The Effect of Fault Variables in the Performance of Quadrilateral and MHO Relays

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***Abstract*—In this paper, the influence of fault variables in the quadrilateral and mho relays are evaluated. The mho and quadrilateral relays are developed to be more accurate as possible according to manufacture datasheets. Therefore, the quadrilateral and mho relays are composed by an over-current, directional, and reactance relays, in which fault type relay to distinguish ground faults from phase-phase faults is used. The influence of the fault variables such as fault type, distance, inception angle, and resistance are investigated in order to evaluate the implemented relays. Also, an explanation about relay fundamentals is exposed. The quadrilateral and mho relays were tested in a standard transmission power system protection in single and double line configurations. Several fault simulations were performed varying the location, as transmission line and buses. The results showed that the quadrilateral relay is reliable for ground faults whereas for three phase faults it has many misoperations. In addition, the usage of the mho relay in phase-to-ground faults depends of resistance coverage needed for high resistance faults and mho relay needs to be improved.**

***Index Terms*—Quadrilateral, Mho, Relay, Protection, Distance.**

I. Introduction

Nowadays, the main protection used in transmission lines is the distance protection, which is more suitable for these type of systems than the over-current and differential protection, because it depends only of the line parameters, it is less dependent of power flow conditions, relay coordination is easier, and so on [1]. The over-current protection is not suitable in transmission lines because the relay coordination is difficult and a constant supervision of relay parameters is needed [2]. Similarly, the differential protection is not the best option for long transmission lines due to the costs of communication links.

Distance protection has many shapes, which can be infinite due to digital technology [1], and the relays are classified according to their shape operation. However, depending on the adopted shape, the relay will have a determined response that can be visualized using the R-X diagram [3]. Nowadays, the most used shapes are the mho and quadrilateral. The mho is more suitable for faults not involving the ground, whereas the quadrilateral is more suitable for ground faults. The advantage of using the quadrilateral relay is the high resistance coverage. However, this high coverage can cause relay misoperations for high load situations.

In this paper, the quadrilateral and mho relay were implemented, in which the modeled quadrilateral relay is composed with various distance characteristics as blinder, reactance and directional. Moreover, the mho relay is composed with mho, reactance and directional. For the relay ground units, fault type characteristic is used, which is needed to avoid the ground relay units to trip for phase-phase-to-ground faults [4]. In addition, the modeled relays have six impedance measurements, which are three phase-ground and three phase-phase units. As matter of fact, the modeled relays were constructed based in various manufacturer datasheets [5]–[9].

In order to evaluate the implemented relays, the IEEE 230 kV proposed system [10] with single and double line configuration was implemented, in which several faults were simulated varying the fault distance, fault type, fault resistance, and fault inception angle using the ATP (Alternative Transients Program). Therefore, the correct and wrong trips that the quadrilateral and mho relays performed were measured and displayed in bar charts. Using this methodology, the problems caused by different fault types, the incremental resistance, as well as incremental fault distance in the global performance of mho and quadrilateral relay are easier to identify.

For an efficient protection, the knowledge about relay components and distance protection problems help identifying misoperations in relay protection systems. Therefore, this paper provides an extensive insight about the distance and digital relaying problems in concern to the different fault conditions, comparing their performance against various fault situations. In conclusion, distance relaying is more influenced by fault resistance and fault distance according to the presented bar charts.

II. Phasor Estimation

The phasor estimator uses the sampled signals to estimate the voltage and current phasors at 60 Hz. The ideal phasor estimation needs to be with minimum error, filter all the harmonics and the DC exponential decay with minimum time delay [11]. An example of phasor estimator is the modified cosine filter, which estimates the phasor as follows:

$$Y_{cp} = \frac{2}{N}\sum_{n=1}^{N} y_n \cos(pn\theta), \quad (1)$$

$$Y_{sp} = \frac{Y_{cp-1} - Y_{cp}\cos\theta}{\sin\theta}, \quad (2)$$

where Y_{cp} and Y_{sp} are, respectively, the real and imaginary phasor parts, N is the samples per cycle, θ is the rotation angle, y_n is the sampled signal, and p is the harmonic content. For the fundamental phasor estimation, the p must be equal to one.

