$*r$: real part
$*i$: imaginary part

Zbc and Zca are calculated in the exactly same way.

The other part is in charge of the decision as to whether the relay operates or not. If a fault occurs, the impedancemoves into the operating zones of the relay and then the tripping logic outputs a trip command. The operating zones of the relay represented on the R-X plane have a characteristic such as impedance, reactance, mho, quadrilateral and so on. The characteristic of quadrilateral type and mho type is commonly used in recently developed relays, so those have been modeledas the following. Fig. 3 and 4. Most of model's input parameters can be obtained directly from KEPCO's relay setting rule. The rest of input parameter are fixed or recommended by manufacturers.

The quadrilateral type and mho type model can be represented a variety of operation zone shape as their setting parameters are changed. So They can cover most of digital relay widely used in Korea such as DLP, M-DAR, MDT-A2, MDT-F and MXL1E.

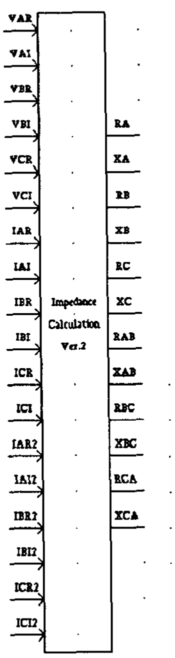
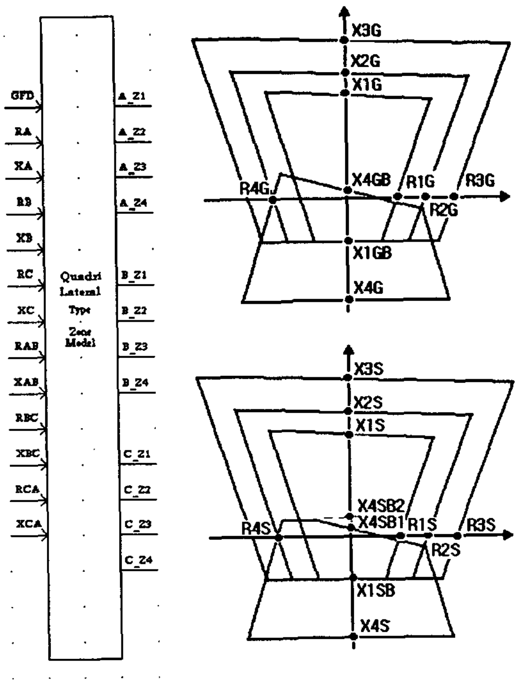
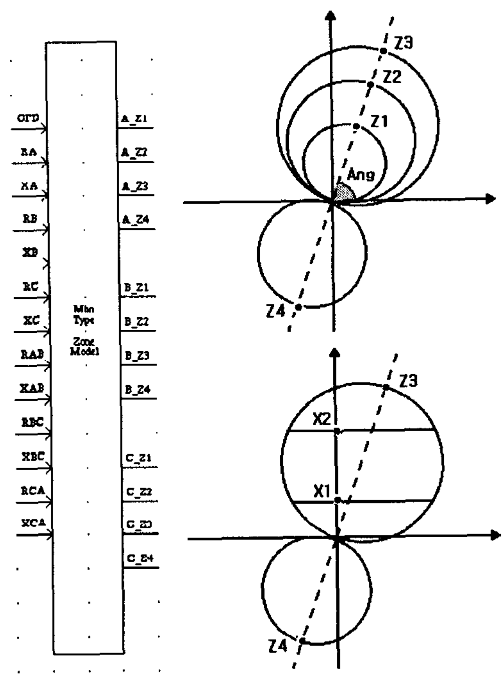


