Mho Relay for Protection of Series Compensated Transmission Lines

A. B. Shah, V. K. Sood, O. Saad

***Abstract*--This paper presents the design of a Mho relay model for the protection of two parallel 500 kV, 280 km long transmission lines. The transmission lines are 40% compensated with fixed series capacitors, installed at the remote end of the lines. The Mho relay model is tested with this system using the EMTP-RV simulation package. The residual current compensation algorithm is used to compensate for the error in the impedance measurement and detect fault location under earth fault conditions. The algorithm detects faults by measuring and comparing phase angles between voltage and current signals through a phase comparator, using four specially shaped characteristics (three forward Zones and one reverse Zone) and applying appropriate logic functions. This paper presents the simulation results for improving the measuring accuracy of distance protection under various fault types and fault locations.**

***Keywords*: Series-compensated line, distance relay algorithm, transmission line protection, EMTP-RV simulation.**

I. Nomenclature

R0, R1 = Zero and positive sequence resistance respectively of the protected line,
L0, L1 = Zero and positive sequence inductance respectively of the protected line,
I_{ctp} = Primary current of the current transformer (CT),
I_{cts} = Secondary current of the CT,
V_{cvtp} = Primary voltage of the capacitor voltage transformer (CVT),
V_{cvts} = Secondary voltage of the CVT,
Z_{line} = Impedance of the line,
Z_{angle} = Angle of the line impedance,
t_{zone} = Zone delay time,
I_{comp} = Compensation current,
I_{pn} = Phase current,
I_0 = Residual current (Zero sequence current),
k_c = Conventional average compensation factor,
k_{mag} = Magnitude compensation,
k_{rad} = Angle compensation,
ZR1, ZR2, ZR1a, k_1, k_2, θ_1, θ_2, α_1, α_2 = Comparator design constants [9],
ZR11, ZR12 and ZR13 = Impedances of Zones 1, 2 and 3 respectively,
R_f = Resistance in fault path.

II. Introduction

Utilities have difficulty in getting approvals for new power transmission lines due to environmental concerns and the huge cost involved. To better utilize their existing transmission assets, series compensation techniques are used to compensate for the inductive reactance of long transmission lines [1]. Adding series compensation is one of the simplest and cheapest ways of increasing transmission line capacity, power transfer capability, system stability, voltage regulation [2]-[3] and lowering losses. Furthermore, it can optimize the sharing of real power between parallel lines connected to the same busbars [4].

For the lines, installation of series capacitors and their over-voltage protection system with nonlinear Metal-Oxide Varistors (MOVs) etc., introduces certain difficulties for fault location and protective relaying reach, particularly when distance protection schemes are applied [5]. For this reason, it is necessary for the distance protection scheme to do the impedance measurement with sophisticated algorithms with the series capacitor bank in circuit.

Distance relays are used to protect high voltage long transmission lines by detecting short circuit faults on the protected line and thereafter initiating the tripping of circuit breakers related to the particular portion of the line covered by the relay. Different algorithms and models have been put forward for the protection of series compensated transmission lines [6]-[10]. The Mho relay has a circular characteristic with directionality, good phase selection and a simple criterion.

A transmission line demonstrates a predictable impedance, which increases with the length of the line. A distance relay has a pre-established impedance setting, which determines the size of the relay's impedance characteristic, which is typically in the form of a circle in the impedance (R-X) diagram and matched to the length of the line to be protected by the relay. The relay is capable of rapidly detecting faults on the transmission line, indicated by a drop in

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the measured impedance of the line. This means that the relay is capable of detecting faults when the impedance of the line is inside the impedance characteristic of the relay. The operation boundary of the Mho relay can be adjusted to provide consistent zone coverage over the area of interest.

In this paper, a Mho relay model is presented and EMTP-RV simulation package is used to evaluate the performance of a distance protection scheme applied to a 500 kV, two parallel lines, series-compensated transmission network. Simulation results are presented for single, two and three phase-to-ground faults created at the beginning of the protected line and at the remote end, behind the capacitor of the network. Normally, a single phase-to-ground fault is the most common fault experienced on a transmission line.

III. METHODOLOGY

A. Test System Model (Fig. 1)

The 500 kV test system, modeled in simulation package EMTP-RV [11], is comprised of two parallel lines L1 and L2. The line lengths are indicated in the figure. The two lines are paralleled at Buses A, B and C. Series compensation capacitors are located just ahead of Bus B. The series capacitors are protected by a parallel metal oxide varistor MOV, spark airgap and breaker.

