Protection of Partially Grounded Microgrid Interconnection Line using Residual Voltage Compensation

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***Abstract*—Protection relays at the Point(s) of Interconnection of a microgrid should trip as fast as possible to disconnect the microgrid from the utility grid for a fault on the interconnection line. A Single-Line-to-Ground (SLG) fault on a utility feeder that supplies a microgrid (or distributed energy resource) with an ungrounded interconnection transformer is difficult to detect using the current- or voltage-based protection functions. This paper studies the use of phase distance relay at the low-voltage (microgrid) side of the interconnection transformer to provide coordinated protection against ground faults on the high-voltage (utility) side. The apparent impedance measured by the phase distance relay is not accurate if traditional methods are used. The study shows the closer the fault to the relay, the larger the apparent impedance seen by the relay, which conflicts with the fundamental distance protection principle. Thus, it is proposed to utilize residual voltage compensation method to solve this issue such that the phase distance relay can correctly identify SLG faults, accurately measure the apparent impedance and fault location, and reliably isolate the fault without jeopardizing the stability of the downstream microgrid system. Various cases have been simulated and analyzed using ASPEN and PSCAD software tools to demonstrate the effectiveness of the proposed method. The results show effective performance of the system under different fault scenarios.**

***Index Terms*— Distributed Energy Resources, Microgrid, Residual Voltage Compensation, Phase Distance Relay, Interconnection Protection.**

I. INTRODUCTION

THE increasing penetration of Distributed Energy Resources (DER) and deployment of microgrids (MGs) requires re-evaluation of traditional distribution protection schemes that are mainly designed for unidirectional flows of power. The selection of protective functions at the microgrid Point of Interconnection (POI) or the DER Point of Connection (POC) depends on many factors such as MG/DER size and type, utility interconnection requirements, interconnection voltage (sub-transmission or distribution), interconnection transformer configuration, and grounding of the grid (ungrounded, solidly grounded or compensated grounded). A review of grounding methods for distribution networks and traditional protection methods is provided in [1]-[3]. An interconnection transformer with ungrounded winding configuration on the utility (HV) side requires analysis of all equipment (insulators, lightning arrestors, breakers, etc.) to manage the over-voltage conditions when SLG faults occur. When a grounded distribution substation is interfacing with a microgrid via an ungrounded (or high-impedance grounded) transformer, a partially grounded network is formed. For a SLG fault on the interconnection line (utility side), the utility feeder protection may trip faster since it would see a large ground fault current (in a solidly grounded system). This, however, leaves the interconnected line ungrounded and hanging for a relatively long time before voltage or frequency elements of the POI protection operate due to insufficient power supply. It is noted that IEEE Standard 1547 [4] requires that all DERs detect an unintentional island and cease to energize the island within 2 seconds of its formation; this includes faults on the interconnection line.

Based on the above discussion, quick isolation of a SLG fault on a utility feeder that is fed by an ungrounded interconnected transformer (on utility side) is a challenging task. When the utility ground connection is lost due to the operation of the utility feeder protection, the whole interconnection line becomes ungrounded. Prior to the opening of the utility breaker, an SLG fault on the utility feeder is seen as a phase-to-phase fault with low fault current by the interconnection relay at the LV (microgrid) side of the interconnection transformer. Once the utility-side breaker opens, the fault current disappears. To protect the microgrid at the POI, two protection methods are normally utilized: (i) sending a Direct Transfer Trip (DTT) from the utility station to the POI relay once a corresponding breaker on the utility-side opens and/or (ii) using an overvoltage relay (59G) energized by a broken-delta voltage transformer on the utility side of the interconnection transformer (neutral overvoltage displacement) [5]-[9].

Fig. 1 shows the protection of the microgrid against external faults on the interconnection line, where the DTT and 59G are used to isolate the microgrid from the utility when a fault occurs on the utility feeder. The cost associated with the installation of a communication system to enable DTT scheme can be excessive. Further, although the broken-delta 59G option is an economical and sensitive solution [10]-[11], the 59G settings must be chosen very carefully to ensure protection selectivity. More specifically, longer operating times will be required for 59G function to ensure the protection will not operate for an out-of-zone fault (upstream of utility breaker). Studies have shown that 59G may fail to isolate the fault before the DER protection trips the generator within the microgrid territory.