Fig. 2 Impedance Calculation Model Icon in RTDS



(a) Icon (b) Characteristic

Fig. 3 Quadrilateral Type Model in RTDS



(a) Icon (b) Characteristic

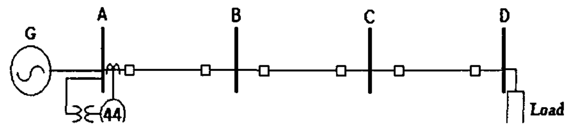
Fig. 4 Mho Type Model in RTDS

The last stage(③) is composed of digital input and digital output. This stage was not modeled because most of components needed on this stage have already been made as the library model of RTDS

3. SOFTWARE MODEL TESTS

One rack of RTDS is used for the software model tests. The rack consists of 10 3PC cards, 1 IRC card and 1 WIC card. The one line diagrams and data for the software model tests are shown in Fig. 5 and 6. Those systems are the154 kV system. The transmission lines are each 100 km in length and are modeled as distributed parameter lines but not frequency dependent. The transmission lines in the single circuit system are modeled as ideally transposed line. The mutual coupling data with the parallel line was taken account in the transmission lines for the double circuit system. The main CTs and PTs are included and operated in their linear region during the tests. Currents and voltages are low pass filtered and then are DC-Offset removalfiltered. Thereafter the signals are subjected to a DFT whose sampling rate is 32 samples per 60 Hz cycle. The phase of DFT is controlled by the frequency tracking routine that alters phase to maintain synchronism between the sampling rate and the system frequency. Then the results are used in various relay calculating functions such as impedance elements where Z=V/I type calculations are performed. The calculated values for Z are compared with theoretical values and are checked to verify whether they lie inside preset impedance zones and trip signals are issued if appropriate. The preset impedance of zone 1, 2, 3 and 4 is 85, 150, 250, 150 % of the protected line impedance

respectively. For the purpose of testing the relay model accuracy the symmetrical and unsymmetrical faults have been applied at 50, 75, 90, 150, 170, 250, 270 % of the protected line length from the relay location.



Gen. data :

V = 154 0 kV,

Z1 = 0.001 [ohm]

Z2 = Z0 = 0.0 [ohm]

Line data for each section :

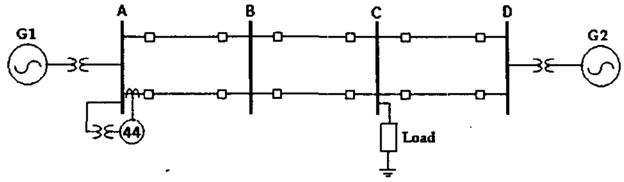
Z1=Z2=1.85+j37.67[ohm],

Z0=36.18+j122.77[ohm]

Load data :

120+j30[ohm]

Fig. 5 One line diagram of test power system (single circuit line)



Gen1. data :

V = 154 9.6 kV,

Z1 = 0.001 [ohm]

Z2 = Z0 = 0.0 [ohm]

Gen2. data :

V = 1540.0 kV,

Z1 = 0.001 [ohm]

Z2 = Z0 = 0.0 [ohm]

Line data for each section :

Z1=Z2=4.25+j28.9715[ohm],

Z0=21.38+j98.7843[ohm],

Zm = 17.123+j57.2101[ohm]

Load Data :

120+j30[ohm]

Fig. 6 One line diagram of test power system (double circuit line)

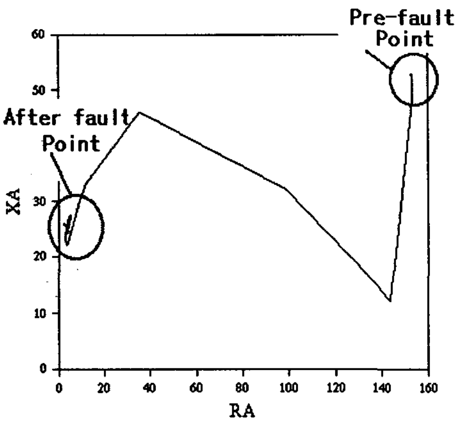
4. RESULTS OF MODEL TEST

With the fault points being changed, the variety of faults have been applied for the software model test. The software model's output values for the impedance from the relay location to the fault point are compared with theoretical values and then checked to verify whether trip signals from the software model are issued appropriately or not. The accuracy of impedance calculation is measured by means of comparison between the software model's outputs and theoretical values. The results of the comparison are summarized in Table 1. The maximum error((theoretical value-output value/ theoretical value)) is below about 1 %.

