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Design and Prototype Implementation of an Adaptive Mho Distance Relay by the KU Method

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ABSTRACT

This paper presents the design, simulation and implementation of an adaptive mho distance relay to compensate during a phase-to-phase fault with fault resistance using the KU method. The phase-to-phase fault with fault resistance occasionally produces a trajectory of impedance outside the zone of the distance relay protection. Therefore, in this case, the distance relay will not send the trip command to the circuit breaker. This paper presents an analysis of three zones with adaptations to the mho distance relay to compensate during a phase-to-phase fault with fault resistance in a single circuit (radial) transmission line. This new concept was simulated using Matlab/Simulink and implemented using Dspace (DS11104). The prototype adaptive distance relay was tested in the laboratory using the relay equipment, Freja300 and the results analyzed and discussed.
Key words: distance relay, adaptive distance relay

INTRODUCTION

In general, short-circuit protection is provided by distance protection. Its mode of operation is based on the measurement of the voltage and current, which are used to calculate the impedance of the circuit. In the classic case, this impedance is proportional to the distance to fault. A distance relay effectively measures the impedance between the relay location and the fault. For a fault at the remote end of the line, the voltage at the local relay equals the current multiplied by the impedance of the line, i.e. IZ. Therefore, the ratio of the voltage to the current measured at the relay equals the impedance of the line, Z (Cook, 1985). Since the ratio V/I is proportional to the line length between the relay and the fault, the ratio V/I is, therefore, the impedance to the fault (Saengsuwan, 1999). A distance relay is designed to operate only for faults occurring between the relay location and the selected point and to remain stable for all faults outside this region or zone. The first zone is normally set between 85 to 90% of the protected line, the reach of the second zone is generally set between 120 to 150% of the protected line and the third zone of protection usually extends to 150% of the next line section (Ziegler, 1999). This time-stepped distance scheme ensures adequate discrimination for faults that may occur between different line sections. The first zone operates with no intentional delay time, the second zone with approximately 300-500 milliseconds delay time and the third zone has a delay time of approximately 1000 milliseconds (Horowitz and Phadake, 1992).

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The phase-to-phase fault with fault resistance occasionally produces a trajectory of impedance outside the zone of the distance relay protection. Therefore, in this case, the distance relay will not send the trip command to the circuit breaker. This paper presents an analysis of three zones with an adaptation of the mho distance relay to compensate during the phase-to-phase fault with fault resistance in a single circuit (radial) transmission line. This paper solved the problem of the mho distance relay mentioned above. The method used is called the "KU Distance Relay".

General operation of the mho distance relay

The mho distance relay is currently widely used. Figure 1 shows the general characteristics of the mho distance relay *Z* (Phadake, 1988), which is suitable for a phase fault and low-resistance fault protection. However, in the case where there is high fault resistance, the impedance is outside the zone of protection and the distance relay does not trip.

The impedance equations for the distance relay at a bus during the phase-to-phase fault are shown in Table 1 (Ziegler, 1999). A distance relay is designed to operate only for faults occurring between the relay location and the protection line and to remain stable for all faults outside this region or zone.

A radial transmission system is shown in Figure 2, with a phase-to-phase fault having a resistance of R_F. The impedance at the relay is described by Equations 1 to 4:

$$Z_{BC} = \frac{E_B - E_C}{I_B - I_C} \quad (1)$$

$$E_{BC} = E_B - E_C = 2(R_L \cdot I + jX_L \cdot I) + R_{F(BC)} I \quad (2)$$

$$I_C = -I_B = I \quad (3)$$

$$Z_{BC} = \frac{2(R_L \cdot I + jX_L \cdot I) + R_{F(BC)} \cdot I}{2I} = R_L + jX_L + \frac{R_{F(BC)}}{2} \quad (4)$$

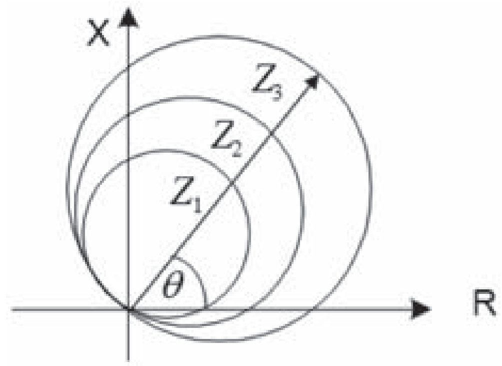

Figure 1 Mho characteristics.