This study investigated the issues with conventional current distance algorithm to protect the SLG fault on interconnection line and proposed an enhanced distance protection algorithm using residual voltage compensation with minimal modifications to the existing distance relay. To ensure correct operation, the performance of the modified algorithm was examined in the PSCAD simulation tool and compared with the existing algorithm using the same simulation cases.

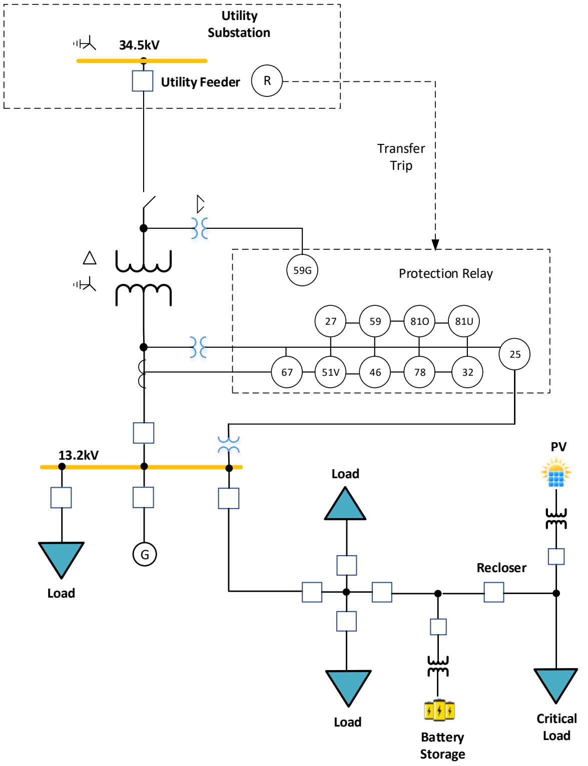

Fig. 1. An example single-line diagram of a microgrid with POI protection

II. Loss of Utility Protection

The protection against Loss of Utility (LOU) is a challenging issue that should be resolved for a microgrid that is normally connected to a utility feeder. When communication channel is available, a DTT can be used to trip the microgrid POI breaker once the utility-side breaker opens in response to a fault or power quality incident.

Using 59G function to detect SLG faults on the microgrid interconnection line is also challenging due to the grounding of the interconnection line at the utility side. When the utility system is ungrounded, the voltage seen by the relay during a SLG fault is almost three times the phase nominal voltage to neutral (see Fig. 2 and Equation (1)). This voltage will be detected by 59G function located at the broken delta potential transformer terminal.

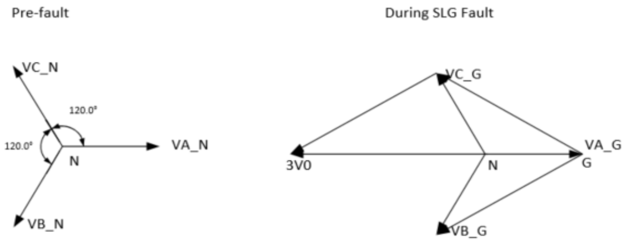

Fig. 2. Voltage phasor diagram during a SLG fault on an ungrounded system

$$3V_0 = V_a + V_b + V_c$$
$$= 0 + \sqrt{3}|V_a|\angle -150^\circ + \sqrt{3}|V_a|\angle 150^\circ = 3|V_a|\angle 180^\circ \qquad (1)$$

On the other hand, when the utility side is grounded, the neutral voltage displacement during SLG faults will be reduced and varied based on the system zero-sequence impedance and the fault location on the line. Table 1 provides the simulation results for a 34.5kV interconnection line modeled in the ASPEN software. It can be observed that the zero-sequence voltage (V_0) decreases when the SLG fault moves away from the microgrid POI, which makes setting of the 59G function a challenge; with sensitive settings, it may mis-operate for a fault outside the line. Therefore, the operation of 59G is typically delayed until the utility breaker trips/opens, which may take up to 1 second depending on the feeder protection function and fault location. The main issues with this delay are (i) over-voltage conditions during that period, (ii) adverse impact on the auto-reclosing of utility feeder breaker, and (iii) conflict with the ride through requirements of microgrid DERs. The DTT scheme can solve these issues by sending trip signal from the utility substation to the microgrid POI relay, albeit at the higher cost.