III. Distance Protection Fundamentals

Distance protection fundamentals are based in the operation of electromechanical relays. With the usage of digital technology in relay protection, the operation of electromechanical relays is emulated in digital devices, taking advantage of accumulated knowledge in electromechanical relays with the benefits of digital technology.

The general torque equation for distance protection is given by [12]:

$$\begin{aligned} S_{op} &= k_1 I_R \angle\phi + k_2 V_R \angle 0, \\ S_{pol} &= k_3 I_R \angle\phi + k_4 V_R \angle 0, \end{aligned} \quad (3)$$

where I_R and V_R are, respectively, the currents and voltages measured by the relay, S_{op} is the operation torque and S_{pol} is the polarization torque.

The relay will operate when $\Re(S_{op}S_{pol}^*) > 0$. All the distance characteristics can be designed through the change of the $k_1, ..., k_4$ variables, as summarized in Table I.

TABLE I
k values for each distance characteristic.

Characteristic	k_1	k_2	k_3	k_4
Mho	Z_{L1}	-1	0	1
Reactance	Z_{L1}	-1	Z_{L1}	0
Directional	Z_D	0	0	1
Phase selector	1	0	0	1
Right blinder	Z_{BR}	-1	Z_{BR}	0
Left blinder	Z_{BL}	-1	Z_{BL}	0

Fig. 1 depicts the distance characteristics in a R-X diagram, namely mho and quadrilateral. To form a quadrilateral characteristic is needed 4 settings (Z_{L1}, Z_{BR}, Z_{BL}, and Z_D), which one representing a quadrilateral side, whereas to form the mho characteristic is necessary only one setting (Z_{L1}).

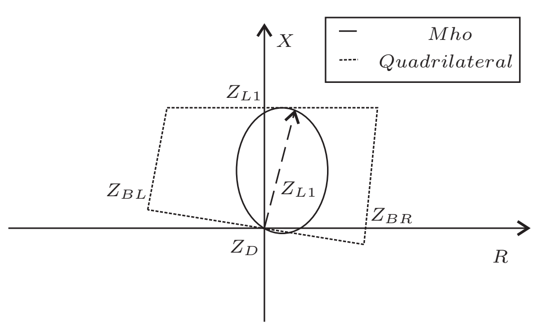

Fig. 1. R-X Diagram.

IV. Relay and Power System Modelling

In this paper, the relay uses a Butterworth anti-aliasing filter with 480 Hz cut-off frequency for a 960 Hz sampling frequency. The A/D conversion is made at fixed time step without errors. Moreover, the adopted relay phasor estimator was the modified cosine filter.

A. Distance Relay Parameters

The adopted parameters for the quadrilateral relay are summarized in Table II.

TABLE II
Quadrilateral relay parametrization.

	Right Blinder	Left Blinder	Reactance	Directional
Z	$100\angle 0°$	$10\angle 180°$	$0.8L_1$	$1\angle angle(L_1)$

The adopted settings for the reactance and directional are the same for the mho and quadrilateral relays. The mho and quadrilateral characteristics are set to protect 80 % of the line L_1 with resistance coverage of 100 Ω.

B. Power System Modelling

The power system used to evaluate the quadrilateral and mho relays was based in the system proposed by the IEEE [10] for transmission line systems. The used power system has a synchronous machine, a transformer, 3 lines, and an equivalent source as depicted in Fig. 2.

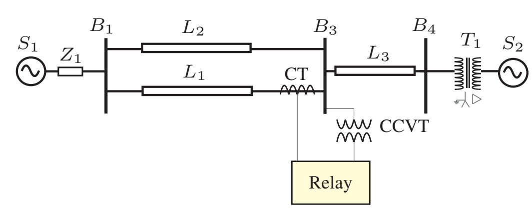

Fig. 2. Power System.

The source parameters and initial power flow are summarized in Table III.

TABLE III
Source Parameters

	Source 1			Source 2	
V_1	$1.035\angle 31.8°$ pu	V	V_2	$0.932\angle 40°$ pu	V
Z_0	$6.10 + i16.70$	Ω			
Z_1	$2.70 + i8.37$	Ω			

The source 2 is modeled as a synchronous machine according to [10], as well as transformer T_1. The L_1, L_2, and L_3 are modeled with distributed frequency parameters, which allows to simulate faults along the lines. The length of L_1, L_2, and L_3 are, respectively, 400, 400, and 300 km.