Line L1 of the power system is protected with the distance relay model placed at the beginning of the line, next to Bus A. The distance relay monitors the phase voltage and line current through a capacitor voltage transformer (CVT) and current transformer (CT) respectively. The block diagrams of the CVT and CT are shown in Fig. 2 and 3, respectively.

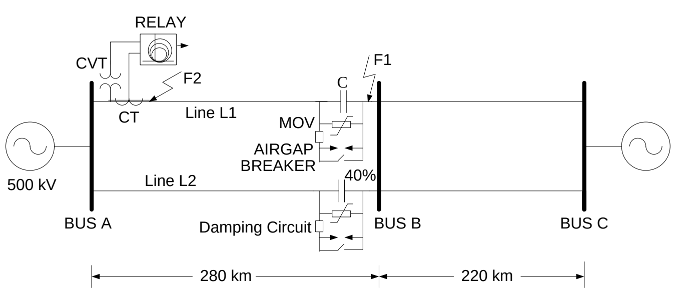

Fig. 1. Test system

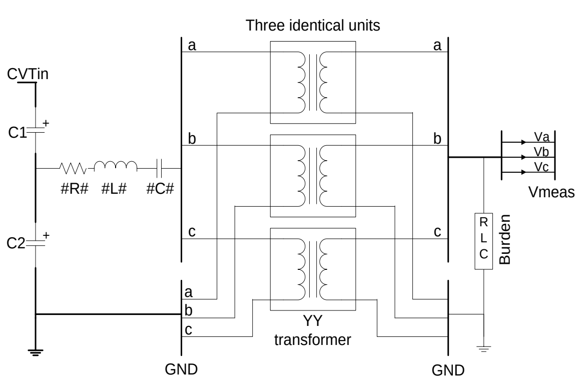

Fig. 2. Capacitor voltage transformer

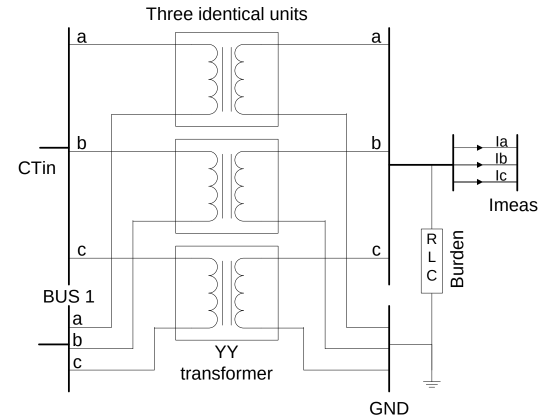

Fig. 3. Current transformer

B. The Relay Model (Fig. 2)

The block diagram of a conventional Mho relay model for a series compensated transmission line is shown in Fig. 4.

The relay has two 3-phase inputs, three phase voltages from the CVTs and the three line currents from the CTs, and provides one logical output which gives a Trip indication to the protection system. The Mho relay is comprised of 3 fundamental blocks:

- Block A - Fault Detection and Compensation Block,
- Block B - Zone Detection and Time Delay Block, and
- Block C - Logic Block.