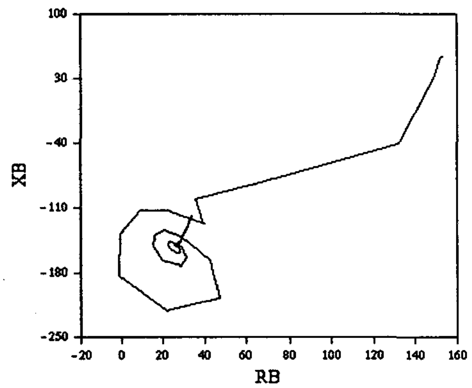
Table 1 Summary of tests

Error (%) / Fault Point (%)	Single Circuit		Double Circuit	
	Phase-Phase Fault	Ground Fault	Phase-Phase Fault	Ground Fault
50	0.53	0.01	0.3	0.4
75	0.86	0.14	0.37	0.09
90	0.6	0.44	0.4	0.4
150	0.71	0.09	0.17	0.13
170	0.5	0.5	0.3	0.6
250	0.84	0.01	0.23	0.05
270	0.97	0.01	0.41	0.35

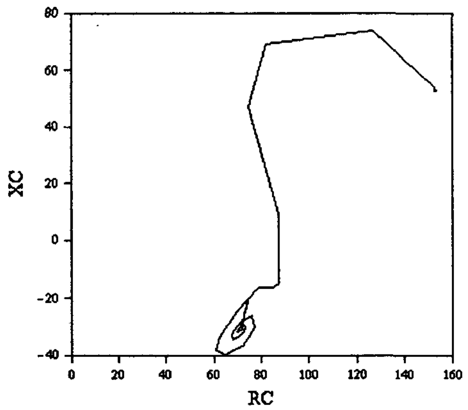
All the trip signals from the software model can be monitored in runtime. Figure 7 shows the impedance trajectories for phase "A","B","C" in RTDS/PSCAD run time window, when a ground fault is applied at phase "A", 85 % of the protected line length. X(Y) axis denotes real(imaginary) part of impedance in Fig. 7.



(a) Impedance Trajectories for phase 'A'



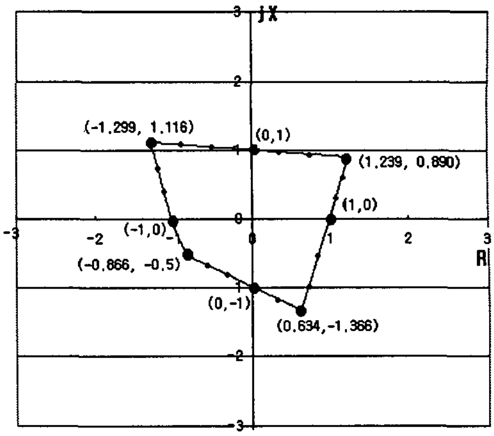
(b) Impedance Trajectories for phase 'B'



(c) Impedance Trajectories for phase 'C'

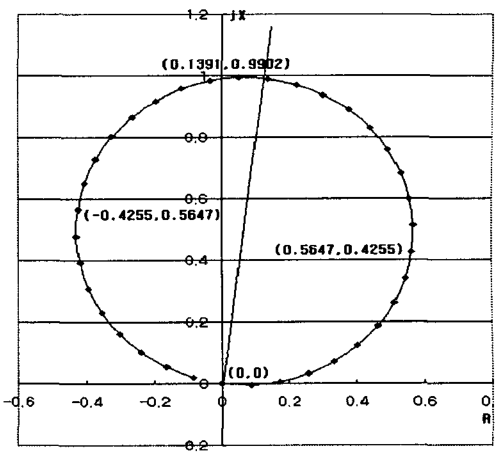
Fig. 7 Impedance Trajectories(Phase A, Ground Fault, 85%)

