Ground Fault Protection of Microgrid Interconnection Lines Using Distance Relay with Residual Voltage Compensation

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Abstract—**Protection of utility feeders that supplies an ungrounded/impedance-grounded Microgrids (MGs) or Distributed Energy Resources (DERs) is a challenging task, especially for Single-Line-to-Ground (SLG) faults. Normally, the interconnection line can be protected using: (i) a Direct Transfer Trip (DTT) from the utility station and/or (ii) an over-voltage relay (59G) energized by a broken-delta potential transformer on the utility side of the interconnection transformer. However, the cost associated with the installation of a communication system to enable DTT scheme can be excessive. Further, proper settings of the 59G relay to ensure selectivity is not always possible, that is, longer operating times will be required to make sure the protection will not operate for an external fault. More importantly, an SLG fault on the utility feeder is seen as a phase-to-phase fault by the interconnection relay at the MG/DER side of the connection with lower fault current, which makes the interconnection protection more challenging.**

This paper studies the use of phase distance relay at the MG/DER side of the interconnection transformer to provide coordinated protection against ground faults on the 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 higher the apparent impedance seen by the relay. Therefore, it is proposed to utilize residual voltage compensation method to solve this issue such that the phase distance relay can correctly identify the SLG fault, accurately measure the apparent impedance, determine the fault location, and reliably isolate the fault without jeopardizing the stability of downstream system (i.e., MG/DER) and/or causing dangerous overvoltage/arcing conditions.

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 system grounding (ungrounded, solidly grounded or compensated grounded). A review of grounding methods for distribution networks as well as 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 connected to a microgrid through an ungrounded (or 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 interconnection line ungrounded and hanging for a relatively long time before voltage or frequency elements of the POI protection operate. 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 supplied by an ungrounded interconnection 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 (MG) side of the interconnection transformer. Once the utility-side breaker opens, the fault current disappears. To protect the microgrid at the POI, three 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; (ii) using an overvoltage relay (59G) energized by a broken-delta potential transformer on the utility side of the interconnection transformer (neutral overvoltage displacement) [5]-[9]; and (iii) overvoltage relay (59G) supervised by directional negative sequence over-current (67Q).

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 implement 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 the utility breaker). Studies have shown that 59G may fail to isolate the fault before the DER protection trips the generators within the microgrid territory.

This study investigated the issues associated with conventional distance algorithms to detect SLG faults on interconnection lines; the study also proposes 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.

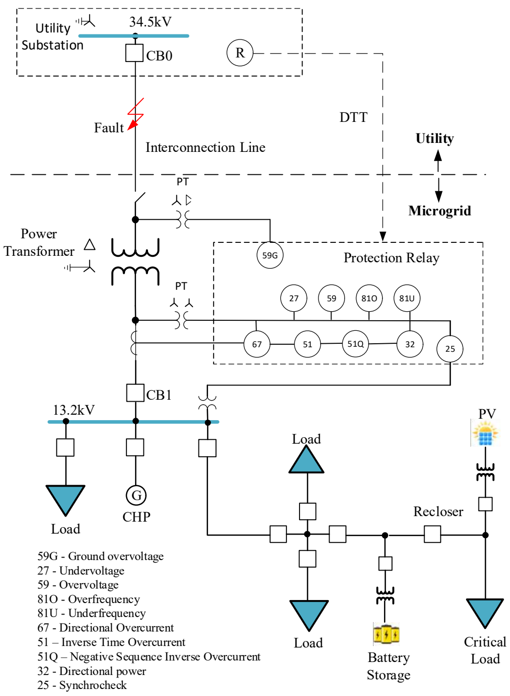

Fig. 1. An example single-line diagram of a microgrid with POI protection

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 nominal phase voltage to neutral (see Fig. 2 and Equation (1)). This voltage will be detected by 59G function installed at the broken delta potential transformer terminal.

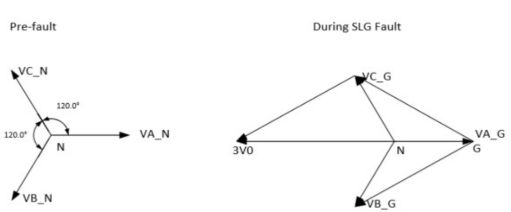

Fig. 2. Voltage phasor diagram during a SLG fault on an ungrounded system

$$3V_0 = V_a + V_b + V_c$$

$$= 0 + \sqrt{3}|V_a|\angle -150° + \sqrt{3}|V_a|\angle 150° = 3|V_a|\angle 180° \quad (1)$$

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, voltage-based protection 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.