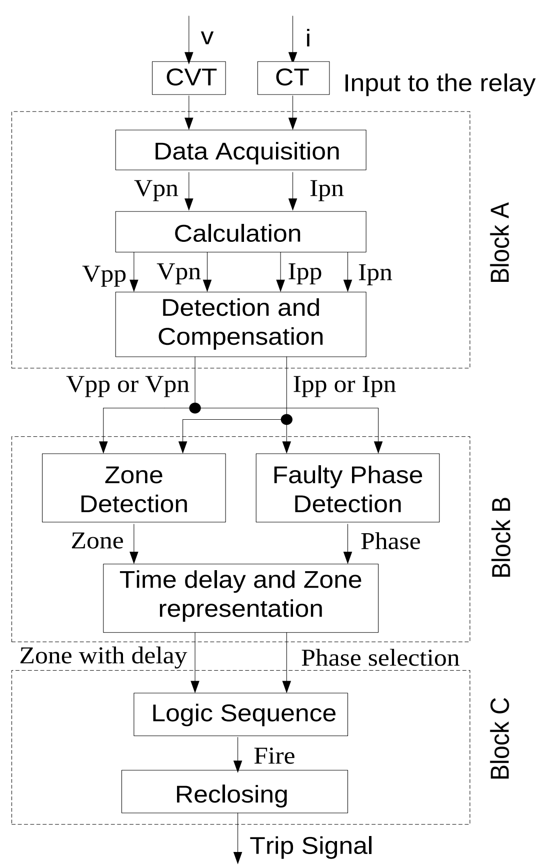

Fig. 4. Relay model

1) Fault Detection And Compensation Block A

The fault detection and compensation block receives inputs from the CVT and CT and, based on internal calculations, derives both phase-to-phase or phase-to-ground voltages and currents as outputs. Block A has three sub-blocks, described below.

a) Data acquisition sub-block: Input voltages and input currents are filtered with a band-pass filter to remove harmonics from the three phase voltages and currents. If I_a, I_b and I_c are the input currents, then the residual current is derived as:

$$I_0 = (1/3)*(I_a + I_b + I_c) \tag{1}$$

b) Calculation sub-block: Since a fault may or may not involve the ground connection, input voltages and currents, after being filtered, are converted into phase-to-phase and phase-to-neutral values by the calculation sub-block. Since this sub-block receives only phase-to-ground values, phase-to-phase values are obtained by subtracting two voltages or two currents i.e. $V_{ab} = V_{an}-V_{bn}$.

c) Detection and compensation sub-block: This sub-block provides both phase-to-phase or phase-to-ground voltages and currents as outputs depending on the type of fault. The selection is carried out based on the current flowing through the circuit. During a fault condition, current in each phase varies depending on the type of fault.

The impedance seen by the relay is given by the ratio V/I (=Z). An important feature of designing a distance protection scheme is to select appropriate values of voltage (V) and current (I) signals, so that the impedance seen by the relay during the fault condition is the positive phase sequence (p.p.s.) impedance from the relay location to the fault location [12]. The impedance measured by the relay is influenced by the fault type and also by a number of power system parameters such as MOV rating, series capacitance etc. Here, an algorithm called "residual current compensation" is employed where the compensation current is added to the phase currents to obtain the impedance measurement from the relay location to the fault location. The current seen by the relay for impedance measurement is given by:

$$I = I_{pn} + I_{comp} \tag{2}$$

Here, $I_{comp} = k_c * I_0$ and $k_c = k_{mag}$ with angle (k_{rad})

$$k_{mag} = \sqrt{\frac{(R0 - R1)^2 + (L0 - L1)^2}{(R1)^2 + (L1)^2}} \tag{3}$$

$$k_{rad} = \tan^{-1}\left(\frac{L0 - L1}{R0 - R1}\right) - \tan^{-1}\left(\frac{L1}{R1}\right) \tag{4}$$

2) Zone Detection And Time Delay Block B

After computations on the inputs received from Block A, the output from this block provides information about the phase(s) and the zone(s) where the fault has occurred. In total, six outputs are obtained from this block: one each for Zones 1, 2 and 3, and one each for phases a, b and c. Block B has three sub-blocks, as described below.

a) Zone detection sub-block: Phase comparators are employed for the zone detection. A phase comparator compares the two input quantities in phase angles and operates if the phase angle between them is less than or equal to 90° [13]. The 3-phase input voltages and currents are fed through the phase comparators to detect the zones. The output signals are based on each phase and zone such as Zone1_a, Zone1_b, Zone2_a etc. For instance, if the fault occurs on phase a and in Zone 2, then Zone2_a gives the output signal for further processing and the other output signals provide a zero signal. During this process, the relay can detect the zone where the fault has occurred.

Impedance of the line is proportional to the length of the protected line. During a fault condition, the voltage and current values will change and, therefore, impedance will be affected. The fault zone indication is based upon whether the impedance measured at the relay location is greater than or less than the protected line impedance.

$$\text{Zone 1 primary impedance magnitude} = Length * Z_{line} \tag{5}$$

where

Length = 0.85 of the protected line of 280 km

$$Z_{line} = \sqrt{(R1)^2 + (L1)^2}$$

$$\text{Zone 1 primary impedance angle, } Z_{angle} = \tan^{-1}\left(\frac{L1}{R1}\right)$$

The setting value of each zone is expressed as a percentage of the line length. Normally, the first Zone covers only up to 80 to 90% of the protected line length. The second Zone covers the remainder of the line left unprotected by the Zone 1 setting, plus 50% of the adjacent line section. The third Zone is used for back-up protection and covers the first and section line sections, plus 20 to 25% of the adjacent line.