It is rather difficult to decide whether trip signals are issued or not, when the impedance trajectories move around the boundaries of each zone of relays. The quadrilateral type model and the mho type model shown in Fig. 3 and 4 are tested and verified under the conditions that the impedance inputs are very close to their zone boundaries. Figure 8 and 9 show pick-up points on R-X plane for zone 1 of quadrilateral and mho type model respectively. All the zones are verified in the same way. The models can operate properly unless the differences between the input values and the values on their zone boundaries are less than 1.0e-4.



Forward & backward reactance angle = 5 [deg]
Forward right & left blinder angle = 75 [deg]
Backward right & left blinder angle = 75 [deg]
Zone 1 resistance = 1.0 [ohm]
Zone 1 reactance = 1.0 [ohm]
Zone 1 backward reactance = 1.0 [ohm]

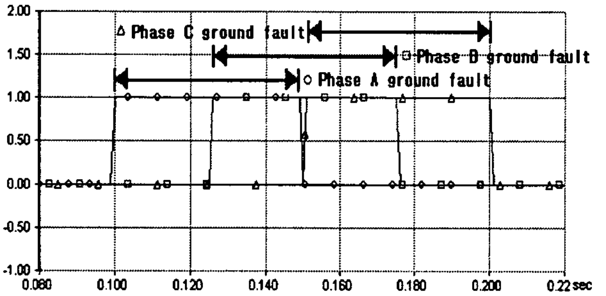
Fig. 8 Pick-up points on R-X plane for quadrilateral type model. (Zone 1)



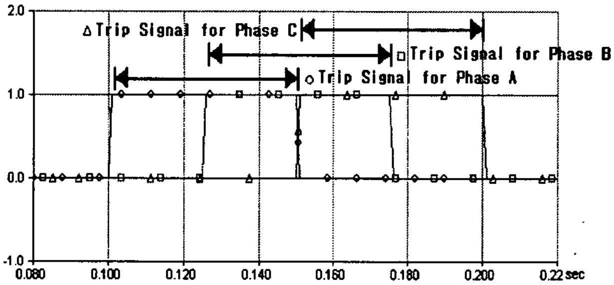
Characteristic angle : 82 [deg],
Zone 1 Imp = 1.0 [ohm]

Fig. 9 Pick-up points on R-X plane for mho type model. (Zone 1)

With the fault phases, types and applying orders being changed at regular intervals, the variety of faults have been applied for the software model test and then checked to verify whether trip signals are issued from the models appropriately or not, which are connected with the fault-related phases. Figure 10 shows trip signals which are issued by quadrilateral type model, when ground faults are applied on phase "A","B","C" of single circuit line shown in Fig.5 in turn at 25 msec intervals. Each fault lasts 50 msec. It takes about 5.0e-2 msec for the software model to issue trip signals, when the faults are applied.



(a) Fault applying signals



(b) Trip signals

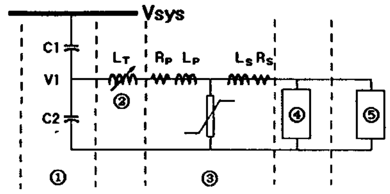
Fig. 10 Fault applying signals and trip signals(Phase A,B,C, Ground Fault, 25msec intervals)

The results of mho type model are almost same.

4. CASE STUDY

A. SIMULATION RELAY PERFORMANCE DURING CVT TRANSIENTS

Capacitive Voltage Transformers(CVT) as shown in Fig. 11 are commonly used in high-voltage transmission line. CVT has been worked satisfactorily with conventional relays for many years. However, as the requirement for faster protective relays grows, so doesthe concern over the poor transient response of some CVT for certain system conditions. Poor CVT transient response causes the distance relay to overreach. The burden and ferroresonance-suppression circuit of CVT alsoaffect the performance of distance relaying.