V. Discussion and Results

The relays were evaluated in two power system configurations, such as: single and double line. In the single line configuration, the L_2 is disconnected.

Several faults were simulated in the power system lines and buses using the ATP program, varying the fault resistance, type, inception angle, and distance. Table IV summarizes the faults simulated on lines L_1 and L_2.

TABLE IV
Faults simulated in L_1 and L_2.

Fault type	AG, AB, ABG and ABC	
Fault inception angle	0, 45 , 90	degrees
Fault distance	10, 20, 30, ..., 370, 380, 390	km
$R_g, R_{ab}, R_{bc}, R_{ac}$	1, 2, 5, 10, 20, 50, 100	Ω

For the line L_3, the simulated faults are the same as shown in Table IV, but the fault distance only reach to 290 km, whereas for buses 1 and 2, the simulated faults are without the fault distance variable. A total of 819, 21, and 609 faults were simulated on L_1 and L_2, buses 1 and 2, and L_3, respectively, for each fault type.

A. Distance Protection Evaluation

The main goal of this paper is to show the performance of the quadrilateral and mho relay for different fault conditions using relay models similar to commercial relays.

The quadrilateral relay uses a composition of various characteristics, such as: directional, 2 blinder, and reactance relays. In order to have a better relay response, the relay is supervised by an overcurrent relay, and for the relay ground units are used a relay fault type unit. For relay phase-phase units, the fault type unit is not used, which avoids the ground relay units to trip in phase-to-phase-to-ground faults. In such faults, the ground unit tends to overreach [4].

In this paper, the correct trips in each fault type are evaluated. For instance, if the fault is phase-A-to-ground (AG), the relay will operate the respectively phase-A-ground unit. For phase-A-to-B-phase faults (AB), the relay will operate the AB phase-phase unit. For phase-A-to-phase-B-to-ground (ABG), relay ground units are disabled and it only operate the relay AB phase-phase unit. For three-phase faults (ABC), only relay phase-phase units operate.

Table V summarizes the activated relay units for each fault type.

TABLE V
Activated Relay Units.

Fault Type	Relay Units					
	Z_{AT}	Z_{BT}	Z_{CT}	Z_{AB}	Z_{BC}	Z_{CA}
A-G	√	-	-	-	-	-
A-B	-	-	-	√	-	-
A-B-G	-	-	-	√	-	-
A-B-C	-	-	-	√	√	√

A percent bar chart is elaborated with the correct trips in order to have a better perception of the performed evaluation. These bar charts are made dividing the correct trips by the total simulations performed on each fault type. For instance, if 300 phase A-ground faults are simulated and the phase-ground A relay unit trips 100 times, the relay will have a bar with 33%, and so on for the other fault types. For the bar chart elaboration, only the relay phase-phase and phase-ground trips are considered for the respectively fault type, according to Table V.

B. Fault Distance Influence

The fault distance influences the relay performance, since more distance is the fault from the relay more impedance is seen by the relay. This parameter influences in faults near the protection zone limit. Analyzing the bar charts is possible to get instantaneous feedback about the fault distance influence.

Fig. 3 depicts the fault distance influence in quadrilateral relay performance for single line configuration.

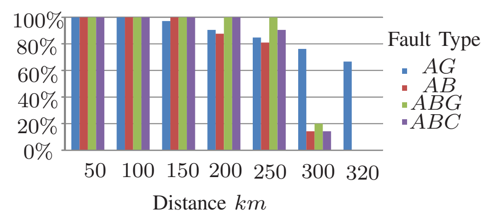

Fig. 3. Quadrilateral relay performance with the fault distance for single line configuration.

The fault distance presented great influence in the quadrilateral performance from 250 km in all fault types. For AB, ABG and ABC faults with fault distance from 300 km, the relay performance was not good. The relay did not trip for ABG faults between 301 and 320, which can be limitation to the quadrilateral shape for this fault type.

Fig. 4 depicts the fault distance influence in quadrilateral relay performance for double line configuration.