Table 1 Example 34.5kV Line Fault Simulation Results

SLG Fault Location	Measurement At Relay Location	Fault Values at DER 13.2kV	Angle (deg)	V0 at DER 34.5kV bus	Angle (deg)
0% of interconnection line (DER 34.5kV bus)	Zab (Ω)	4.550	87.00	13.30	150.30
	Zbc (Ω)	10.660	163.10		
	Zca (Ω)	11.050	10.10		
	Ia (A)	1161.000	-113.10		
	Ib (A)	1176.000	59.60		
	Ic (A)	149.000	159.20		
	Va (kV)	6.578	-66.30		
	Vb (kV)	6.601	-173.50		
	Vc (kV)	7.824	60.00		
50% of interconnection line	Zab (Ω)	4.010	84.50	11.93	150.1
	Zbc (Ω)	9.680	160.60		
	Zca (Ω)	9.960	8.60		
	Ia (A)	1285.000	-111.50		
	Ib (A)	1295.000	61.90		
	Ic (A)	148.000	159.30		
	Va (kV)	6.499	-67.40		
	Vb (kV)	6.465	-173.10		
	Vc (kV)	7.827	60.00		
100% of interconnection line (Utility 34.5kV bus)	Zab (Ω)	2.280	81.70	6.408	150.8
	Zbc (Ω)	6.330	158.30		
	Zca (Ω)	6.530	7.40		
	Ia (A)	1941.000	-111.10		
	Ib (A)	1951.000	-64.80		
	Ic (A)	140.000	160.90		
	Va (kV)	5.995	-72.30		
	Vb (kV)	5.854	-169.40		
	Vc (kV)	7.841	59.90		

Other protection functions such as overcurrent, under-/over-voltage, under-/over-frequency, rate of change of frequency and/or voltage can be used to detect the formation of the island or loss of grid. However, these types of protection have non-detection zones and may fail to detect islanding situation, especially when load and DER generation are comparable. For example, the over-current protection pickup setting must be set higher than the maximum load flow (both directions). However, due to the limited fault current rating of inverter-based DERs, the fault current contribution of a microgrid may be very small. Some microgrids embed rotating-machine-based DERs that provide adequate fault current to operate over-current relay(s) at the POI; thus, adaptive settings may be needed to account for various DER combinations. Frequency-based protections at the POI suffer from the same shortcoming as the voltage-based protections as they should also be set to operate with delay.

Fig. 3 shows the fault current contribution of a microgrid for a SLG fault on the utility feeder as measured on the microgrid/LV side of the interconnection transformer. As can be observed, the utility feeder breaker opens at 0.65sec due to the SLG fault, which causes the microgrid fault current contribution to reduce further. The 59G relay at the microgrid POI operated to isolate the microgrid at 0.75sec; this, however, may not be fast enough for some microgrid applications with seamless transition requirements.

Distance relays are widely used for protecting the high-voltage AC transmission and sub-transmission lines. The benefits and performance of distance relays (compared to traditional over-current relays) in distribution feeders with distributed energy resources are discussed in [12]. In addition, using distance relays, a fault can be located since the measured fault impedance is a representative of the distance from the relay location. The fault impedance is typically calculated using Equations (2)-(4) for single-phase-to-ground faults and Equations (5)-(7) for phase-phase, phase-phase-to-ground and three-phase faults. The MHO and Quadrilateral characteristic are typically used to determine the operation zone for a distance protection considering the variation of the fault resistance. The distance function operation can also be secured from operation during heavy load condition by using load encroachment. If the fault impedance falls inside the MHO or QUAD characteristics, the relay will claim a within-the-zone fault and operate to isolate the fault.

