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Distance Relay Over-reach Prevention by Impedance Starter Adjustment in: Ph-to-Ph Faults

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ABSTRACT

This paper presents the proper method for calculation of the phase-to-phase loop resistance reach of distance protection with Quad characteristic and the impedance starter at the sub-transmission level to prevent mal-operation of the distance relay when processing its algorithm. In this work, based on the practical experiences on several industrial distance relays, it is shown that there is a possibility of improper detection of the fault loop by distance protection and then improper relay operation for out of zone faults. After review of the subject, and expressing the mathematical relations governing the problem, the appropriate phase-to-phase loop resistance reach determination method is put forward. Finally, using the information obtained from a practical incident, the efficiency of the proposed method is verified.

1) Introduction

The protection of transmission and sub-transmission lines is conducted by overcurrent, line differential and distance protections among which the use of distance protection is very common [1]. Mal-operation of protection equipment, including distance protection, due to improper choose of the setting, configuration or algorithm; has been reported in past which in general may result in very adverse consequences such as blackouts [2]. Distance relays have different types of starters, including under impedance (Z<), overcurrent (I>), voltage/current (U/I) and voltage/current/angle (U/I/Φ) [3-5]. Under impedance starters in the old generation of distance relays have a formula that is relatively similar or completely similar to the formulation of distance protection zones, while in the new generation of industrial distance relays, such as ABB REL670, the impedance starters are optimized and have a different formulation in comparison to distance zones [6]. Based on experience with the undesired performance of older generation of quad characteristics employed in distance relays with impedance starters such as ABB REL511 and MICOM P44x (widely used in different regional electric companies in Iran), it is necessary to provide settings that take into account relay limitations and also past undesired performance experiences. According to the

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manufacturer's instructions: it is necessary for the zone starter to include all of the distance protection zones with a suitable adjustable or non-adjustable margin, based on the type of relay. According to the presented formulation, the relay's impedance starter is activated when the impedance enters the starter zone limit. In some cases, in addition to impedance criteria, flowing a minimum current is also a necessary condition for operation of the phase-to-phase and phase-to-ground loops. In this paper, by considering the mathematical equations for calculation of phase-to-phase loops, it is shown that there is a possibility of impedance measured by relay to enter the starter zone as well as the protection zones for faults outside the zone and then mal-operation of the protection system could be expected. It should be mentioned that the resistance magnitude for phase-to-phase faults is usually low since it is a solid connection of metal-to-metal, but nevertheless, when using the Quad characteristic, the value of the resistance reach of the phase to phase loop is selected similar to the magnitude of the resistance reach of the phase to the ground loop. In summary, the fault impedance can enter the starter zone and subsequently the protection zones despite the absence of a fault on one of the phases. This paper, firstly, review this problem as the possible cause of undesirable performance of the relay with the impedance starter for phase-to-phase out of zone faults, and calculates the appropriate setting based on the relay's limitations validated by using the data obtained by a practical incident.

2) Impedance of Phase-to-Phase Loops for Phase-to-Phase Fault

Distance relays have 6 calculation loops, including 3 phase-to-ground loops and 3 phase-to-phase loops, which are managed by the relay starter [7]. As mentioned earlier, the impedance starter should include all of the distance protection zones with realization of the proper margin. One of the main disadvantages of this concern is the possibility of detecting the wrong faulted phase and in some cases the improper performance of the distance protection, which is evaluated in this section by comprehensive evaluation of impedance of the phase-to-phase loops for phase-to-phase fault. In Figure 1, the simplified equivalent circuit for phase-to-phase fault is shown.

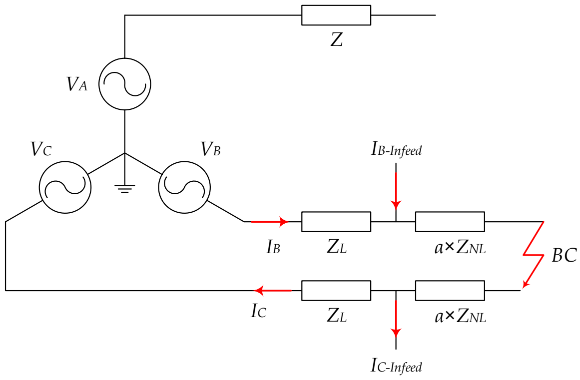

Fig. 1. Phase-to-phase fault from distance relay point of view.