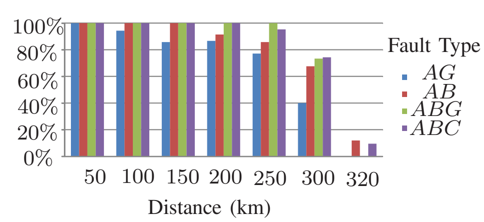

Fig. 4. Quadrilateral relay performance with the fault distance for double line configuration.

The fault distance presented great influence in the quadrilateral performance from 250 km in all fault types. For AB, ABG and ABC faults with fault distance from 300 km, the relay performance was not good. The relay did not trip for ABG and AG faults between 301 and 320, which can be a limitation for the quadrilateral shape in this fault type. For AG faults, the quadrilateral relay performance declined from 50 km to ahead.

Comparing the quadrilateral relay performance for power system with single and double line, the quadrilateral relay presented a better response for single line. This performance is due to the fact the inter-lines mutual zero impedance influences in the impedance estimation of the relay.

Fig 5 depicts the fault distance influence in mho relay performance for single configuration.

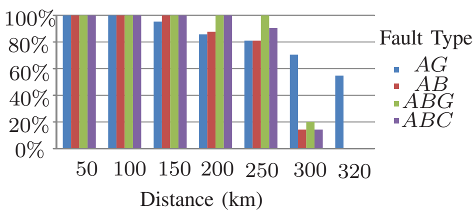

Fig. 5. Mho relay performance with the fault distance for single line configuration.

The fault distance presented great influence in the mho relay performance from 250 km in all fault types. For AB, ABG, and ABC faults with fault distance from 300 km the relay performance was not good. Moreover, for AG faults the relay performance declined from 100 km, but after that the relay performance decreased gradually.

Fig. 6 depicts the fault distance influence in mho relay performance for double line configuration.

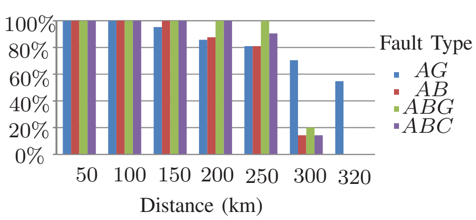

Fig. 6. Mho relay performance with the fault distance for double line configuration.

The fault distance presented great influence in the mho relay performance from 250 km in all fault types. For all faults occurring with fault distance from 300 km the relay did not trip. Therefore, for AG the relay performance declined from 100 km, but after that the relay performance decreased gradually.

Comparing the mho relay performance in single and double line configurations, the mho relay presented a better response for single line. This performance is due to the fact the inter-lines mutual zero impedance influences in the impedance estimation of the relay.

C. Fault Inception Influence

The fault inception angle influences the phasor estimator, since the angle determines the amount of DC exponential decay. In order to evaluate that influence, the relay is evaluated in 0, 45, and 90 degrees.

Fig. 7 and 8 depict the fault inception angle influence in quadrilateral relay performance for single and double line configurations, respectively.

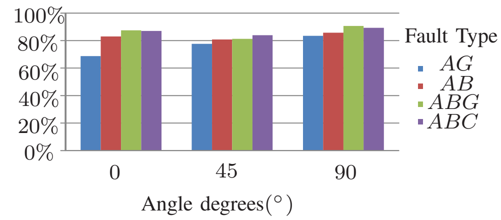

Fig. 7. Quadrilateral relay performance with the fault inception angle for single line configuration.

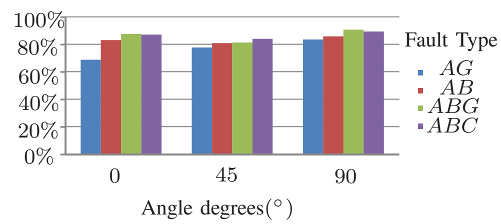

Fig. 8. Quadrilateral relay performance with the fault inception angle for double line configuration.

Regarding the AG faults, the quadrilateral relay presented a poor response for a fault inception angle with zero degrees, but with the increasing of fault inception angle the results improved. For the other fault types, the quadrilateral relay was not affected.

Fig 9 depicts the fault inception angle influence in mho relay performance for single line configuration.