$$Z_{ag}=\frac{V_a}{(I_a+k_0 I_R)} \tag{2}$$

$$Z_{bg}=\frac{V_b}{(I_b+k_0 I_R)} \tag{3}$$

$$Z_{cg}=\frac{V_c}{(I_c+k_0 I_R)} \tag{4}$$

$$Z_{ab}=\frac{V_a-V_b}{I_a-I_b} \tag{5}$$

$$Z_{bc}=\frac{V_b-V_c}{I_b-I_c} \tag{6}$$

$$Z_{ca}=\frac{V_c-V_a}{I_c-I_a} \tag{7}$$

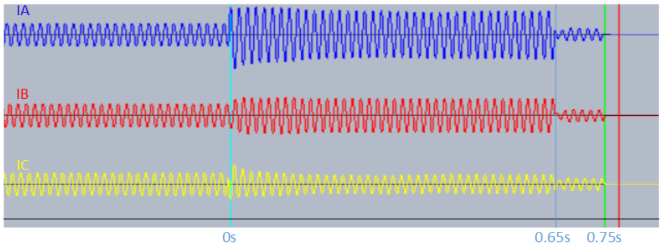

Fig. 3. An example microgrid current contribution for an external SLG fault

The effects of a wye-delta or delta-wye power transformer between distance relays and fault have already been studied [13]. The wye-delta or delta-wye transformer between a distance relay and the fault changes the complexion of the fault current and voltage by magnitude and phase angle shift as viewed by the distance-relay. More specifically, other than three-phase faults, Equations (5)-(7) cannot give correct reach and fault phase identification. The transformer causes the positive-sequence components of the currents and voltages on the relay side to shift 30° in one direction, while the negative-sequence quantities are shifted 30° in the other direction; the zero-sequence quantities are not transferred through the (wye-delta or delta-wye) power transformer.

Several studies have been conducted to improve the performance of the phase distance elements using current/voltage transformation in order to detect the fault beyond the transformer. As an example, for an LLG fault on the microgrid interconnection line with a YD11 step-up transformer, Equations (8)-(10) [14] can be used (instead of Equations (5)-(7)) to calculate the fault impedance. However, about 70% of the fault happening distribution systems are SLG faults, for which no zero-sequence current will be seen by the relay due to the delta-wye transformer configuration. Conventional ground distance protection functions cannot be used to respond to SLG faults when there is a wye-delta or delta-wye power transformer between the distance relay and the fault.

$$Z_{ab}=\frac{-3V_b}{I_a+I_c-2I_b} \tag{8}$$

$$Z_{bc}=\frac{-3V_c}{I_a+I_b-2I_c} \tag{9}$$

$$Z_{ca}=\frac{-3V_a}{I_b+I_c-2I_a} \tag{10}$$

III. DISTANCE PROTECTION WITH RESIDUAL VOLTAGE COMPENSATION

This study has been performed on the microgrid system of Fig. 1, which is connected to a 34.5kV interconnection line through a step-up (YD1) transformer. Based on the results of Table 1, using the existing phase distance relay algorithms, the impedance seen by the relay is decreased when the SLG fault moves away from the relay. This is not in line with the concept of distance protection because Equations (2)-(10) do not provide accurate value of the expected apparent impedance for SLG faults (Z_t+k*Z_l, where k is the percentage of the line at fault location, Z_t and Z_l are transformer and line impedance respectively). In other words, with a wye-delta or delta-wye transformer, Equations (5)-(7) only works for 3LG fault, while Equations (8)-(10) only works properly for phase-to-phase faults (LL, LLG, and 3LG faults); but, none of them can correctly detect SLG faults on the interconnection line.

A residual-voltage-compensated method is proposed in this study to resolve the abovementioned issue. The 3V0 signal that is supplied to the distance relay by the broken-delta High-Voltage (HV) Potential Transformer (PT) is used to compensate the calculated impedance such that the correct fault impedance is measured by the relay. A typical protection connection diagram is shown in Fig. 4, where an ungrounded microgrid system is connected to a grounded utility system. For such systems, a broken-delta PT along with a 59G relay is typically installed on the utility side to provide voltage-based protection against external (utility-side) SLG faults at the POI. In this case, the broken-delta PT can be readily connected to the distance relay on the microgrid side, with minimal effort, to detect faults on the interconnection lines. No other changes to the electrical wirings and the relay will be needed.

The voltage and current seen at the relay location are affected by the transformer winding configuration; therefore, the positive-sequence current is also impacted. The angle shift will depend on the transformer winding configuration. The block diagram of the new distance relay is shown in Fig. 5, which consists of the following major modules: phasor calculation module, impedance calculation module, impedance compensation module, angle shift module, and fault detection module. The impedance compensation module and angle shift module use transformer zero-sequence voltage on the HV side (V_0_H) and transformer positive-sequence current on the LV side (I_1) to calculate the magnitude compensation and angle shift. Other modules are typical distance relay modules with no changes made to them.