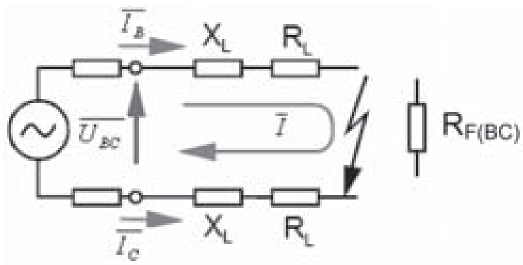

Figure 2 Phase *BC* short-circuit with a fault resistance (single-ended infeed).

Table 1 The impedance equations for a phase-to-phase fault.

Type of Faults	Impedance equations
AB, *AB* to *G*	$\frac{E_a - E_b}{I_a - I_b}$
BC, *BC* to *G*	$\frac{E_b - E_c}{I_b - I_c}$
CA,*CA* to *G*	$\frac{E_c - E_a}{I_c - I_a}$

MATERIALS AND METHODS

Simulations

In this paper, the Matlab/Simulink system was used for simulations. Figures 3 and 4 show the model of the transmission line used in the simulation and the transmission line model in MATLAB/Simulink, respectively. The circuit of the transmission line system for simulation has a setting value for the relay at the boundary of zone

1 ofs 8.71+j26.69 Ω, for zone 2 of 12.29+j37.68 Ω and for zone 3 of 22.54+j69.08 Ω (Dechphung and Saengssuwan, 2007). The impedance equations of the distance relay used for calculating the impedance of the phase-to-phase fault are shown in Table 1. The distance relay is installed at bus-1 and the setting value of the mho relay is shown in Table 2. The impedance of the phase-to-phase fault with a fault resistance is 50 Ω ($R_{F(Phase\ to\ Phase)}$ =50 Ω) as shown in Table 3.

The simulations fixed the starting time of the fault at 15 milliseconds and tested all types of phase-to-phase fault at the same time with the output results stored (m-file). The voltages and currents of all three phases were used to calculate the impedance of the fault using only a fundamental frequency (50 H_z) and a sampling rate of 1 kH_z. Using Fourier analysis, the Fourier series is represented by Equation 5:

$$f(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty} a_n \cos(n\omega t) + b_n \sin(n\omega t) \qquad (5)$$

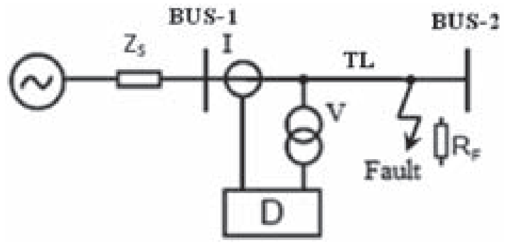

Figure 3 Model of the transmission line for simulation.

for $$a_n = \frac{2}{T}\int_{t-T}^{t} f(t)\cos(n\omega t)dt$$

$$b_n = \frac{2}{T}\int_{t-T}^{t} f(t)\sin(n\omega t)dt$$

$T = 1/ f_1$; f_1 is the fundamental frequency

From Equation (4), the impedance of the transmission line with $R_{F(Phase\ to\ Phase)}$ is.

Characteristics of mho distance relay in the case of a non-adaptive *R-X* diagram

Simulation of the characteristics of the mho distance relay for the phase-to-phase short-circuit using the MATLAB/Simulink program is shown in Figure 4. Assuming that phase *AB* short circuits at 85% of the line length, the trajectory impedance of the *AB* faults without fault resistance

Table 2 Setting values used for the mho distance relay.

	Z (Ω)	Angle (°)	R_F/phase (Ω)
Zone 1	28.08	71.92	25
Zone 2	39.64	71.92	25
Zone 3	72.67	71.92	25

Table 3 Impedance of transmission line with $R_{F(Phase\ to\ Phase)}$ (50 Ω).

	Z (Ω)	Angle (°)
Zone 1	42.99	38.37
Zone 2	53.01	45.29
Zone 3	83.86	55.45

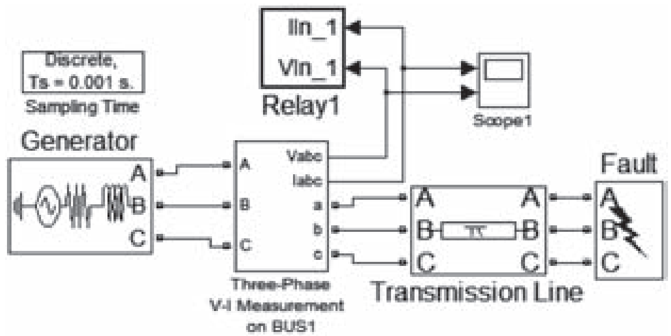

Figure 4 Transmission line model in the MATLAB/Simulink.