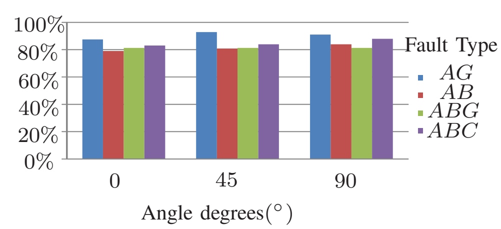

Fig. 9. Mho relay performance with the fault inception angle for single line configuration.

Excepting the AG, the other fault types did not have been influenced by fault inception angle. In spite of AG faults increased slightly the mho relay performance with the increasing of the fault inception angle.

Fig 10 depicts the fault inception angle influence in mho relay performance for double line configuration.

With regard AG faults, when the fault inception angle was zero degrees, the mho relay presented a poor response due to the fact of ground zero currents from parallel line. Also for AB faults, the mho relay was greatly affected. For the other fault types, the mho relay presented a better response.

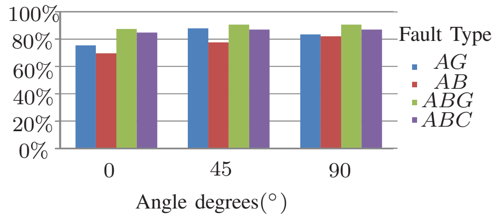

Fig. 10. Mho relay performance with the fault inception angle for double line configuration.

D. Fault Resistance Influence

The fault resistance is the fault parameter that influence in distance relays. In order evaluate the relays performance from low to high resistance faults, the resistance varies from 1 to 100 Ω.

Fig 11 depicts the fault resistance influence in quadrilateral relay performance.

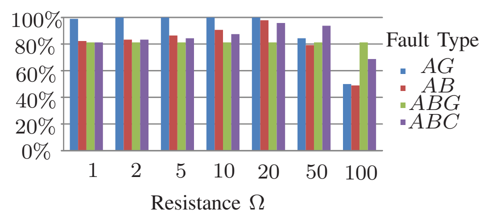

Fig. 11. Quadrilateral relay performance with the fault resistance for single line configuration.

The fault resistance did not influence the quadrilateral relay performance in ABG faults. For ABC faults, the quadrilateral relay increased the performance until 20Ω, and then it declined. For AG faults, the quadrilateral relay presented poor response only for high resistance faults from 50 to 100Ω, whereas for AB faults the quadrilateral relay performance was poor. However, the relay performance increased until 100Ω, and then it declined.

As expected, the quadrilateral relay for AG faults presented a good response, but it can be improved if the right blinder parameter increases. However, with the increasing of the right blinder, the relay tends to misoperate for high load situations.

Fig 12 depicts the fault resistance influence in quadrilateral relay performance.

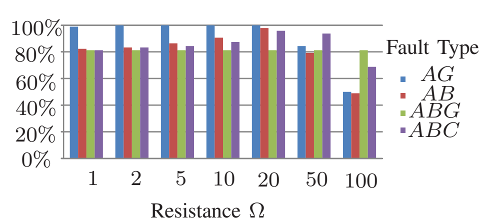

Fig. 12. Quadrilateral relay performance with the fault resistance for double line configuration.

The fault resistance did not influence the quadrilateral relay performance in ABG faults. For ABC faults, the quadrilateral relay increased the performance until 20Ω and then it declined slightly. In the AG faults, the quadrilateral relay did not have 100% efficiency and it presented a poor response in high resistance faults as 50 and 100Ω. Excluding the ABG faults, for 100 Ω the relay presented a poor response.

As expected, the quadrilateral relay for AG faults presented a good response, but it can be improved if the right blinder parameter increases. The problem with the increasing of the right blinder is that the relay tends to misoperate for high loads situation. Comparing the quadrilateral relay in single and double line configurations, the relay presented a worst response for double lines.

Fig. 13 depicts the fault resistance influence in mho relay performance for single line configuration.

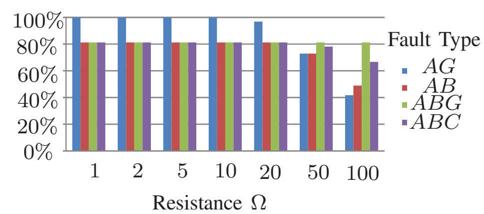

Fig. 13. Mho relay performance with the line resistance for single line configuration.