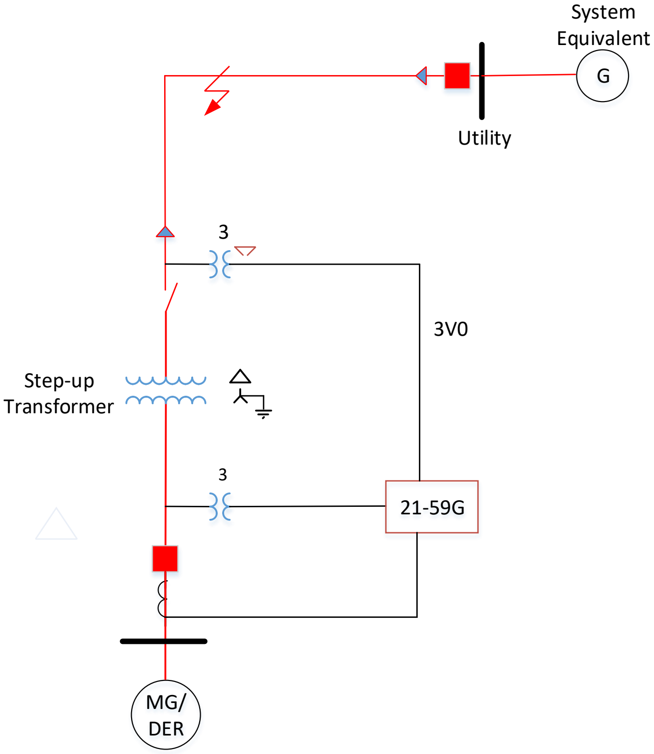

Fig. 4. Protection diagram for MG/DER interconnection line protection

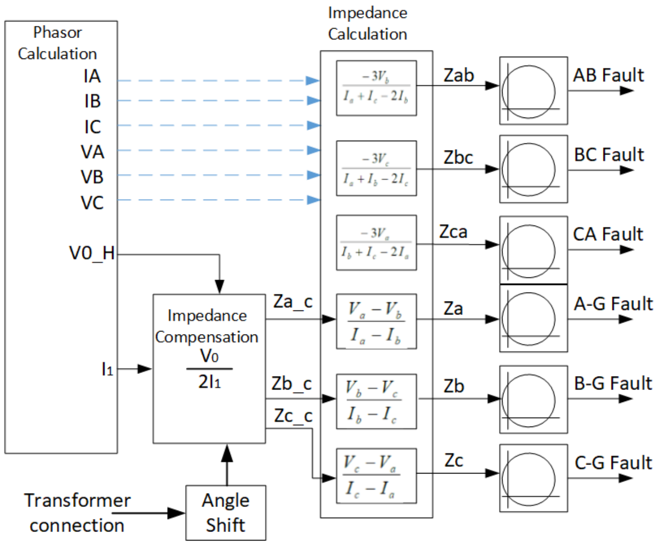

Fig. 5. Block diagram of distance relay with residual voltage compensation

IV. TESTING OF THE RESIDUAL-VOLTAGE COMPENSATED DISTANCE FUNCTION

The PSCAD/EMTDC software was used to model the microgrid system of Fig. 1 / Fig. 4 and simulate the proposed distance relay to verify its effectiveness. To do a comparative analysis, the distance relay at the POI was simulated with and without residual voltage compensation for various fault scenarios including different fault type and locations, with and without grounding resistance. The microgrid includes a combination of rotating-machine-based generators and inverter-based resources.

For a SLG fault at 0% of the interconnection line (on the HV side of the interconnection transformer), the currents and voltages seen by the relay are shown in Fig. 6 (conventional relay) and Fig. 7 (proposed relay); the impedance diagrams for the same fault scenario are shown in Fig. 8 (conventional relay) and Fig. 9 (proposed relay) respectively. As it can be observed, the distance protection with residual voltage compensation operated correctly with Zca reaching into the MHO circle while the conventional distance algorithm has not operated.

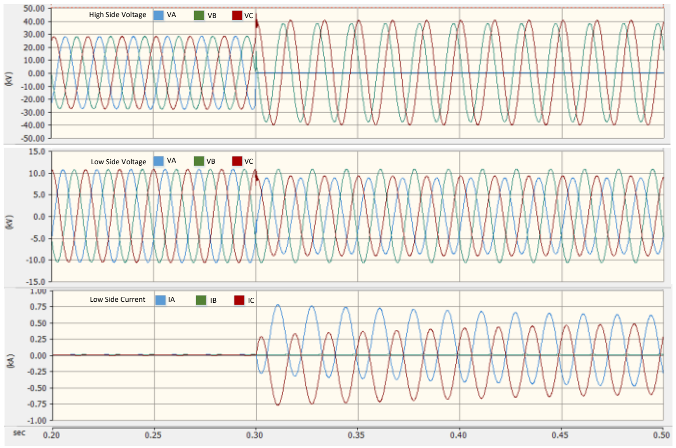

Fig. 6. SLG fault voltage and current waveforms as seen by the conventional distance relay (fault occurred at 0.3sec and was not isolated by the relay)