In this figure, Z_L and Z_{NL} are the impedance of the line and the impedance of the following line, respectively, and the coefficient α is a percentage of the length of the next line. In order to consider the worst case, all infeed currents (from other lines connected to the busbar as well as the remote terminal) are ignored. With this assumption, the observed impedance usually decreases more at the relay location due to the increase in current, and as a result, the probability of impedance entering the distance zone increases. Based on this figure, the following equation can be derived using the KVL law in the BC fault loop.

$$U_B - Z_L I_B - \alpha \times Z_{NL} \times I_B - \alpha \times Z_{NL} \times I_C - Z_L I_C - U_C = 0 \quad (1)$$

This equation can be simplified by assuming that the voltages are completely balanced and also assuming $I_B = -I_C$.

$$U_B - U_C = \sqrt{3} U_A \measuredangle -90° = 2 \times I_B \times (Z_L + \alpha \times Z_{NL}) \quad (2)$$

The assumption of voltage balance from angle point of view, especially for faults far from the relay location, which is discussed in this article, is somewhat appropriate, but from magnitude point of view, it depends on the system conditions and is not correct in general. Nevertheless, due to the absence of connection to the ground in the investigated fault, the assumption of voltage balance is acceptable, but it is necessary to consider the effect of this assumption using a reduction factor in the impedance calculation. Impedances seen by phase-to-phase loops considering phase A as reference will be as follows.

$$Z_{AB} = \frac{U_A - U_B}{I_A - I_B} = \frac{\sqrt{3} U_A \measuredangle -150°}{I_B} = 2 \times (Z_L + \alpha \times Z_{NL}) \times 1\measuredangle -60°$$
$$Z_{BC} = \frac{U_B - U_C}{I_B - I_C} = \frac{\sqrt{3} U_A \measuredangle -90°}{2 I_B} = Z_L + \alpha \times Z_{NL} \quad (3)$$
$$Z_{CA} = \frac{U_C - U_A}{I_C - I_A} = \frac{\sqrt{3} U_A \measuredangle -30°}{I_B} = 2 \times (Z_L + \alpha \times Z_{NL}) \times 1\measuredangle 60°$$

As expected, the impedance of the phase-to-phase BC loop is equal to the impedance of the fault, i.e. $Z_L + \alpha \times Z_{NL}$. However, the impedance of other loops is also reduced and approach to distance protection zones by a phase shift angle and twice the amplitude in comparison to BC loop. In sub-transmission and transmission, the impedance angle of the line is more than 70 degrees, and as a result, for the investigated example, the impedance of Z_{AB}, especially in the sub-transmission level has a significant resistance, and if the resistance reach of the phase-to-phase loop is high, it is possible to enter the starter zone. Therefore, despite the absence of a fault on phase A, detection of fault on phase A is possible. If the current of phase A exceeds a minimum value (which is adjustable in some relays and non-adjustable in some other relays), despite the absence of a fault on this phase, the AB fault loop is evaluated by the relay as a completely valid fault loop and the possibility of mal-operation is provided. In this situation, assuming that the impedance of the fault loop AB is completely resistive and considering a 20% safety margin, the condition of the resistive reach of zone 1 in order to prevent interference with zone 1 of the next lines by setting α in equation (3) equal to zero can be written as follows.

$$R1PP < 2 \times 0.8 \times 2 \times |Z_L| \; \Omega/loop \quad (4)$$

In this equation, R1PP is the phase-to-phase resistive reach of the Quad characteristic in the relay. It should be mentioned that the first factor 2 in (4) is used to convert the impedance of ohm/phase to ohm/loop. The condition of non-interference of zone 2 with the assumption of a 20% safety margin and the assumption of 80% coverage of the next line by zone 1 is as follows.

$$R2PP < 2 \times 0.8 \times 2 \times |Z_L + 0.8 \times Z_{NL}| \tag{5}$$

In this equation, R2PP is the phase-to-phase resistive reach of zone 2 with Quad characteristic. Based on this equation, the selection of phase-to-phase loop resistance depends on the impedance of the protected line and the impedance of the next line, and it is not possible to choose the phase-to-phase resistance without considering the relay algorithm. The results of this analysis make it clear that in the impedance starters, choosing the phase-to-phase resistance reach must be done by considering the limitations of the relay. It is worth noting that in general, resistance reach reduction of Quad characteristic could have adverse effect when fault resistance seen by distance relay is high. Taking into account the infeed effect, additional resistance seen by distance relay in phase-to-phase loop is $R_F \times \frac{I_{Remote}}{I_{Relay}}$ which could be significant in general. However, considering the fact that R_F is a very low value for metal-to-metal faults, it is acceptable to reduce resistance reach of a Quad characteristic to cover the relay limitations. Moreover, most industrial relays still use MHO characteristic for phase-to-phase faults, which covers the low fault resistance.