Regarding AG faults, the mho relay presented good performance until 20Ω. From this resistance, the mho relay performance decreased and in 100Ω it presented a poor response. Therefore, if a good response for high resistance faults is needed, another characteristic should be used. For the other fault types, the mho relay was affected by high resistance faults (100Ω). This result was expected because for AB faults the resistance has not great influence, in theory.

Fig. 14 depicts the fault resistance influence in mho relay performance for double line configuration.

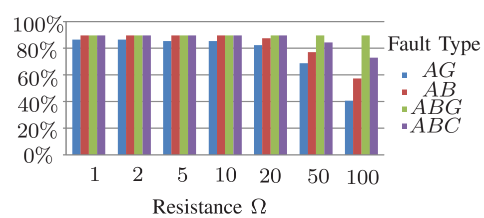

Fig. 14. Mho relay performance with the line resistance for double line configuration.

With regard AG faults, the mho relay presented a constant performance until 20Ω around 80%. From this resistance, the performance decreased and in 100Ω the relay presented a poor response. Therefore, if a good response for high resistance faults is needed, an usage of another characteristic can be a solution. For AB and ABC faults the mho relay was only affected by high resistance faults (100 Ω). In addition, for

ABG faults the mho relay was not affected by the fault resistance.

Comparing the mho performance in the power system with single and double line, the mho relay presented the worst response for double lines in AG faults despite the usage of inter-lines ground compensation. Moreover, the quadrilateral relay presented a better response for AG faults than the mho relay.

E. Relay Wrong Trips

The relay in zone 1 is set to protect the line at 80% of the protected line length. However, the protection was not 100% reliable and it can present misoperations. In order to identify distance protection design failures, these misoperations are analyzed.

Regarding the quadrilateral relay phase-ground units, there were 41 wrong trips in the line L_1. The quadrilateral relay was not suppose to trip for faults ahead 80% of L_1. Despite the relay wrong trips, the relay did not have bad performance because trips in L_1 ahead 80%, but before bus 2 did not interfere in the power system quality. For this reason, the relay was not set to 100%. However, for three-phase faults the quadrilateral relay was not reliable and it present many misoperations due to the phase-phase relay units as depicted in Table VI. For this case, a usage of another characteristics can be a solution. Despite the wrong trips for three phase faults, the relay phase-phase units worked well for the AB and ABG faults.

TABLE VI
RELAY WRONG TRIPS FOR ABC FAULTS.

	$L1 > 80$	L_3	Bus 1	Bus 2
AB	1	21	0	12
BC	3	22	0	12
CA	0	21	0	12
Total simulations	147	609	21	21

The mho relay was performed very well. The mho relay phase-phase units did not present any wrong trip. However, the mho relay phase-ground units presented 31 wrong trips for faults from 80% of the L_1. Despite the wrong trips, the mho relay did not present a bad performance because trips from 80% of the line L_1 but before bus 2 did not interfere in the power system quality. For this reason, the relay was not set for 100%.

In the double line configuration, for faults simulated outside the protected line the mho and quadrilateral relays did not present misoperations. They reached 100% efficiency which means that the relays with supervision by directional, reactance and fault type are excellent in reliability.

VI. Conclusion

In this paper, the quadrilateral and mho relays were implemented and tested with several fault simulations performed by ATP in a power system with single and double line configuration.

Bar charts were elaborated to show the influence of each fault variable in the quadrilateral and mho relay performance. The quadrilateral relay results demonstrated that the fault inception angle did not present a great influence. However, the fault resistance and distance play an important role in the quadrilateral relay performance. Despite settings can be changed to improve the performance in resistance coverage, this improvement can provoke mal operations in high load situations. In single line configuration, the quadrilateral relay misoperated for three-phase faults, suggesting another type of shape to be used.

The mho relay worked properly for faults involving more than one phase. However, for phase-to-ground faults the usage of the mho relay depended on the coverage resistance needed, which can be not suitable for the needed power system quality. For high resistance faults, the mho relay evaluated is not recommended. However, the usage of other types of voltage polarization can improve the relay and be experienced in future work.

The obtained results provided a quick perception of the mho and quadrilateral relay problems in the protection of transmission lines with single and double configurations.

Acknowledgment

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