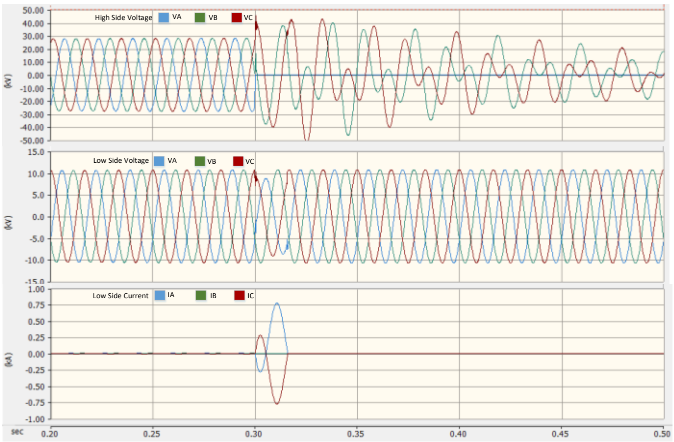

Fig. 7. SLG fault voltage and current waveforms as seen by the proposed distance relay (fault occurred at 0.3sec and was cleared by the relay)

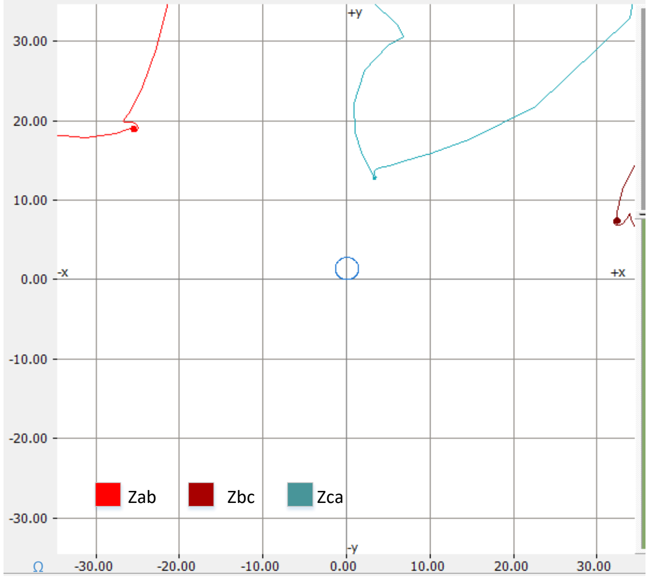

Fig. 8. Impedance diagram for a SLG fault at 0% of the interconnection line (not residual voltage compensated)

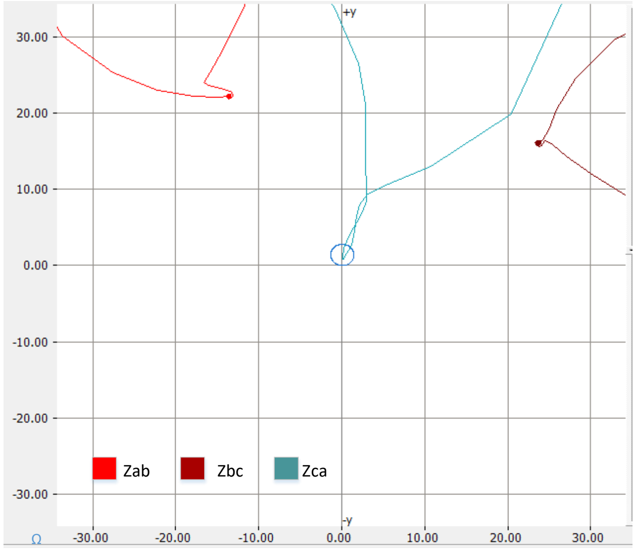

Fig. 9. Impedance diagram for a SLG fault at 0% of the interconnection line (residual voltage compensated)

Let us now consider a SLG fault at 75% of the interconnection line (HV side of the transformer); the impedance diagrams for this fault scenario are shown in Fig. 10 (conventional relay) and Fig. 11 (proposed relay). As can be observed in these figures, the distance protection with residual voltage compensation operated correctly with Zca reaching into the MHO circle while the distance with conventional algorithm did not operate. The Zca moves even closer to the MHO circle as the fault moving away from the distance relay in Fig. 10 when compared with Fig. 8.