To improve the security and provide a securer operation, the over-voltage element (59G1) can be supervised by 67Q to distinguish SLG faults on the interconnection line. Fig. 3 shows the logic diagram, where 59G1 pickup is set to be higher than 3V0 at relay location for a remote line-end SLG fault; 59G2 pickup is set to higher than 3V0 to cover close-in SLG faults; and 59G3 pickup is set to higher than 3V0 with 1-sec delay to detect maximum unbalanced load conditions. The 67Q pickup is normally set higher than I2 caused by maximum unbalanced load condition. Despite its advantages, this scheme still requires the 59G settings to be determined based on fault location and pre-fault system operation conditions.

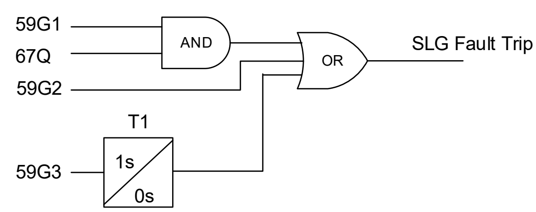

Fig. 3. POI protection using over-voltage relay (59G) with negative-sequence directional overcurrent (67Q) supervision

Other protection functions such as overcurrent, under-/over-voltage, under-/over-frequency, rate of change of frequency and/or rate of change of voltage can also be used to detect the formation of the island or loss of the utility grid at the MG/DER POI. However, these types of protection have non-detection zones and may fail to detect islanding situation, especially when load and DER generation are comparable. In addition, the over-current protection settings must be set higher than the maximum power flow at the POI (for 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. On the other hand, 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 in a microgrid. 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.

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		

Fig. 4 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 operating time may not be fast enough for some microgrid applications with seamless transition requirements.

Distance relays are widely used for protection of high-voltage AC transmission and sub-transmission lines. The benefits and performance of distance relays (compared to traditional over-current relays) in distribution feeders embedding DERs are discussed in [12]. In addition, using distance relays, a fault can be located since the measured impedance to the fault 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 of 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.

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

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

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

$$Z_{ab} = \frac{V_a - V_b}{I_a - I_b} \quad (5)$$

$$Z_{bc} = \frac{V_b - V_c}{I_b - I_c} \quad (6)$$

$$Z_{ca} = \frac{V_c - V_a}{I_c - I_a} \quad (7)$$

Where I_a, I_b, I_c are phase currents; V_a, V_b, V_c are phase voltages; I_R denoted the zero-sequence current seen by the relays; and k_0 indicates zero-sequence compensating factor

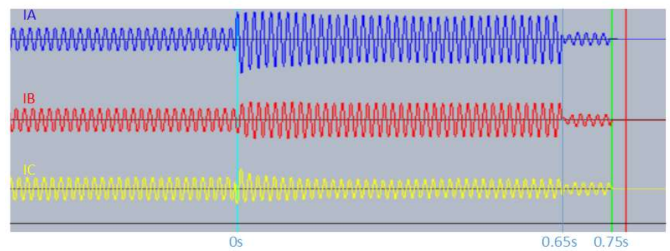

Fig. 4. An example microgrid current contribution for an external SLG fault

The effects of a wye-delta or delta-wye power transformer between distance relays and fault have already been studied [13]. A wye-delta or delta-wye transformer between a distance relay and the fault changes the complexion of the fault current and voltage (i.e., creating 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 with wye-delta or delta-wye transformer. 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; further, 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 faults beyond the transformer. As an example, for an LLG fault on the microgrid interconnection line with a YD11 step-up transformer, Equations (8)-(10) can be used (instead of Equations (5)-(7)) to calculate the fault impedance [14]. However, about 70% of the faults happening in distribution systems are SLG faults, for which no zero-sequence current will be seen by the relay due to the delta-wye transformer configuration. Also, 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 Other protection functions such as overcurrent, under-/over-voltage, under-/over-frequency, rate of change of frequency and/or rate of change of voltage can also be used to detect the formation of the island or loss of the utility grid at the MG/DER POI. However, these types of protection have non-detection zones and may fail to detect islanding situation, especially when load and DER generation are comparable. In addition, the over-current protection settings must be set higher than the maximum power flow at the POI (for 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. On the other hand, 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 in a microgrid. 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.

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 (i.e., Z_t+k*Z_l, where k is the percentage of the line at fault location; and 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 work for 3LG fault, while Equations (8)-(10) only work 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. 5, 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) 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. 6, 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.