($R_{F(Phase\ to\ Phase)}$ = 0 Ω) in zone 1 and the non-adaptive characteristic of the mho distance relay are shown in Figure 5. The simulation results of the proposed system without fault resistance ($R_{F(Phase\ to\ Phase)}$ = 0 Ω) are shown in Table 4. The fault display showed the correct value for the tripping zone because the impedance equation used was (1) and the apparent trajectory impedance was inside the zone setting. However, the trajectory impedance and the simulation result of *AB* faults with fault resistance ($R_{F(Phase\ to\ Phase)}$ = 50 Ω) is shown in Figure 6 and Table 5 respectively. In this case, the fault display showed an incorrect value for the tripping zone because the impedance equation used was (4) with the apparent trajectory impedance included with the fault resistance. As the trajectory impedance could fall outside the zone setting (depending on the fault resistance value), this could result in both errors appearing in the fault display of the distance relay and thus the control engineer would analyze a fault error.

Adaptive mho distance relay

The fault component of the power system is an uncontrolled parameter, which is influenced by many conditions, and can be made up of fault

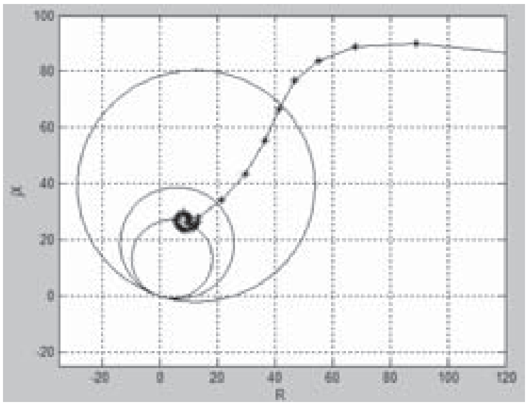

Figure 5 Trajectory impedance of the *AB* faults ($R_{F(Phase\ to\ Phase)}$ = 0 Ω) in zone 1without any adaptive characteristic of the mho distance relay.

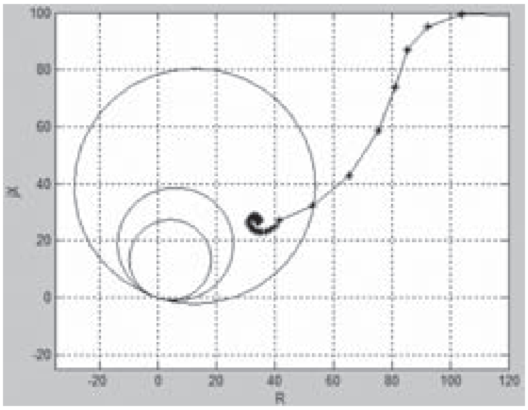

Figure 6 Trajectory impedance of *AB* faults ($R_{F(AB)}$ = 50 Ω) in zone 1 without any adaptive characteristics of the mho distance relay.

Table 4 Faults display of the mho distance relay at $R_{F(Phase\ to\ Phase)}$ = 0 Ω without any adaptive characteristics.

Type & zone	Fault display								
of fault	*ABZ* 1	*BCZ* 1	*CAZ* 1	*ABZ* 2	*BCZ* 2	*CAZ* 2	*ABZ* 3	*BCZ* 3	*CAZ* 3
AB zone 1	**TRIP**								
BC zone 1		**TRIP**							
CA zone 1			**TRIP**						
AB zone 2				**TRIP**					
BC zone 2					**TRIP**				
CA zone 2						**TRIP**			
AB zone 3							**TRIP**		
BC zone 3								**TRIP**	
CA zone 3									**TRIP**

arc resistance. The effect of fault resistance at the fault location is generally to reduce the effective reach of the distance relay. This paper presents an adaptive characteristic of the mho distance relay during the phase-to-phase fault. This adaptive characteristic of the mho distance relay extends the zone of protection by: 1) dividing the zone of protection using the impedance line into two parts, parts A and B, as shown in Figure 7; 2) when the fault resistance is found, detecting that the measured line angle is less than the setting angle by 5 degrees and the impedance stays in the new protection zone for more than 5 ms, then the protection zone is extended beyond the *R*-axis to the right, equal to the value of the compensating fault resistance (this setting value or $R_{F\_Setting}$ is 25 Ω); 3) drawing the lines as follows. The first line starts at the origin (point 1) and goes parallel to the *R*-axis to point 2. Then, the second line is drawn from the setting value of the impedance or point 3 parallel to the *R*-axis to point 4. This adaptation produces a delay time of 1 second to compensate for the operating time in zone 3 and for the adaptive mho distance relay to return to the mho distance relay (Dechphung and Saengssuwan, 2008).