b) Faulted phase detection sub-block: Phase comparators are employed for the faulted phase detection. The 3-phase input voltages and currents are fed to the phase comparators. Output of this block provides the sequence of phases a, b or c through the phase comparators and the impedance trajectory of each phase in the impedance (R-X) diagram. Selected values for phase comparator design constant parameters k_1, k_2, θ_1, θ_2, α_1, α_2 are shown in Appendix.

c) Time delay and zone representation sub-block: This sub-block incorporates two functions. The first is a Time Delay function. When signals are received from zone detection and faulty phase detection, they pass through a logical OR function to determine the zone where the fault has occurred.

After the detection of the faulted zone, Zone 1 relay trips instantaneously. However, Zone 2 and Zone 3 relays have some intentional time delays added to coordinate with the relays at the remote bus, before providing an output. Time delays may vary depending on the circumstances.

The second function in this sub-block is the zone representation function which draws a distance relay characteristic on the impedance (R-X) diagram. With internal mathematical calculations, this sub-block decides the centers and radii of the circles on an R-X diagram for different zones according to the data chosen for the system.

These circles pass through the origin and have different radii for different zones. Each circle denotes a particular length of the line. The diameter of the circle is proportional to the impedance of the line or indirectly the length of the line covered by the each zone. For instance, if the length of the line is 280 km and if Zone 1=0.9 is selected, it means that circle 1 will cover 90% of the protected line length. When a fault occurs within that area, this can be located within Zone 1 circle in the R-X diagram.

3) Logic Circuit Block C

The output of this block determines the final decision of the relay for tripping a circuit breaker. If the fault is temporary and can be isolated within the reset time of the relay, then this block will not send a trip signal. However, if the fault is permanent, then it will send a trip signal for the circuit breaker. This block has two sub-blocks.

a) Logic sequence sub-block: The zone detection signals from Block B are passed through a logical OR function, and the output gives the final zone decision and identifies where the fault has occurred. Now, as information about the zone and the faulted phase(s) is available, a logical AND function provides an output based on the combination of faulted zone with faulted phase.

b) Reclosing sub-block: A single phase auto-reclosing scheme is employed, in which only the faulted phase pole of the circuit breaker is tripped and reclosed. At the same time, synchronizing power still flows through the healthy phases. For a multi-phase fault, all the three-phases are tripped and reclosed simultaneously [13]. When the zone and faulted phase(s) are decided then it is necessary to determine whether the fault is temporary or permanent in nature before tripping the three phases circuit breakers.

Whenever this block receives the information about faulted phase(s) and zone where the fault occurs, the relay sends a trip signal for the faulted phase(s). The relay checks the status of the fault again after a reset time and depending upon the nature of the fault; thereafter, either the relay sends a trip signal for the three phase circuit breakers or restores the line after the reset time.

IV. RESULTS

Numerous tests were carried out with the test system. Due to space restrictions, only a sample of the tests carried out are presented next.

A. Single phase-to-ground (a-g) fault at F1 (Fig. 5)

This case shows results from a permanent single phase-to-ground fault (a-g) placed at 280 km from the relay, behind the capacitor (at location F1) with fault resistance R_f =10 ohms. The fault occurs at time=0.06s, and the simulation is run for a total time period of 0.7s.

Fig. 5(a) shows the trip signals for phases a, b and c. For phase "a" the trip signal is generated after 0.3816s (including 0.3s Zone 2 delay). The relay checks the status of the fault after reset time (0.18s) and due to the permanent fault; all three phase circuit beakers are tripped after 0.5174s.

Figs. 5(b) and (c) show Line L1, 3-phase current and voltage waveforms, respectively measured at the relay location. When the fault occurs at 0.06s, the current for phase "a" increases and at the same time its voltage decreases. The relay trips the phase "a" circuit breaker at 0.3816s, therefore, no current passes through the phase a. Due to a permanent fault, after reset time (0.18s), the relay trips the three phase circuit breakers at 0.5174s and the protected line is completely disconnected from service.

