Short Circuit Arc and the Performance of Distance Protection in 150 kV System

Handy Wihartady, Marjan Popov, Lou van der Sluis

***Abstract*—Most short circuit arc occurrences in the string insulator or arcing horn are due to transient over voltage caused by direct or indirect lightning stroke. This situation leads to single-phase to ground fault that will be detected by transmission line protection (distance relay and autoreclosure). In the previous work [1], the arc parameters in 150 kV system are found through comparison between actual voltage and current measurements and simulation results during single open pole process. In this paper, those parameter which represent short circuit arc fault are used for simulating several single-phase to ground faults in different cases to evaluate the performance of existing distance protection setting. The small arc resistance makes the evaluation of the impact of system line configuration to the performance of distance protection easier. Fault situations are generated using ATPDraw-EMTP, meanwhile the characteristic setting and the performance of distance protection are evaluated using Transview-Test Universe Omicron.**

***Keywords*: short circuit arc, distance protection.**

I. Introduction

Single-phase to ground fault is the most frequent faults in overhead transmission lines. Basically, the fault is caused by low resistant arc (short circuit arc in the string insulator or arc fitting) or high resistant arc (arc through branches of tree). In Indonesia, a country were lightning occurs very often, lightning strikes are the main cause for single-phase to ground faults. High transient impulse voltage, as a result of direct or indirect lightning strikes, pushes electric strength in the air between arcing horn or string insulator, functioning to insulate phase conductor to the ground, to a higher value. When the impulse voltage is higher than the air breakdown voltage, the air as an insulating medium will become fully conductive and it will no longer be sufficient to isolate the voltage [2]. Consequently, a breakdown in the air appears between the arcing horns or in the surface of the string insulator, connects the phase wire to the ground and develops the fault.

The short circuit arc has non-permanent fault characteristic, thus it is possible to overcome and clear the fault while maintaining the system stability and preventing outage operation of the lines. In order to overcome and clear the non-permanent faults, the zone 1 setting of distance protection, as a main protection, incorporated with dead time setting of a Single Phase Auto Reclosure (SPAR) must be in agreement with the short circuit arc behavior

In the previous work, the arc parameters in 150 kV are obtained by simulating several fault arc incidents in 150 kV system during single open pole process. The current and the voltage during arcing fault in the simulation are compared with the measurements taken from disturbance fault recorder. In this paper, those parameters will be used for simulating several single phase to ground fault situation in different line configuration by using ATPDraw. The terminal current and voltage which result from the simulation are extracted into impedance form. Then, the impedance is plotted together with distance setting characteristic in R-X diagram (resistance-reactance or impedance diagram) to analyze the behavior and influence of short circuit arc and system line configuration to distance relay performances by using Transview-Test Universe Omicron software.

II. Arc Parameter

Research area is focused on 150 kV transmission line in Indonesia which consist of two string insulator arrangements, with and without arcing horn. In the first type, short circuit arc will occur in the arcing horn in the form of sparkover. In other type, arc will occur in the surface of string insulator as a flashover. Both arc situation have been investigated and resulted in different arc parameters as follow [1]:

TABLE I
Arc Parameter in Different Arc Fitting

Arc Parameter	Sparkover	Flashover
l_0 (cm)	120	215
u (kV)	1.38	0.9
r (mΩ)	53	40
τ_0 (ms)	0.5	0.9
v_l (cm/ms)	45	22
v_τ (µs/cm)	0.833	0.466

With : l_0 = initial length of the arc column
u = total characteristic arc voltage
r = total characteristic arc resistance
τ_0 = initial time constant
v_l = speed of arc elongation
v_τ = speed of time constant decrease

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III. IMPEDANCE EXTRACTION

The impedance value measured by the distance relays is at fundamental frequency. Although the input current and voltage consist of harmonics, they are filtered in such a way so that the final output takes into account the impedance at fundamental frequency only. Since an impedance extraction will also be used for distance relay performance evaluation, it is important to get impedance value for the fundamental frequency. The algorithm used for impedance derivation is the recursive full-cycle Discrete Fourier Series (DFS) which is also widely used in the distance protection. The current and voltage samples are transformed into phasor quantities by the recursive full-cycle DFS filter [3,4] according to this algorithm:

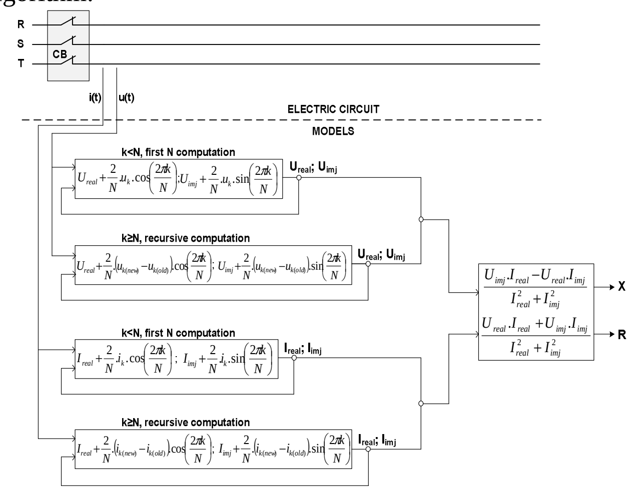

Fig. 1. Impedance extraction by using MODELS, block diagram representation.

Above block diagram describes DFS impedance extraction by using MODELS in EMTP [5]. Compared to the post processing impedance extraction done by Transview, the implementation of DFS in MODELS gives identical result in R-X diagram with the same input current and voltage as it can be seen in Fig. 2. Both diagrams are in primary values, without the presence of voltage and current transformer. By this comparison, it is concluded that Transview software is reliable to be used for analyzing distance protection performances.

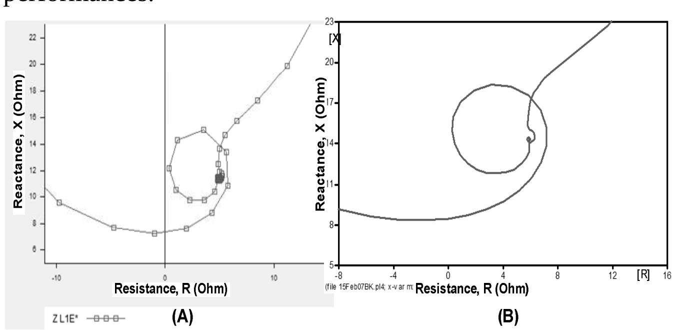

Fig. 2. Impedance extraction result. (A) Transview; (B) MODELS.

IV. QUADRILATERAL DISTANCE RELAY DESIGN CHARACTERISTIC

In distance protection, the impedance measuring principle is the reverse of short circuit calculation rule. The voltage and current are used as input for calculating the measured impedance. The resulting impedance is compared with balanced point setting to decide whether the fault occurs inside or outside the operating area. Numerical distance relay from various brands have two different domain design characteristics for their setting for both phase-to-phase and phase-to-earth elements, which are ohm-loop and ohm-phase domains. In the ohm-loop domain, the measured impedance consists of positive, negative and zero sequence impedance which depends on the type of the fault. In the ohm-phase domain, it is identical with positive sequence impedance. The difference between those two domains is important for the protection engineer to avoid mistakes in implementing the setting calculation of the relay or during distance relay testing.

A. Phase to Phase Element

For double phase fault, the measured ohm-loop impedance is two times larger than the measured ohm-phase impedance. If the input setting for zone 1 in the phase-to-phase element is $Z_1 = R_1 + jX_1$ which is in the reference of the positive sequence impedance, then the design quadrilateral characteristic for both ohm-loop and ohm-phase domains are illustrated in Fig. 3.

$$Z_{ml} = 2 \times Z_{mp};\ X_{ml} = 2 \times X_{mp} \tag{1}$$

$$R_{ml} = 2 \times R_{mp};\ R_{ml} = 2.R_1 + R_f;\ R_{mp} = R_1 + \frac{R_f}{2} \tag{2}$$