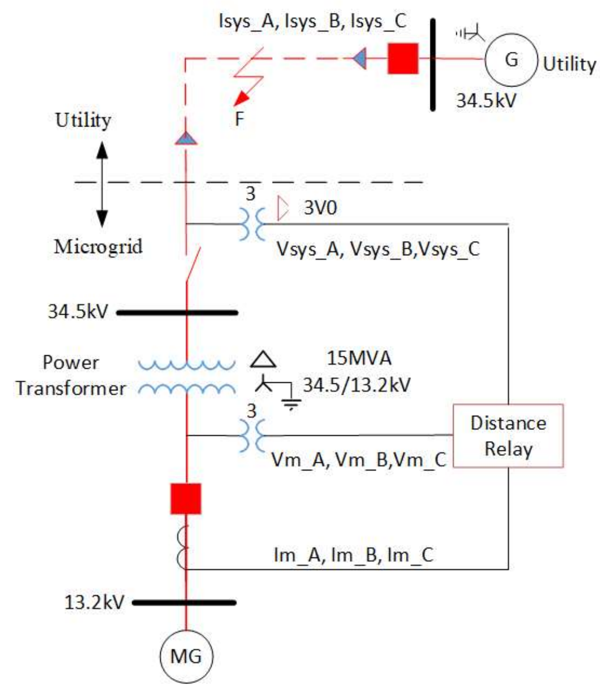

Fig. 5. Protection diagram for MG/DER interconnection line protection

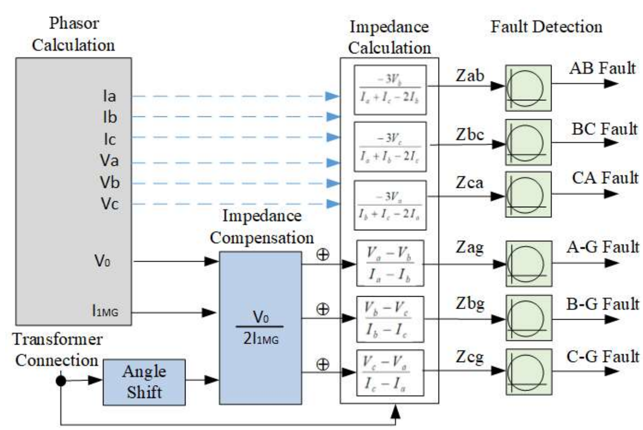

Fig. 6. Block diagram of the proposed distance relay with residual voltage compensation

IV. Simulation Results

The PSCAD/EMTDC software was used to model the microgrid system of Fig. 1 and simulate the proposed distance relay (Fig. 5) 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 types 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. 7 (conventional relay) and Fig. 8 (proposed relay); the impedance diagrams for the same fault scenario are shown in Fig. 9 (conventional relay) and Fig. 10 (proposed relay), respectively. As it can be observed, the distance protection with residual voltage compensation operated correctly with Z_{ca} reaching into the MHO circle while the conventional distance algorithm has not operated.

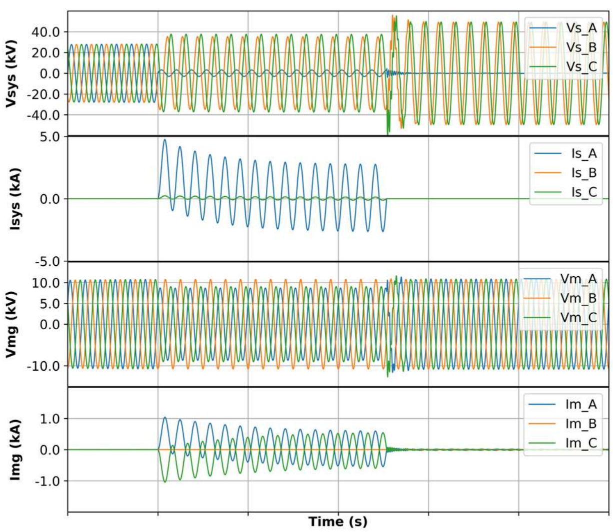

Fig. 7. SLG fault voltage and current waveforms as seen by the conventional distance relay (fault occurred at 0.3sec and was not isolated by the relay)