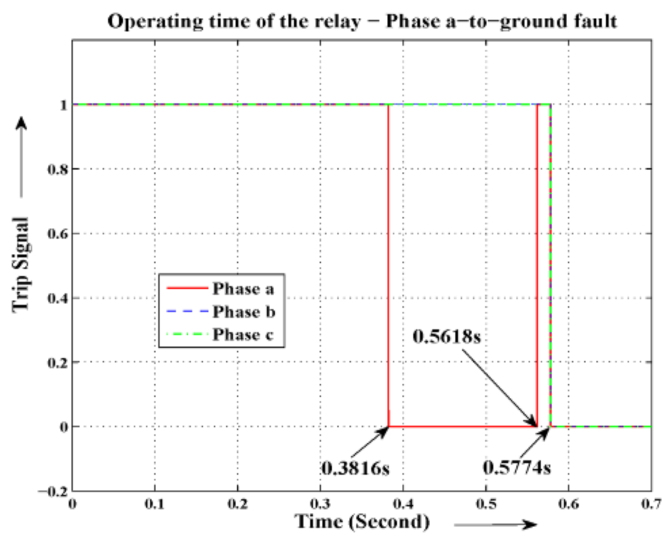

Fig. 5(a) Trip signals for phases a, b and c

The impedance (R-X) diagram (Fig. 5(d)) shows the three circles covering Zones 1, 2 and 3 and another smaller circle covering reverse zone operation. The trajectory of the impedance detection for phases a, b and c is also shown. The figure indicates that only the trajectory of the phase "a" impedance enter the Zone 2 tripping region of the relay. The rest of the impedance trajectory was located outside the region. The trajectory of the 3 phases indicates that the fault involved only phase "a" and is covered by Zone 2 region.

Fig. 5(e) shows the capacitor voltage (top trace), capacitor current (middle trace) and the MOV current (bottom trace) for phase "a". The results show that when the fault occurs at 0.06s, the capacitor voltage and current increase. The voltage increase is enough to trigger the MOV to conduct also to protect the capacitor. The capacitor and the MOV take turns conducting currents.