Where Z_{ml} = the measured loop impedance
Z_{mp} = the measured phase impedance

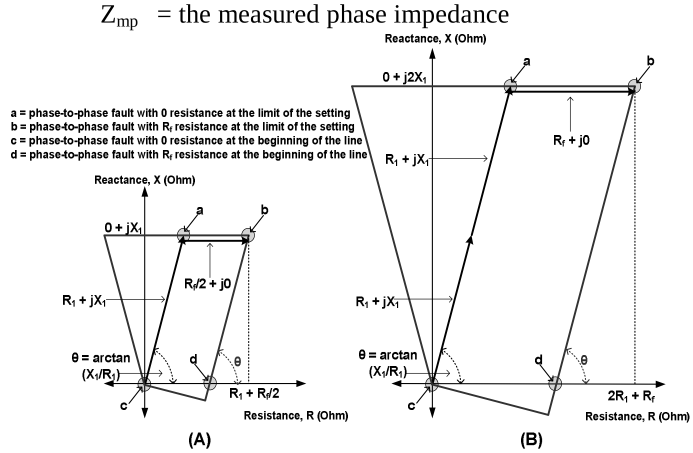

Fig. 3. Design characteristic in ohm-phase (A) and ohm-loop (B) in phase to phase element.

B. Phase to Earth Element

In phase-to-ground fault, the ohm-loop impedance is $(1 + K_N)$ times larger than the ohm-phase impedance. If the input setting for zone 1 in phase-to-phase element is $Z_1 = R_1 + jX_1$, which is in the reference of positive sequence impedance, and zero sequence impedance of the line is defined as $Z_0 = R_0 + jX_0$, then the design quadrilateral characteristic both ohm-loop and ohm-phase domains for phase-to-ground faults are illustrated by Fig. 4.

$$Z_N = \frac{Z_0 - Z_1}{3};\ K_N = \frac{Z_0 - Z_1}{3.Z_1} = \frac{Z_N}{Z_1} \tag{3}$$

$$Z_{ml} = (1 + K_N).Z_{mp}\,;\, X_{ml} = \left(1 + \frac{X_N}{X_1}\right).X_{mp} \qquad (4)$$

$$R_{ml} = \left(1 + \frac{R_N}{R_1}\right).R_{mp} \qquad (5)$$

$$R_{ml} = R_1.\left(1 + \frac{R_N}{R_1}\right) + R_f\,;\, R_{mp} = R_1 + \frac{R_f}{1 + \frac{R_N}{R_1}} \qquad (6)$$

Where Z_N = earth return impedance

K_N = zero sequence compensation factor

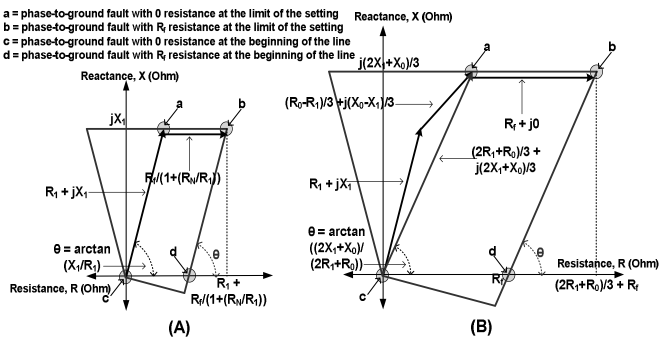

Fig. 4. Design characteristic in ohm-phase (A) and ohm-loop (B) in phase to earth element.

V. Simulation Cases

The fix arc models are used in different simulation cases using ATPDraw to evaluate the performance of the existing distance protection setting. By post processing stage using Transview, the terminal fault current and voltage at each measuring point are extracted at impedance fundamental frequency and plot automatically in the R-X diagram, at the same place where the distance setting characteristic is drawn. The distance relay characteristic is drawn by using Test Universe Omicron software in rio file (standard setting file characteristic of the software) with ohm-phase domain. All impedance values are in primary side without considering the presence of voltage and current transformer. For all simulation cases, 40 ms duration for short circuit arc fault phase A to ground and 1.2 + j0.31 Ω for effective tower footing resistance (Z_{EF}) are applied.