3) Results

In order to evaluate the formulation presented in order to select the Quad characteristic resistance reach in distance relays with impedance starter, the results of a practical incident are used, in which zone 1 is set equal to 80% of the line length. In Figure 2, the arrangement of the studied 63kV system is shown along with the performance of the protection system for phase-to-phase AB fault.

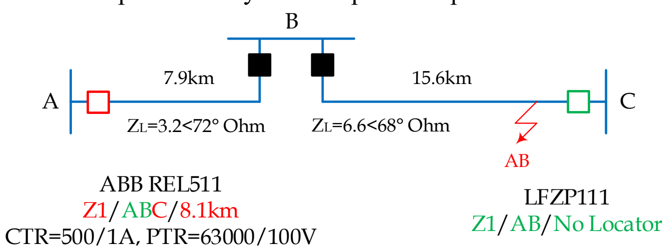

Fig. 2. Phase-to-phase fault from distance relay point of view.

Based on this figure, the operation of the protection system in C substation is correct, while with the operation of zone 1 of ABB REL511 relay in A substation for the fault even outside zone 3, the distance relay of B-C line in B substation which has detected the fault in zone 2 (with 400ms time delay) did not have a chance to operate. It should be mentioned that based on the instructions on calculating the setting of the protective relays in the sub-transmission level, the phase-to-phase resistive reach of zone 1 is equal to 25 ohm/loop and for zone 2, it is equal to 30 ohm/loop. In Figure 3, the recorded voltage and current waveforms in the ABB REL511 distance relay in A substation are depicted.

The duration of fault clearance in the system is about 180ms, which is much longer than the fault clearance by distance protection zone 1 (about 80ms), which is due to the change of impedance seen at the distance relay location after the circuit breaker operation in C substation. Based on this figure, it can be seen that the voltage and current at the distance relay location increased after the circuit breaker operation in C substation. In Table 1, the events recorded in the ABB REL511 distance relay are displayed.

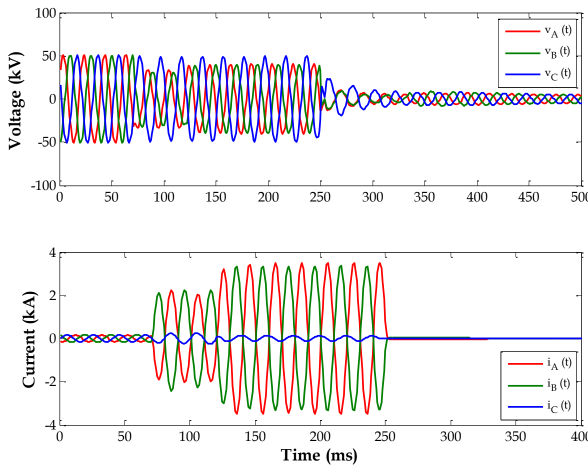

Fig. 3. Voltage and current waves recorded by ABB REL511.

Table 1: Recorded events by ABB REL511

#	Name	Time	Status
01	ZM4-START	14.56;12.025	On
02	ZM5-START	14.56;12.025	On
03	GFC-STFWL1	14.56;12.025	On
04	GFC-STFWL2	14.56;12.025	On
05	GFC-STFWL3	14.56;12.025	On
06	TR01-TRIP	14.56;12.085	On
07	TR01-TRL1	14.56;12.085	On
08	TR01-TRL2	14.56;12.085	On
09	TR01-TRL3	14.56;12.085	On
10	ZM1-TRIP	14.56;12.085	On
11	ZM1-START	14.56;12.085	On
12	ZM2-START	14.56;12.095	On
13	ZM2-START	14.56;12.195	Off
14	ZM1-TRIP	14.56;12.205	Off
15	ZM1-START	14.56;12.205	Off
16	GFC-STFWL3	14.56;12.215	Off
17	ZM4-START	14.56;12.225	Off
18	ZM5-START	14.56;12.225	Off