Next, the phase-to-phase fault impedance with fault resistance can be calculated in (4) with the fault resistance set at 50 Ω and the relay can be set using the improved characteristics of the mho distance relay to compensate. It has been extended by inserting two straight lines in the *R-X*

Table 5 Faults displayed by the mho distance relay at $R_{F(Phase\ to\ Phase)}$ = 50 Ω without any adaptive characteristics.

Type & zone	Fault display								
of fault	*ABZ* 1	*BCZ* 1	*CAZ* 1	*ABZ* 2	*BCZ* 2	*CAZ* 2	*ABZ* 3	*BCZ* 3	*CAZ* 3
AB zone 1							**TRIP**		
BC zone 1								**TRIP**	
CA zone 1									**TRIP**
AB zone 2							**TRIP**		
BC zone 2								**TRIP**	
CA zone 2									**TRIP**
AB zone 3									
BC zone 3									
CA zone 3									

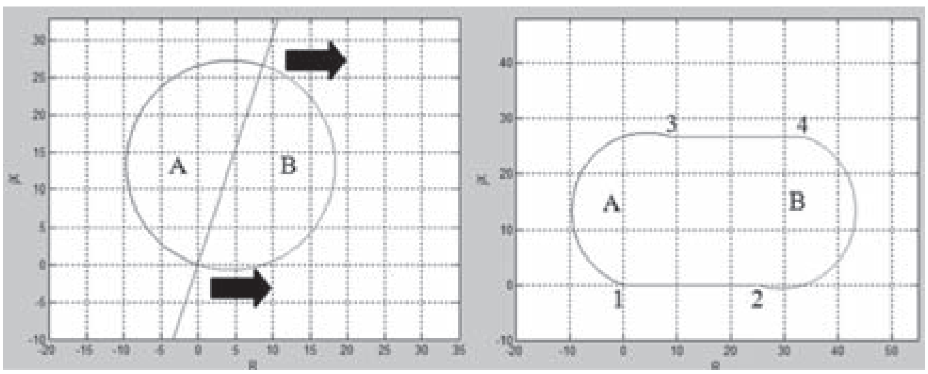

Figure 7 The method for improving the characteristic of distance relay.

diagram of the mho distance relay. Figures 8, 9 and 10 show the trajectory impedance of the phase-to-phase faults with the fault resistance of 50 ohms in boundary zone 1, zone 2 and zone 3, respectively, with the adaptive characteristic of the mho distance relay. The simulation results of all phase-to-phase faults are shown in Table 6.

Implementation

Simulation of the adaptive mho distance relay was carried out using the compensation of the phase-to-phase short circuit with fault resistance. This new concept was called the KU Distance Relay and was modeled with Dspace (DS11104). In Matlab/Simulink, this consisted of the three voltage inputs based on the voltage outputs from the relay test system (Freja300) and three current inputs based on the current output of the relay test system (Freja300). DAC as the analog voltage output for the checking all inputs of distance relay by digital scope (at sampling rate 1 kH_Z), digital output as the digital output distance relay to show the tripping command of distance relay, mathematics block as the mathematics equation for calculated fault, create the protection zone and the tripping output of distance relay, etc. This new algorithm was burned in Dspace (DS11104) from Matlab/Simulink using Ctrl-C on the keyboard. The circuit of the distance relay is shown in Figure 11. DS11104 is new hardware including the adaptive mho distance relay within the new algorithm. DS11104 was selected because it was easy to reliably burn the software from Matlab/Simulink, at very high speed (in real time) for system protection. The adaptive mho distance relay with DS11104 was tested with Freja300 (relay testing system). DS11104 and Freja300 are shown in Figure 12.