A. Radial Single Circuit Case

In this case, the infeed current occurs only in TL SS side because system source is connected to its bus. The fault location is 80% line length from TL SS, as it can be seen in Fig. 5. In this overhead line, string insulator with arcing horn arrangement is used.

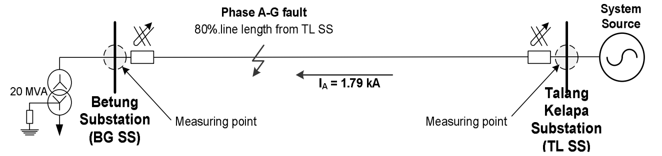

Fig. 5. Radial single circuit case.

This condition is perfect example to describe the fundamental impedance behavior with respect to the primary arc fault phase-to-ground and effective tower footing resistance. The analysis of the impedance and distance relay setting is focused in zone 1 protection area. The investigated numerical distance relay has sampling rate 1204.8 Hz or sampling period 0.83 ms. The relay will be operated in zone 1 if the measured impedance is continuously in the area of zone 1 setting for 13.3 ms or 16 times of sampling.

Fig. 6 shows phase A fault impedance trajectory (Z_A) and different zone 1 setting (80, 85 and 90% of Z_L) in R-X plane at TL side. Each dot in the Z_A path represents the sampling period of 0.833 ms. In this fault condition, the Z_A trajectory comes into the protected line impedance Z_L, but it is slightly shifted to the right position of 80%.Z_L and a bit higher. This describes the effect of the primary arc impedance (Z_{ARC}) and the effective tower footing impedance (Z_{EF}). The total impedance Z_{ARC} and Z_{EF} as a result of impedance extraction in the fundamental frequency is more or less constant 2.14 + j0.41 Ω. For zone 1 setting 80%.Z_L, the Z_A trajectory is not continuously inside the protection area for 13.3 ms. In this situation, the distance relay does not operate correctly, there is a possibility that it will not operate instantaneously. For zone 1 setting 85 and 90%.Z_L, the Z_A trajectory is continuously inside the protection area for more than 13.3 ms. Based on this case, it is recommended to increase zone 1 setting into 85 or 90%.

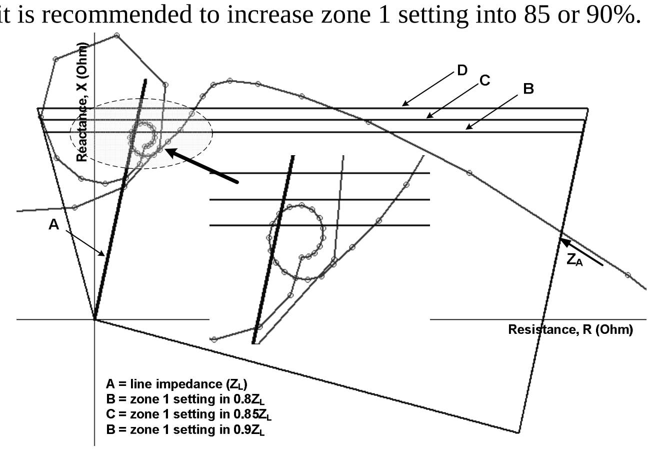

Fig. 6. Fault impedance phase A (Z_A) trajectory at TL side.

B. Radial Double Circuit Case

Two different fault conditions, double (case A) and single circuit (case B) operations, are simulated to see the effect of the total fault impedance ($Z_T = Z_{ARC} + Z_{EF}$) at single infeed, double infeed as well as parallel line mutual inductive coupling to the distance relay performances. Existing distance relay setting does not consider zero sequence compensation factor (parallel zero sequence current and mutual impedance). In this transmission line, string insulator with arcing horn arrangement is used.