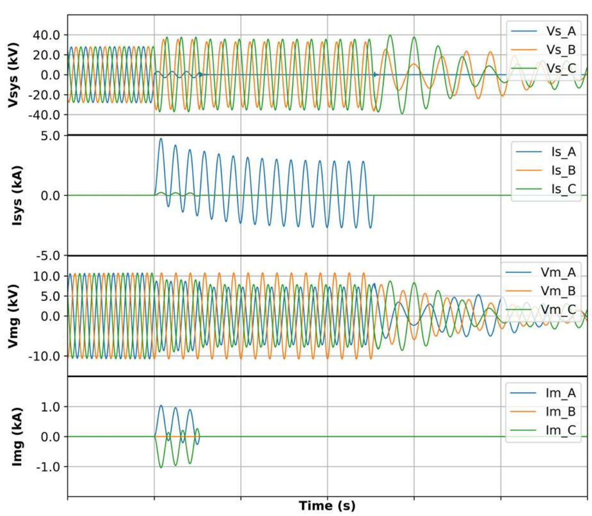

Fig. 8. SLG fault voltage and current waveforms as seen by the proposed distance relay (fault occurred at 0.3sec and was cleared by the relay)

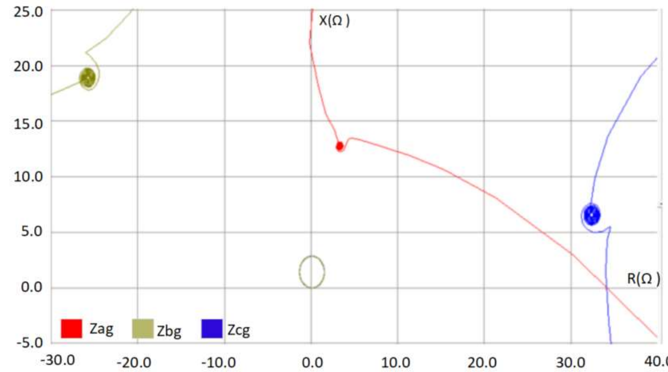

Fig. 9. Impedance diagram for a SLG fault at 0% of the interconnection line (without residual voltage compensation)

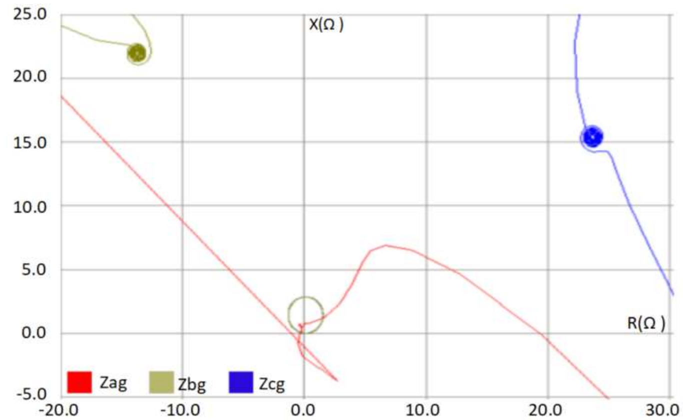

Fig. 10. Impedance diagram for a SLG fault at 0% of the interconnection line (with residual voltage compensation)

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. 11 (conventional relay) and Fig. 12 (proposed relay). As can be observed in these figures, the distance protection function with residual voltage compensation operated correctly with Z_{ca} reaching into the MHO circle while the distance relay with conventional algorithm did not operate. It is important to note that, with conventional distance relay, the measured Z_{ca} gets even closer to the MHO circle as the fault moves away from the distance relay (compare Fig. 11 with Fig. 9).

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.

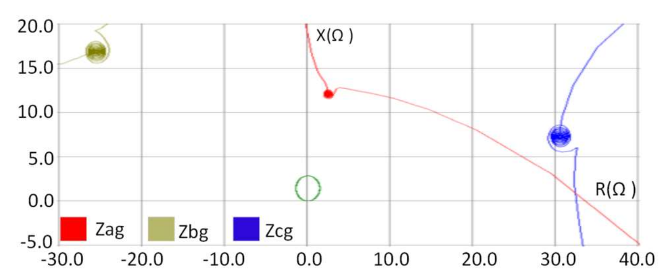

Fig. 11. SLG fault at 75% of the interconnection line (without residual voltage compensation)

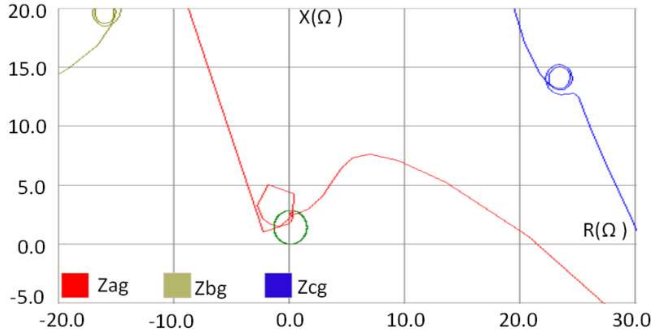

Fig. 12. SLG fault at 75% of the interconnection line (with residual voltage compensation)

V. Conclusion

Protection of a microgrid/DER at the POI/POC is not a straightforward task. Depending on the fault current contribution and characteristic of the MG/DER as well as the interconnection transformer configurations, conventional current-/voltage-/frequency-based protection elements 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. The proposed method is 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 of seamless islanding.