In this table, in the status section, "On" means that the signal is activated and "Off" means that the signal is deactivated. It should be mentioned that the GFC signal stands for General Fault Criteria and means the activation of the starter output. For example, GFC-STFWLx means detection of fault in phase x in forward direction. Additional information regarding the used abbreviations is provided in the appendix. It is worth noting that based on the information provided in the relay manual, the formulation of phase-to-phase impedance calculation by GFC is quite similar to the formulation of phase-to-phase impedance calculation by protection zones. Based on the information shown in Figure 4, the relay has detected a fault in phase C in addition to phases AB (activation of GFC-STFWL3 signal). 60ms after detecting the fault in phase C, the activation of the zone 1 trip signal ZM1-TRIP can be seen in Table 1. In Figure 4, the impedance seen by the distance relay in A substation along with the protection zones and the starter zone before the circuit breaker operation in the C substation is depicted.

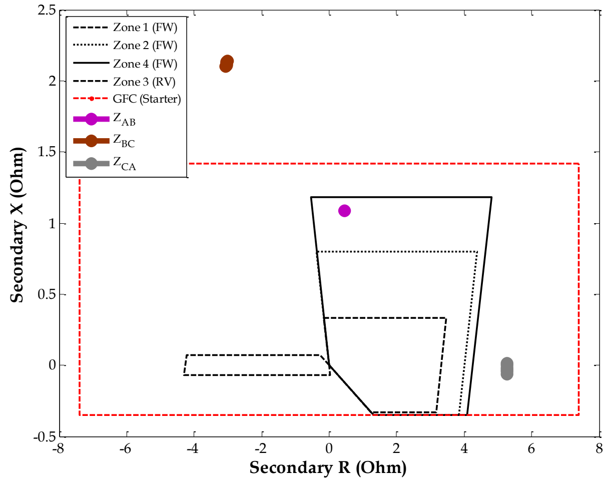

Fig. 4. Phase-to-phase impedance seen by ABB REL511 before operation of circuit breaker in C substation.

According to this figure, the angle of CA impedance is about -3 degrees (outside the distance zone but inside the starter zone), the angle of AB impedance is about 70 degrees (inside zone 3) and the angle of BC impedance is about 138 degrees (outside the zone), which are in good agreement with the results presented in the previous section. Impedance of the phase-to-phase loops at the distance relay location of A substation after operation of circuit breaker in C substation and disappearing the infeed effect is shown in the following figure.

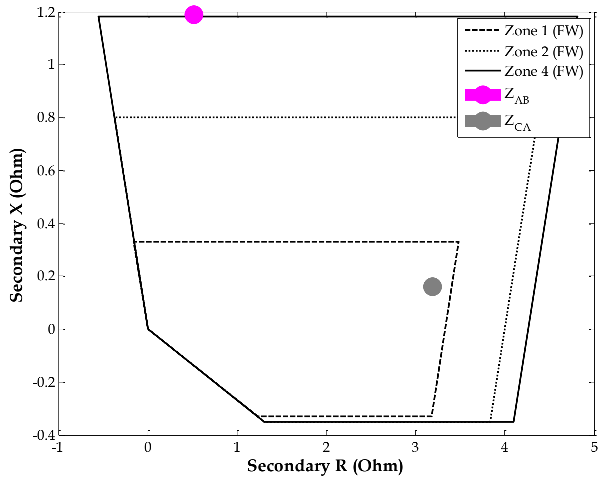

Fig. 5. Phase-to-phase impedance seen by ABB REL511 before operation of circuit breaker in C substation.

As it can be seen, despite the absence of fault on phase C, CA impedance has a high resistance value and enters zone 1. According to the arrangement shown in Figure 2 and based on equation 3, the value of Z_{CA} is equal to $\frac{500A/5A}{63kV/0.1kV} \times 2 \times (3.3\measuredangle 72^\circ + 6.6\measuredangle 68^\circ) = 3.09 + j0.452\Omega$ which has a very good agreement with results obtained in previous section due to lack of sensitivity to the non-ideal phase difference between the faulty phases; as shown, by the practical result obtained in Figure 5. At first, the settings have been reviewed without considering the limitations of the relay algorithm and the phase to phase resistance reach of zone 1 is reduced from 6 ohm/loop to 0.928 ohm/loop using the construction provided by Iran Grid Management Company (IGMC). Table 2 shows the information recorded by the ABB REL511 relay during the test using new setting values.