① Capacitive divider stack
② Tuning reactor
③ Step-down Transformer
④ Ferroresonance-suppression Filter
⑤ Burden

Fig. 11 Generic CVT structure

The simple system as shown in Fig.12 is built with CVT and distance relay model to determine the performance of proposed distance relay model during CVT transients. These tests are performed under different conditions because the transient response of CVT is affected by system impedance ratios, fault locations and fault resistance.

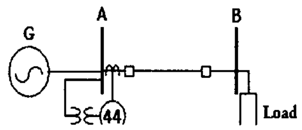


Fig. 12 One line diagram of study system

These kinds of tests are very useful to the relay engineer but it is very hard and dangerous to test with real devices because of the ferroresonance.

B. RESULTS

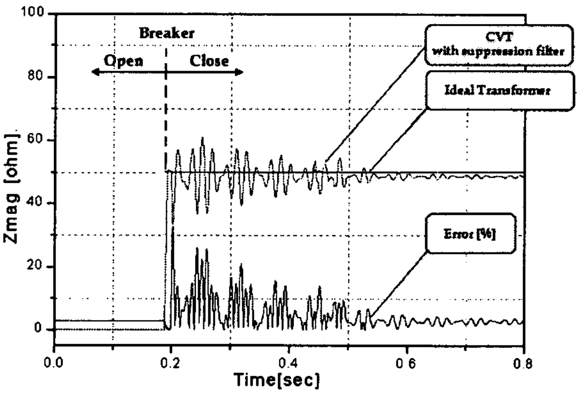


Fig. 13 The magnitudes of impedance during CVT transients

Figure 13 shows the calculated impedance of the distance relay model during CVT transients. The active ferroresonance-suppression circuit is adopted. The circuit acts like a band-pass filter and thereby introduces extra time delay in the CVT secondary output. When a fault is applied at the end of the radial line, relays can not pick up on time due to CVT transient errors.

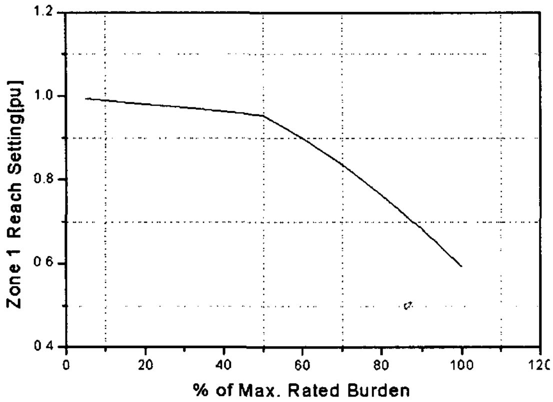


Fig. 14 Distance Relay Performance as a function for CVT Burdens

Figure 14 shows the distance relay performance as a function of CVT burden. The CVT transient characteristic is influenced by the magnitude and angle of the connected burden. Solid-state and digital relays have very small burden. The burden of these relays is nearly resistive. When using a CVT, the relay engineers need to calculate the total burden of all devices connected to the CVT and make sure the burden is not excessive to assure proper distance relay protection.

5. CONCLUSION

This paper describes how to implement and verify the software distance relay model that can be running on RTDS(Real Time Digital Simulator). They can operate properly around their zone boundaries. The maximum error of impedance calculation is below about 1 % and the total operation time is about 5.0e-2 msec. It is possible to represent protection system effectively on RTDS because the software model is stand-alone and can be used with real relays. It is also possible to conduct interactive real-time tests when the system effects of the relay action need to be investigated.

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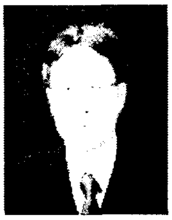

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