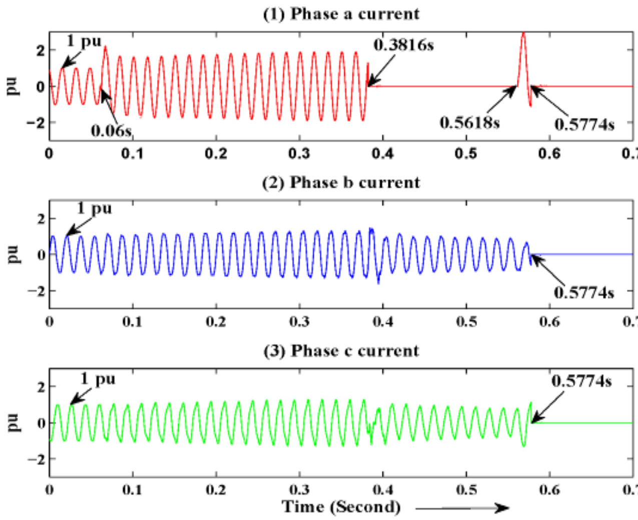

Fig. 5(b) 3-phase currents in line L1

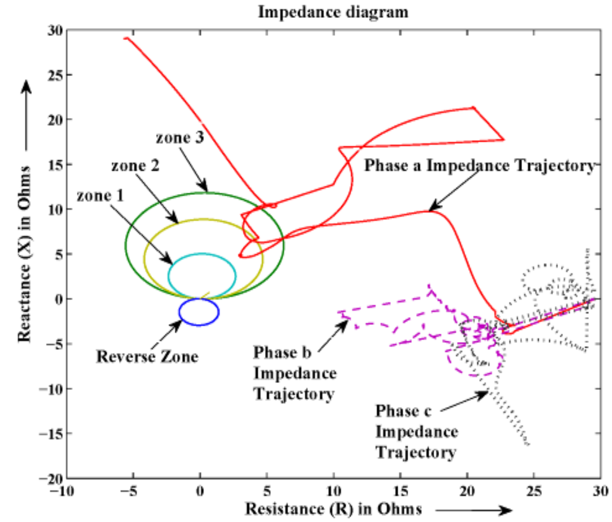

Fig. 5(d) Impedance (R-X) diagram

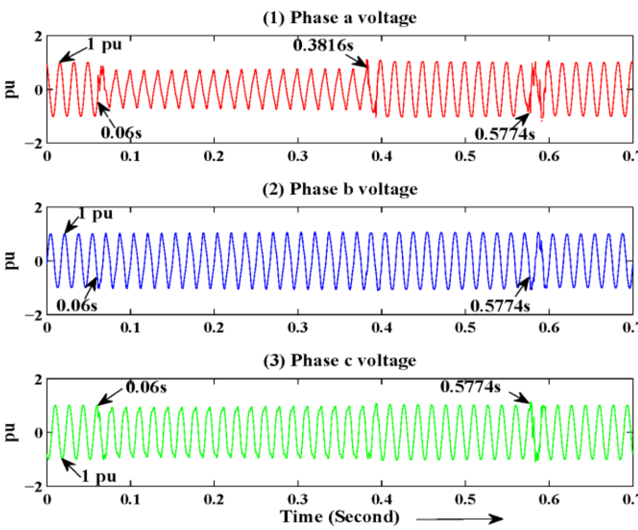

Fig. 5(c) 3-phase voltages in Line L1

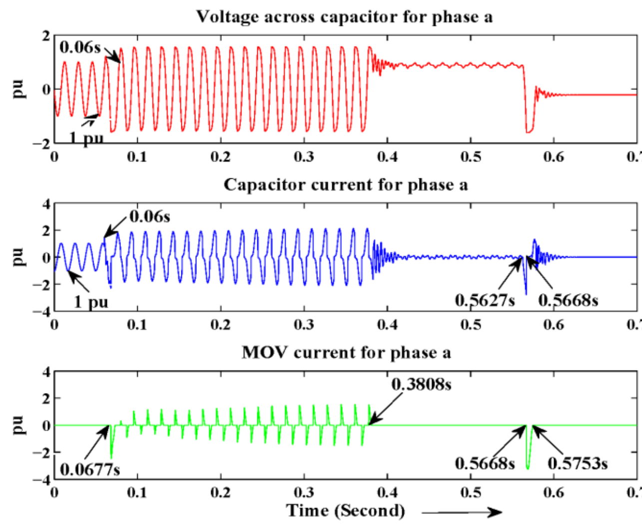

Fig. 5(e) Capacitor voltage (top), Capacitor current (middle) and the MOV current (bottom) for phase a

B. Three phase-to-ground (a-b-c-g) fault at F1 (Fig. 6)

This case shows results from a permanent three phase-to-ground fault (a-b-c-g) placed at 280 km from the relay, behind the capacitor (at location F1) with fault resistance R_f =10 ohms. The fault occurs at time=0.06s, and the simulation is run for a total time period of 0.7s.

Fig. 6(a) shows the trip signals for phases a, b and c. The trip signals for three phases are generated after 0.1376 s. The relay checks the status of the fault after reset time (0.18s) and due to the permanent fault; all three phase beakers are tripped after 0.3317s. The relay operates in Zone 1 instead of Zone 2 and takes longer operating time due to parallel line operation and high impedance measurement at the relay location.

Fig. 6(b) and (c) show the Line L1, 3-phase current and voltage waveforms, respectively measured at the relay location. When the fault occurs at 0.06s, the current for three phases are increased and at the same time voltage decreases. The relay trips the three phase's circuit breakers at 0.1376s, therefore, no current passes through the protected line. Due to permanent fault, after reset time (0.18s), the relay trips the three phases circuit breakers at 0.3317s and the protected line completely disconnects from the service.