In case A, two circuits are operated with fault location at line 1, 80 % from KR SS. The Z_A trajectory and the distance relay setting in R-X plane at each line side responses to this fault are shown in Fig. 7. In line 2, the KR distance relay sees the fault in front of its position at zone 3 protection area. Whereas the MR distance relay sees the fault behind its position at zone 4 protection area. Both KR side and MR side distance relays at line 2 are used as back up protection when the MR distance relay at line 1 fails to operate. In line 1, both KR and MR Z_A trajectories do not come exactly in the line impedance position as described in their R-X plane. The KR Z_A trajectory is at the right position and higher than 80%.Z_L. The MR Z_A trajectory is at the right position of 20%.Z_L. Those occur because of two reasons: the infeed current from the opposite side of the line (KR side 2.54 kA and MR side 1.39 kA) to Z_T; the mutual zero sequence impedance Z_{0M} and the zero sequence current which flows in line 2 (1.39 kA).

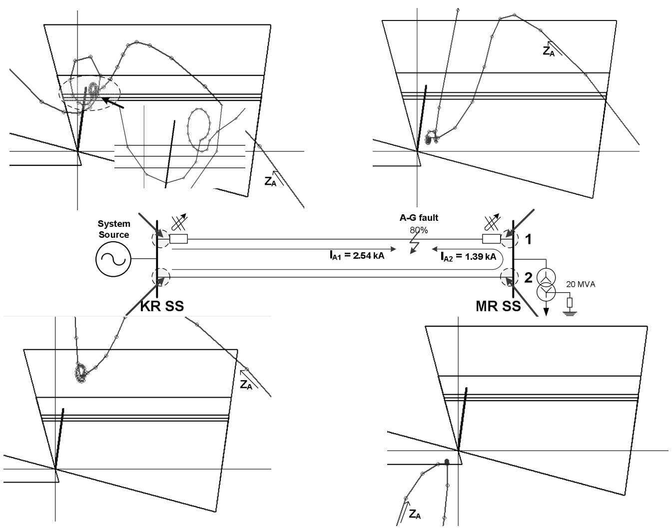

Fig. 7. Fault impedance Z_A trajectory at each side of the distance relay; case A.

Another case (case B) is simulated to see how far the infeed current and mutual zero sequence impedance affects the KR - MR line section. In case B, the fault location is still 80 % from KR SS. The line configuration is different now; line 2 is not operated and earthed at each line side. With this configuration, the infeed current and the mutual zero sequence impedance effects are omitted. The Z_A trajectories in both sides are shown in figure 8. From the Z_A trajectory in KR side, it is clearly shown that the underreach condition vanishes and the measured total fault resistance decreases. Those situations confirm the infeed current and the mutual zero sequence effects.

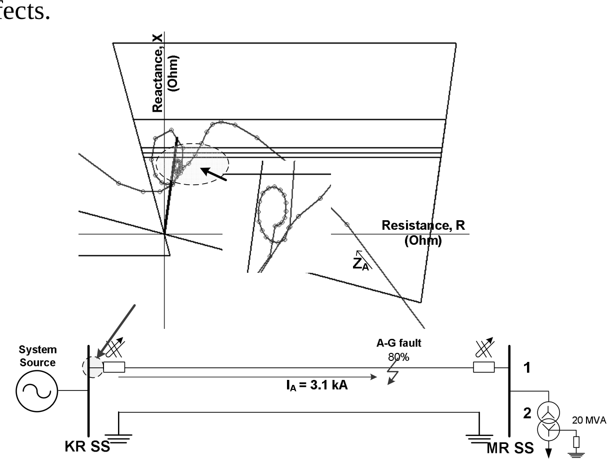

Fig. 8. Fault impedance Z_A trajectory at KR side; case B.

C. Non-Radial Double Source Double Circuit Case

The next case is the arc fault in non-radial double circuit with double system source. The arc fault is located in express feeder Prabumulih (PB) – Bukit Asam (BK), 80% and 95% of the line length from PB SS. This section is surrounded by two large power plants (2x52 MW in GM SS and 4x65 MW in BK SS) and three system sources. Within this situation, a high short circuit current will be expected in the simulation. In this transmission line, string insulator without arcing horn arrangement is used.