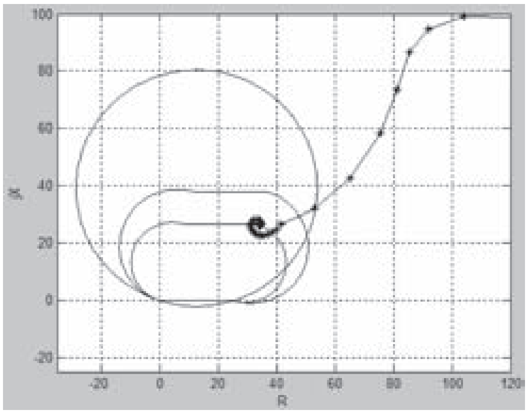

Figure 8 Trajectory impedance of the *AB* faults ($R_{F(AB)}$ = 50 Ω) in zone 1 with the adaptive characteristics of the mho distance relay.

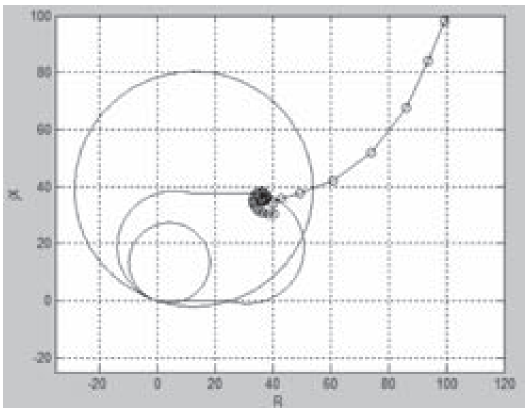

Figure 9 Trajectory impedance of the *BC* faults ($R_{F(BC)}$ = 50 Ω) in zone 2 with the adaptive characteristics of the mho distance relay.

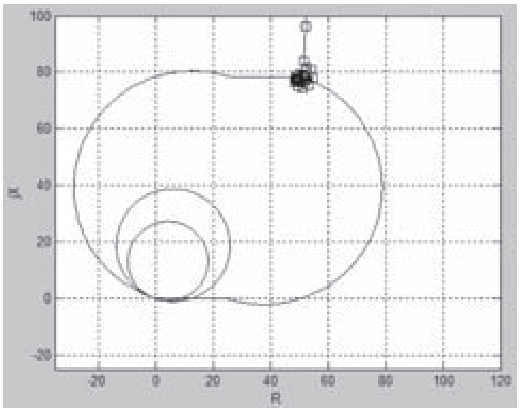

Figure 10 Trajectory impedance of the *CA* faults ($R_{F(CA)}$ = 50 Ω) in zone 3 with the adaptive characteristics of the mho distance relay.

Table 6 Faults display for the adaptive mho distance relay at $R_{F(Phase\ to\ Phase)} = 50\ \Omega$.

Type & zone	Fault display								
of fault	*ABZ* 1	*BCZ* 1	*CAZ* 1	*ABZ* 2	*BCZ* 2	*CAZ* 2	*ABZ* 3	*BCZ* 3	*CAZ* 3
AB zone 1	**TRIP**								
BC zone 1		**TRIP**							
CA zone 1			**TRIP**						
AB zone 2				**TRIP**					
BC zone 2					**TRIP**				
CA zone 2						**TRIP**			
AB zone 3							**TRIP**		
BC zone 3								**TRIP**	
CA zone 3									**TRIP**

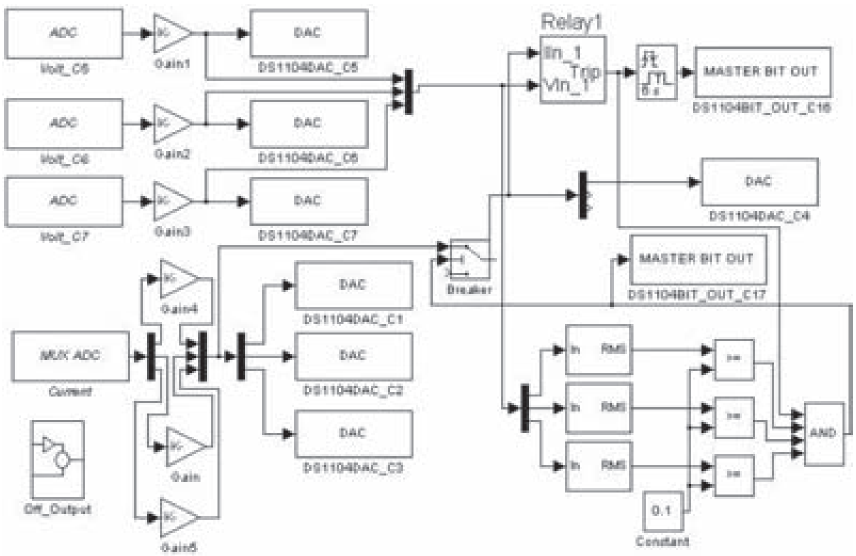

Figure 11 The circuit in MATLAB/Simulink burned in Dspace (DS11104).