A comprehensive set of simulations was conducted to examine the effectiveness of the proposed function under various fault scenarios. The results showed satisfactory performance of the proposed function for all cases.

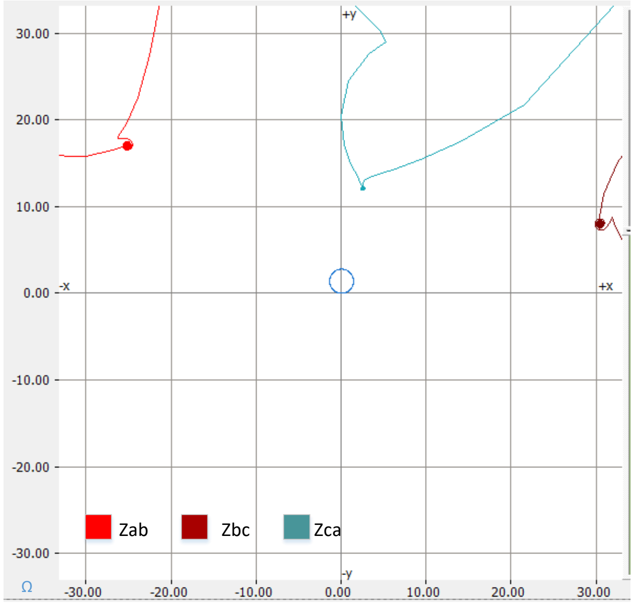

Fig. 10. SLG fault at 75% of the interconnection line (not compensated)

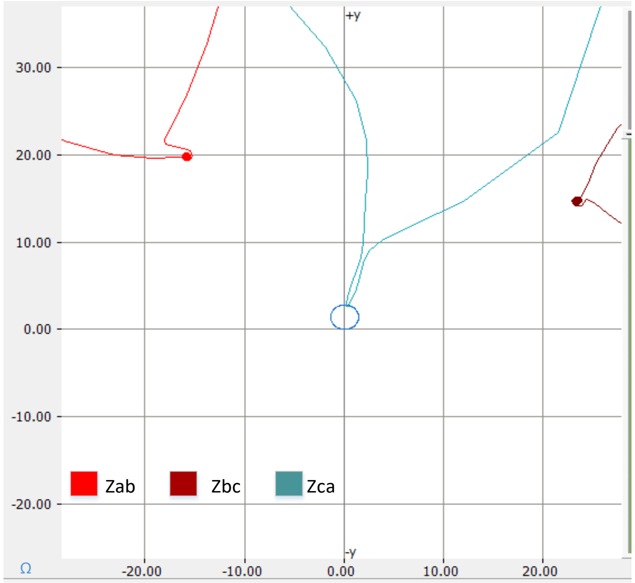

Fig. 11. SLG fault at 75% of the interconnection line (residual voltage compensated)

V. CONCLUSION

Protection of a microgrid/DER at the POI/POC is a straightforward task. Depending on the fault current contribution and characteristic from the MG/DER as well as the interconnection transformer configurations, conventional current-/voltage-/frequency-based protection may not operate properly. Also, when an SLG fault occurs on the utility feeder, the distance relay on the low-voltage side of the interconnection transformer may see it as a phase-to-phase fault, which disappears once the utility-side breaker opens. This paper presented a new distance protection algorithm for protection of interconnection line that connects a MG/DER to rest of the grid through a Delta/Wye transformer.

The proposed method can adequately protect the interconnection line against all ground fault types and address several challenges associated with the microgrid POI protection. Particularly, the residual voltage compensated distance element can detect the SLG faults on the HV side of the interconnection transformer (i.e., utility interconnection line) while the existing methods are not sensitive or fast enough to detect the fault. This method enables detection and location of all external faults such that the microgrid can be quickly isolated from the main grid via operation of the POI breaker. It is also economical as it can be implemented in the existing distance relay platform without any hardware modifications. Together with other protection functions, the proposed method can provide effective POI protection against dangerous overvoltage, reduce arcing condition, and increase the possibility seamless islanding.

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VII. BIOGRAPHIES

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