VI. Reference

[1] Jeff Roberts, Hector J. Altuve, Daqing Hou, "Review of Ground Fault Protection Methods for Grounded, Ungrounded, And Compensated Distribution Systems", WPRC, 2001

[2] E.S. Thomas, R.A. Barber, J.B. Dagenhart, A.L. Clapp, "Distribution system grounding fundamentals", Rural Electric Power Conference, 2004

[3] S. A. Arefifar, "Distribution system grounding impacts on fault responses", 13th International Conference on Harmonics and Quality of Power, 2008

[4] IEEE Std. 1547, "IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces", 2018

[5] PES-TR71, "Microgrid Protection Systems", Power System Relaying and Control Committee

[6] PES Power System Relay Committee, "Impact of Distributed Resources on Distribution Relay Protection", IEEE PES, 2004

[7] G. Antonova, M. Nardi, A. Scott, M. Pesin, "Distributed Generation and Its Impact on Power Grids and Microgrids Protection", Texas A&M 65th Annual Conference for Protective Relay Engineers, 2012

[8] D. Tholomier, T Yip, G Lloyd, "Protection of distributed generation (DG) interconnection", Power Systems Conference, 2009

[9] F.H. Guan, D.M Zhao, X. Zhang, B.T Shan, Z. Liu, "Research on distributed generation technologies and its impacts on power system", International Conference on Sustainable Power Generation and Supply, 2009

[10] S. Suhono, H. Purnama1, H. B. Utomo, "Ground Fault Protection using Open Break Delta Grounding Transformer in Ungrounded System", Journal of Engineering Design and Technology, Vol. 19 No.1 March 2019

[11] D. D. Ronde, R. VanHatten, and A. Wade, "Loss of Effective System Grounding – Best Practices, Protection Challenges, and Solutions", WPRC, 2014

[12] D. Martin, P. Sharma, A. Sinclair, D. Finney, "Distance protection in distribution systems: How it assists with integrating distributed resources", Texas A&M 65th Annual Conference for Protective Relay Engineers, 2012

[13] C. R. Mason, "The Art & Science of Protective Relaying", Wiley, 1956

[14] GE G60 Generator Protection Instruction Manual "Phase distance through power transformers", 2015

VII. Biographies

Yujie Yin is a senior application engineer at GE Grid Solutions. He is a senior member of IEEE, CIGRE B5 WG member and a licensed Professional Engineer in the Province of Ontario. He received his Bachelor of Computer Science and Master of Electrical Engineering from Western University, Canada, in 2004 and 2006, respectively. He also holds a Bachelor of Electrical Engineering degree from HFUT, China. Currently, he is pursuing his Ph.D. at the Mississippi State University, USA.

Amin Zamani is the Direct of the Global Grid Modernization Center of Excellence with GE Grid Solutions. He has more than 10 years of professional experience in North America and elsewhere. Amin specializes in the power system protection and control, hardware-in-the-loop testing, distributed generation interconnection, and microgrids. Amin has received his Ph.D. from University of Western Ontario; he is a Senior Member of IEEE, and a Professional Engineer in the province of Ontario.

Zhiying Zhang received his B.Sc. and M.Sc. degrees from the North China Electric Power University, China, and a Ph.D. degree from the University of Manitoba, Canada, all in Electrical Engineering. He has over 30 years of working experience with Electric Utilities and with relay manufactures in various technical positions. Since 2007 he has been with General Electric, and currently holds the position of principal application engineer at GE Grid Solutions in Markham, Ontario. Zhiying is a registered professional engineer in the province of Ontario, and a senior member of IEEE.

Yong Fu received his BS and MS in E.E. from Shanghai Jiaotong University, China, in 1997 and 2002, respectively and Ph.D. degree in E.E. from Illinois Institute of Technology, USA, in 2006. Presently, he is a professor in the Department of Electrical and Computer Engineering at Mississippi State University. He has been awarded the Tennessee Valley Authority (TVA) Endowed Professorship in Power Systems Engineering. He received the NSF CAREER Award in 2012. His research interests include power system operation, control, and protection, renewable energy integration, and smart grid.