Table 2: Recorded events by ABB REL511 during test

#	Name	Time	Status
01	GFC-STFWL1	12.17;35.886	On
02	GFC-STFWL2	12.17;35.886	On
03	GFC-STFWL3	12.17;35.886	On
04	SOTF I PU	12.17;35.896	On
05	Zone 5 ST ND	12.17;35.916	On
06	ZM5-START	12.17;35.916	On
07	ZM2-START	12.17;35.926	On
08	ZM4-START	12.17;35.946	On
09	ZM2-START	12.17;36.046	Off
10	SOTF I PU	12.17;36.046	Off
11	Zone 5 ST ND	12.17;36.056	Off
12	ZM4-START	12.17;36.056	Off
13	ZM5-START	12.17;36.056	Off
14	GFC-STFWL3	12.17;36.067	Off
15	GFC-STFWL1	12.17;36.077	Off
16	GFC-STFWL2	12.17;36.077	Off

As it can be seen, by reducing the resistance reach of zone 1, the distance protection has not operated in this zone, however, this fault has been seen in zone 2 (activation of the ZM2-START signal). As a result, zone 2 interference occurred, which means that the fault is simultaneously located in zone 2 of the distance relays in A and B substations. According to the results, firstly, the condition of non-interference of zone 2 is checked with the assumption of 20% safety margin and also the assumption of 80% coverage of the next line by zone 1.

$$R2PP < 2 \times 0.8 \times 2 \times |Z_L + 0.8 \times Z_{NL}| \quad (6)$$

By replacing the numerical values, the value of the resistance reach will be equal to 3.54 ohm/loop, which is much less than the new value calculated for the resistance reach of zone 2 (21.6 ohm/loop) and the setting of the resistance reach of Zone 2 at the time of the incident (about 8 ohm/loop). Table 3 shows the data recorded by the ABB REL511 relay after the test.

Table 3: Recorded events by ABB REL511 after modifying zone 2 resistance reach

#	Name	Time	Status
01	SOTF I PU	12.25;36.221	On
02	GFC-STFWL1	12.25;36.221	On
03	GFC-STFWL2	12.25;36.221	On
04	GFC-STFWL3	12.25;36.221	On
05	Zone 5 ST ND	12.25;36.251	On
06	ZM5-START	12.25;36.251	On
07	ZM4-START	12.25;36.271	On
08	Zone 5 ST ND	12.25;36.381	Off
09	ZM4-START	12.25;36.381	Off
10	ZM5-START	12.25;36.381	Off
11	SOTF I PU	12.25;36.381	Off
12	GFC-STFWL3	12.25;36.401	Off
13	GFC-STFWL1	12.25;36.411	Off
14	GFC-STFWL2	12.25;36.411	Off

By applying this new value for the phase-to-phase resistance reach of zone 2, the distance protection start is no longer activated in zone 2, which is appropriate. The figure 6 shows the distance protection zones for phase-to-phase fault after changing the settings.

4) Summary and Conclusion

The problem associated with mal-operation of distance relays caused by impedance starter due to its operation under out-of-zone phase-to-phase faults has been investigated. The mathematical equations are developed and by introduction of appropriate assumptions, it is demonstrated that under sound conditions, it is possible that the phase-to-phase loop impedance enters the starter zone; despite the fault absence; and will pretend a fault condition. Using the developed mathematical relationships, it is proposed to adjust the resistance reach of distance zones of impedance starter-based relays so that the protection remains inoperative for out-of-zone faults. The magnitude of phase-to-phase loop resistance reach of zone 1 is set as a function of the impedance of the line under protection while the phase-to-phase loop resistance reach of zone 2, is set in addition to the impedance of the line under protection, as a function of the impedance of the next line in series with this line. In general, it is not possible to set the phase-to-phase resistance of the impedance starter reach without considering the limitations of the relay. Finally, using a practical case which caused mal-operation of the distance protection under out-of-zone phase-to-phase fault, the effectiveness of the proposed method has been shown in practice through the test of the ABB REL511 distance relay.

5) References

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6) Appendix

The abbreviations employed in this paper are based on the ABB REL511 relay manual and are given in Table 4.

Abbreviation	Stands for	Meaning
GFC	General Fault Criteria	Fault detection by starter
FW	Forward	Forward direction
RV	Reverse	Reverse direction
ST START PU	Start	Start of protection function
ZMx	Measuring Zone x	Distance protection zone
Lx	Phase x	Faulty phase
SOTF I PU	Switch On To Fault I Pickup	Current Based Switch On To Fault Pickup
Trip	Trip	Trip command to circuit breaker