R – X plane that consist of Z_A trajectory and distance relay setting at each measuring point for 80 % fault location are shown in Fig. 9. At PB SS side, the PB 2 distance relay detects the fault behind its protection area because the short circuit current (0.48 kA) in this line flows to the measuring point. This short circuit current also influences the measured impedance in the PB 1 distance relay. The 0.48 kA short circuit current, which flows in the opposite direction of the 1.44 kA short circuit current, causes the measuring error to a negative value [6]. This makes the total measured reactance in the PB 1 distance relay reduced. This situation does not interfere the PB 1 distance relay operating time because the Z_A trajectory is still inside zone 1 protection area. In other situation where the fault location is more than zone 1 reactance range (more than 80 %), there is a possibility that overreach condition will occur and influence the distance relay operating time. Additional analog input current from the parallel line (PB – GM line) to compensate mutual zero sequence effect (in the PB 2 distance relay) is the best way to cope with this situation.

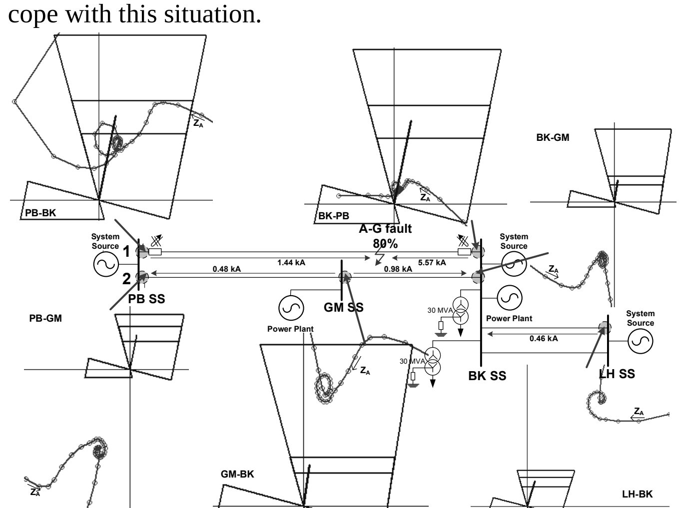

Fig. 9. Fault impedance phase A Z_A trajectory at each side of the distance relay; fault location 80% from PB SS.

Now the analysis is focused to the BK 1 distance relay. As generally known, there are total of ten possible faults that can be seen by the relay. They are A – G, B – G, C – G, A – B, A – C, B – C, A – B – G, A – C – G, B – C – G and A – B – C. When a disturbance occurs, the distance relay will measure all those related impedances, and then decide which kind of fault occurred in the network. At Fig. 9 fault situation, the BK 1 distance relay does not only sense the fault in phase A – G, but also in phase A – B and A – C. In Fig. 10, it is clearly shown that high short circuit current in phase A at BK 1 measuring point (5.57 kA) causes the measured impedance Z_{AB} and Z_{AC} to approach the phase-to-phase element protection area. In this situation, the Z_{AC} measured impedance is less than 13.3 ms inside the zone 1 protection area. Accordingly, the distance relay does not declare that a fault in phase A – B or A – C occur in the network. 13.3 ms is the minimum sensing operating time for the distance protection in this case.

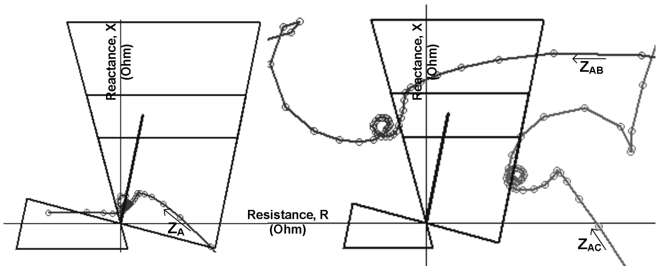

Fig. 10. Z_A, Z_{AB} and Z_{AC} trajectories in phase-to-ground and phase-to-phase elements; 80% from PB SS.