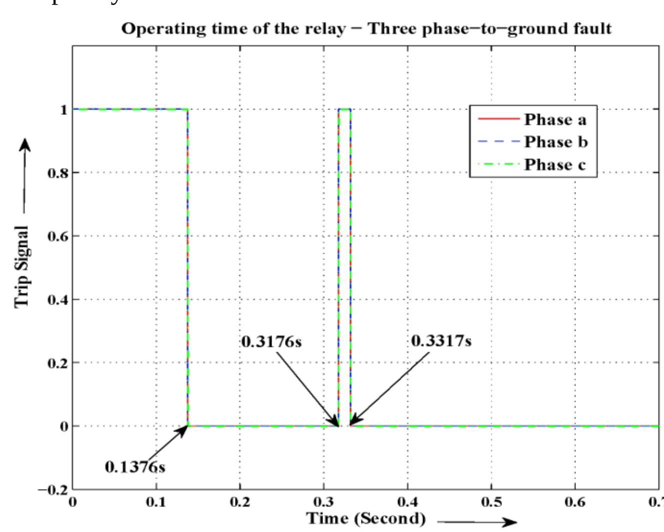

Fig. 6(a) Trip signals for phases a, b and c

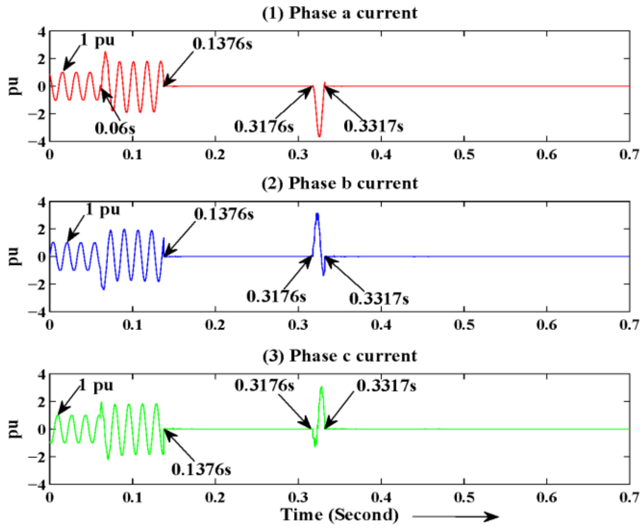

Fig. 6(b) 3-phase currents in Line L1

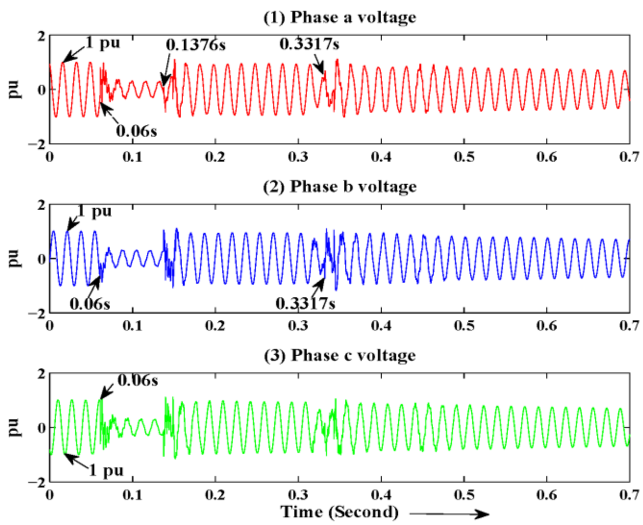

Fig. 6(c) 3-phase voltages in Line L1

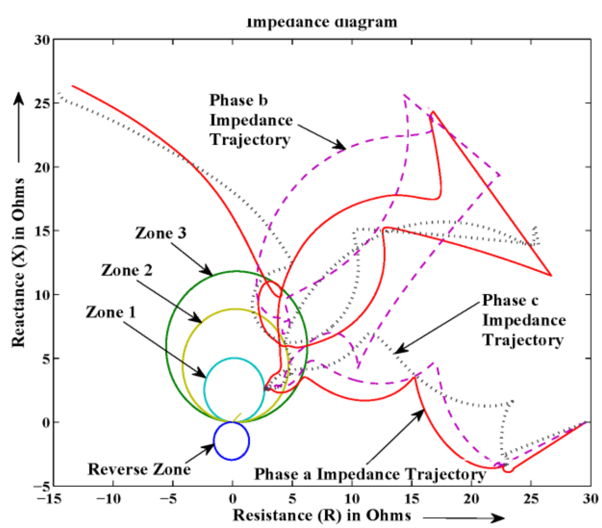

Fig. 6(d) Impedance (R-X) diagram

The impedance (R-X) diagram (Fig. 6(d)) shows the three circles covering Zones 1, 2 and 3 and another smaller circle covering reverse zone operation. The trajectory of the impedance detection for phases a, b and c is also shown. The figure indicates that the trajectory of the three phases "a", "b" and "c" impedance enter the Zone 1 tripping region of the relay. The trajectory of the three phases indicates that the fault involved phases "a", "b" and "c" and is covered by the Zone 1 circle.