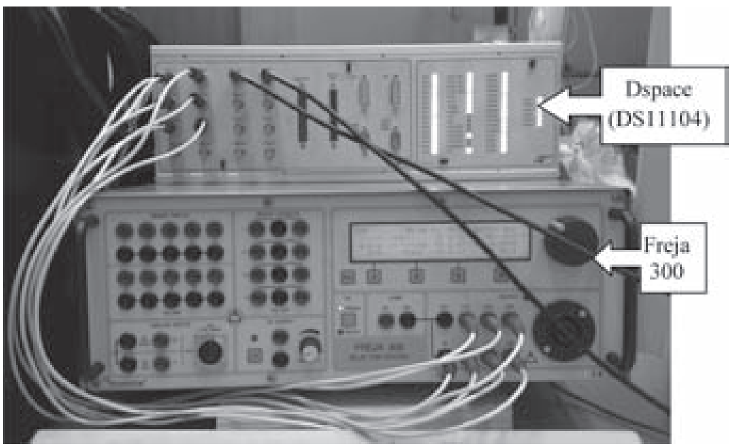

Figure 12 The Dspace (DS11104) and Freja300.

RESULTS AND DISCUSSION

According to the radial of the transmission line shown in Figure 3, all the voltages and currents at the relay location (bus-1) are extracted and fed into the mho distance relay algorithm. However, the fault in the case of a phase-to-phase fault with fault resistance is a trajectory of impedance outside the zone of the *R-X* diagram and the circuit breaker does not trip. The "KU Distance Relay" in the case simulated using MATLAB/Simulink or in the case implemented with Dspace (DS11104) is presented based on an analysis of the three zones adaptive characteristics of the *R-X* diagram of the mho distance relay for fault resistance compensation of the phase-to-phase fault in a radial transmission line. This proposed method solved the problem of the fault displays and the tripping zone as mentioned above. The result of the simulation of the adaptive mho distance relay (KU Distance Relay) is shown in Table 6. The results in Table 7 show a significant improvement in the operation of the mho distance relay using the adaptive KU method, with hardware (Dspace DS11104) in the case of a phase-to-phase fault with a fault resistance up to 50 Ω.

CONCLUSION

The proposed method can be used to solve the error in the fault display and tripping zone in the case of a phase-to-phase fault with fault resistance. The KU Distance Relay is appropriate for applications involving a radial transmission line and a phase-to-phase fault with and without fault resistance. The proposed KU distance relay offers an extension of the normal mho characteristics during a phase-to-phase fault with fault resistance and provides the correct tripping

Table 7 Faults display of the adaptive mho distance relay.

Type & zone of fault, $R_{F(Phase\ to\ Phase)}$	Fault display								
	AB Z 1	*BC* Z 1	*CA* Z 1	*AB* Z 2	*BC* Z 2	*CA* Z 2	*AB* Z 3	*BC* Z 3	*CA* Z 3
AB zone 1, 0 Ω	**TRIP**								
BC zone 1, 0 Ω		**TRIP**							
CA zone 1, 0 Ω			**TRIP**						
AB zone 2, 0 Ω				**TRIP**					
BC zone 2, 0 Ω					**TRIP**				
CA zone 2, 0 Ω						**TRIP**			
AB zone 3, 0 Ω							**TRIP**		
BC zone 3, 0 Ω								**TRIP**	
CA zone 3, 0 Ω									**TRIP**
AB zone 1, 50 Ω	**TRIP**								
BC zone 1, 50 Ω		**TRIP**							
CA zone 1, 50 Ω			**TRIP**						
AB zone 2, 50 Ω				**TRIP**					
BC zone 2, 50 Ω					**TRIP**				
CA zone 2, 50 Ω						**TRIP**			
AB zone 3, 50 Ω							**TRIP**		
BC zone3, 50 Ω								**TRIP**	
CA zone3, 50 Ω									**TRIP**

zone and display zone. The new concept was implemented as the KU Distance Relay with Dspace (DS11104) and tested using a relay test system (Freja300), with the results shown in Table 7. A comparison of the simulation using Matlab/ Simulink with the hardware using the KU distance relay indicated the two systems produced identical results. The drawback of the KU distance relay occurs when it is applied to a complicated circuit of a transmission line, since the contribution of current from another source will cause an error in the calculation of the impedance using this method.

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