For the other simulation, the fault point is located 95% from PB SS approaching BK SS. The phase A short circuit current at BK 1 measuring point becomes 8.26 kA. The Z_A, Z_{AB} and Z_{AC} measured impedances are shown in Fig. 11. The Z_A measured impedance approaches to the origin point whereas the Z_{AB} and Z_{AC} go deeper in the zone 1 phase-to-phase protection area. The Z_{AC} trajectory is inside the protection area more than 13.3 ms. Consequently, the BK 1 distance relay declares a fault in phase A – G and phase A – C. The SPAR setting operation in Indonesia system is triggered by zone 1 phase-to-ground element and signaling scheme elements. For this fault condition, the distance relay also declares phase A – C fault in the network. Therefore, the SPAR operation is prohibited. At the end, only the PB 1 circuit breaker will be reclosed and the BK 1 circuit breaker will be tripped 3 poles responding to non-permanent short circuit arc.

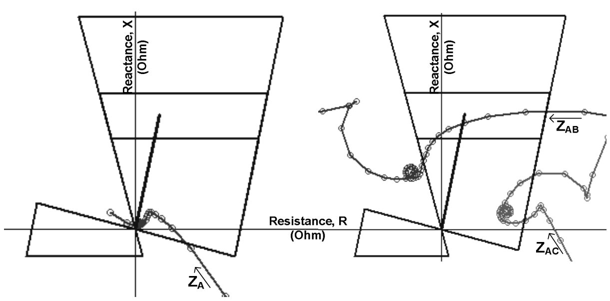

Fig. 11. Z_A, Z_{AB} and Z_{AC} trajectories in phase-to-ground and phase-to-phase elements; 95% from PB SS.

There are two actions that can be done to avoid above situation:

- Evaluate phase to phase resistive range setting for zone 1, especially near strong source area where high phase to ground short circuit current is expected. The BK 1 zone 1 resistive range is reduced into 10.5 Ω in ohm-phase domain. With this new setting, instantaneous zone 1 phase-to-phase tripping (phase A – C) will be avoided as shown in figure below.
- Modify logic setting for phase to phase trip output. Nowadays, most modern numerical distance relay consist of logic editing function, for example: GE URD60 [7] – *flexlogic*, ABB REL670 [8] – CAP 531 and Toshiba GRZ 100 tipe B [9] – *PLC logic editor*. With this function, users can add new logic block function according to their need. With the modification of phase to phase trip output logic, phase select function will supervise phase to phase order trip and make sure that it will only trip in case of phase to phase fault.

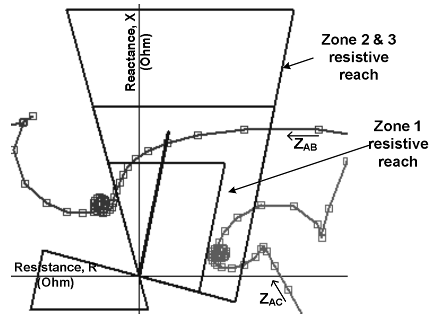

Fig. 12. Z_{AB} and Z_{AC} trajectories with reduced zone 1 resistive range setting; 95% from PB SS.

VI. Conclusions

Three different short circuit arc simulation cases have been evaluated in relation to the existing distance relay protection setting. With post processing impedance extraction using Transview, a clear description about impedance trajectory during fault arc condition in distance element characteristic can be achieved. Thus, it will make the evaluation for distance protection performances in different line configurations easier. Gaining information from the simulation results, several improvements regarding to distance relay protection setting should be done. Those improvements consist of:

- Additional zone 1 setting impedance for distance relay in radial network from 80% into 85% or 90% is needed to cope with the fault arc and the effective tower footing impedance effect.
- Supplementary setting that will compensate mutual zero sequence impedance impact in the case of parallel line is necessary.
- In order to avoid unsuccessful SPAR operation in case of an arcing fault near the strong bus, reviewing existing phase-to-phase resistance and logic trip setting is a necessity.

VII. References

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