Many results were obtained with the test system. The findings of these evaluations are summarized in Table 1. The performance of the relay operation and the algorithm scheme on single phase-to-ground (SLG), two phase-to-ground (2LG) and three phase-to-ground (3LG) permanent faults at two different locations F1 and F2 are shown in Fig. 1. At F1 the fault is located at the remote end, behind the capacitor. At F2 the fault is located at the beginning of the protected line. The relay operation and the algorithm is tested with 75 kV MOV reference voltage and different fault resistances (0, 5, 10 and 20 ohms). Type of faults and fault resistance are listed in columns 1 and 2 respectively in Table 1. Columns 3 and 4 show the two different fault locations, which include the zone of operation, number of cycles and secure/insecure or missing operation for each fault case. The data shown in the table indicates that the relay operates securely and correctly for all close-in faults (F2). For all close-in faults, the relay operates in Zone 1 and an average tripping time is less than 1 cycle or 16.7ms. The table also shows that the relay operates correctly and securely with 20ohms fault resistance in each fault case and at both locations. In summary, out of 56 permanent faults with different fault resistance, 44 secure operations (relay operates in the expected zone), 12 insecure operations (relay operates in other zone than expected) and 0 missing operations (relay fails to operate) were obtained.

V. CONCLUSIONS

This paper evaluates the performance of a Mho relay model and distance protection algorithm for a 500 kV, two parallel lines, 40% series-compensated transmission system. A model based on the EMTP-RV simulation package is used to simulate and test the relay. A scheme based on the residual current compensation is used to compensate the error in the impedance measurement. The distance protection scheme is based on measuring phase angle of the input signals and comparing them through phase comparators and using four specially shaped characteristics.

The simulation results show that the relay model detects the faults correctly and generates trip signals with regards to the location of the fault. The MOV protects the capacitor against over voltage during fault conditions. Furthermore, it is noted that the operating time of the relay is a function of the distance to the fault.

Finally, for close-in faults, satisfactory relay performance was obtained and an average tripping time is less than 1cycle. However, the relay may not be as secure on certain unbalanced fault types generated at the remote end, behind the capacitor. Further research is being carried out to investigate the

TABLE 1. Analysis of the relay operation for permanent fault, MOV V_{ref} = 75 kV and R_f = 0 to 20 ohms

		Location F1					Location F2				
Fault type	Rf ohms	Zone	No. of cycles	Secure Operation	Unsecure operation	Missing operation	Zone	No. of cycles	Secure operation	Unsecure operation	Missing operation
SLG	0	2	20	3	0	0	1	1	3	0	0
	5	2	19	3	0	0	1	1	3	0	0
	10	2	19	3	0	0	1	1	3	0	0
	20	2	19.5	3	0	0	1	1	3	0	0
2LG	0	1	13	0	3	0	1	1	3	0	0
	5	1	2	0	3	0	1	1	3	0	0
	10	1	1.5	0	3	0	1	1	3	0	0
	20	2	19	3	0	0	1	1	3	0	0
3LG	0	1	1.5	0	1	0	1	1	1	0	0
	5	1	0.5	0	1	0	1	1	1	0	0
	10	1	4.5	0	1	0	1	1	1	0	0
	20	2	19	1	0	0	1	1	1	0	0
Total				**16**	**12**	**0**			**28**	**0**	**0**

performance of the relay model and its algorithm at other fault locations, series compensation at the middle of the line and reverse fault conditions.

VI. Appendix

A. System Data

Rated voltage = 500 kV rms,
Rated power = 1450 MW,
Length of the protected line = 280 km,
I_{ctp} = 1074 A,
I_{cts} = 5A,
V_{cvtp} = 410 kV,
V_{cvts} = 115V,
R0 = 0.06162 Ω/km, L0 = 1.05 Ω/km,
R1= 0.0205 Ω/km, L1= 0.35 Ω/km,
Zone1 = 85% of the protected line,
Zone2 = 1.5 and Zone 3 = 2.1,
t_{zone1}= 0.001s, t_{zone2} = 0.3s and t_{zone3} = 0.6s,
Reset time = 0.18s,
$ZR11 = Z_{line}*Zone1$, $k_1=1$, $\theta_1 = Z_{angle}$, $\alpha_1 = \pi$,
$ZR12 = Z_{line}*Zone2$, $k_2 = 1$, $\theta_2 = 0$, $\alpha_2 = 0$,
$ZR13 = Z_{line}*Zone3$, $ZR1a = Z_{line}/2$, $\theta_{1a} = Z_{angle} + \pi$,
Fault resistance (R_f) = 0, 5, 10 and 20 ohms,
MOV reference voltage (V_{ref}) = 75 kV,
Series Capacitance = 67.66 μF/phase.

VII. Acknowledgment

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