# Superimposed Sequence Components for Microgrid Protection: A Review

Opoku, Kwasi and Pokharel, Subash and Dimitrovski, Aleksandar

University of Central Florida

24 December 2021

# Superimposed Sequence Components for Microgrid Protection: A Review

Kwasi Opoku, Subash Pokharel, and Aleksandar Dimitrovski
*Department of Electrical & Computer Engineering*
*University of Central Florida*
Orlando, Florida 32826
Email: opokukwasi@knights.ucf.edu, pokharelsbs@ieee.org, adimitrovski@ucf.edu

***Abstract*—The new challenge to protective relaying in distribution networks (DNs), due to the integration of distributed generation (DG), has become a significant area of focus and research for power engineers. To achieve high penetration of DGs in the DNs, new methods of achieving desired sensitivity, selectivity, and security of fault detection and coordination must be adopted. Recent literature shows that superimposed sequence components offer great potential in fault detection and coordination in such DNs. This paper reviews different proposed solutions to fault detection and coordination in microgrids using superimposed sequence quantities. It also includes a discussion on their application methods, unique advantages, and limitations. This way, it contributes to existing reviews on microgrid protection by presenting the unique considerations necessary for the superimposed method, as well the way conventional protection schemes can be improved for microgrid protection using this method. Results from applying a new approach for detecting faults based on superimposed negative sequence admittance is presented to demonstrate the application of superimposed quantities in fault detection.**

***Index Terms*—Active distribution network, distributed generation (DG), microgrid protection, superimposed sequence component, low voltage ride-through (LVRT)**

## I. Introduction

The global electric power system is going through a transition mainly because of the changing landscape of energy policy and the economics of distributed generations (DGs). This has resulted in the proliferation of renewable energy resources throughout the power system. The active distribution networks (ADNs) and microgrids are the cornerstones of future smart power grids [1], [2]. An effective protection system is a prerequisite for any power system operation. An ideal protection scheme for a microgrid protects it from all types of faults, works for both modes of operations: grid-connected, and islanded and can adapt to the plug-and-play functionality [3].

The new challenges faced by conventional protective relays in active distribution networks have been identified and extensively discussed [3]–[5]. These challenges are generally as a result of the the bi-directional flow of both load and fault currents, the different types of distributed energy resources in the network, and the dynamic nature of microgrids with constantly changing topology and operation modes leading to variation of fault currents. Also, due to the rating of the inverters, fault current contribution of inverter-interfaced DGs (IIDGs) is limited to about 1.2pu in steady state [6]. These issues affect the ability of traditional protection schemes to achieve required sensitivity and speed of fault detection, as well as selectivity and security of fault section location.

Many researchers have proposed solutions to solve microgrids' protection issues, and new approaches continuously evolve. The methods differ by network complexity, type, capacity, DG connection, and the available measurements and infrastructure reliability. However, the common goal of protection schemes is to achieve fast, selective, and sensitive protection most economically and efficiently.

Some solutions build on conventional protection schemes, while others apply novel techniques and methods. The conventional protection schemes have been updated by including the detailed model of IIDGs [7] and considering their control strategy [8]. Impedance-based protection schemes, for instance [9], [10], detect the faults using new measurement quantities and communication systems. The rapid development of communication techniques in distribution networks has made efficient information exchange possible resulting in the protection schemes like multi-agent-based current-differential protection, wide area protection schemes, etc. [11]. The issue of data transmission bandwidth and synchronization makes such methods uneconomical for distribution systems. The traveling wave (TW) based protection schemes presented in [12] detect the fault by comparing the time of initial traveling waves. However, this approach is considered not well-suited for short feeders, and some non-fault events might affect the TW. With adaptive protection schemes [13], [14], the relay settings are automatically readjusted in response to system conditions. However, the pre-assessment of all possible configurations is challenging to achieve, and implementation cost is very high. Several voltage-independent fault detection methods are presented in [15]–[17], where there is no voltage measurement. Latest developments in areas of computation and data analytics, with communication, enabled the innovative protection schemes based on feed-forward neural networks [18].

A set of quantities that seem to offer great potential for effective fault detection are the superimposed sequence components, also known as the incremental fault components, which have been employed in transmission systems for many decades. They have the advantage of not being influenced by the load conditions in the pre-fault and faulted states. Hence, both the magnitude and angle of such incremental quantities can be applied in various schemes to provide a fast, sensitive, and selective method of detecting faults and fault locations in microgrids. This paper reviews the schemes that employ superimposed fault quantities and assesses their unique

This material is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Solar Energy Technologies Office Award Number DE-EE0002243-2144.
The views expressed herein do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

978-1-6654-7902-8/22/$31.00 ©2022 IEEE

advantages and limitations.

The remainder of this article is organized as follows. Section II introduces the theory of superimposed quantities. It is followed in Section III with solutions that have been explored for microgrid protection by applying superimposed quantities. A case study to demonstrate how the technique is applied in a negative sequence admittance detection method is presented in Section IV. Section V discusses some disadvantages of the superimposed quantities, and Section VI concludes the paper.

## II. Theory of Superimposed Quantities

When a fault occurs in a linear network, a pure fault circuit can be obtained from the pre-fault circuit and the faulted circuit using the principle of superposition. The current and voltage values obtained in the pure fault circuit are the superimposed quantities.

Consider a basic network, with line MN with impedance $Z_L$ which connects the grid side (with impedance $Z_M$) at bus M, and a DG (with impedance $Z_N$) at bus N. A fault, $f_1$ occurs on the line, at a distance *x* from bus M, as shown on the equivalent circuit in Fig.1.

Using the superposition theorem, the voltages and currents in the faulted network (Fig.2) can be obtained as a sum of the pre-fault circuit (Fig.1) and a pure fault circuit (Fig.3). In this case, the pure fault circuit is obtained by replacing the voltage sources in the pre-fault circuit with a short circuit and their internal impedance [19]. The fault voltage source $V_f$ is also represented by a fault impedance $Z_f$. The magnitude of $V_f$ is equal to the voltage at the fault point before the incidence of fault. Thus, the superimposed quantities obtained from the pure fault circuit are assumed to be driven only by the fault, i.e., changes in the pre-fault condition. This is different from the faulted circuit which includes both the prefault condition and the change that occurs due to the fault.

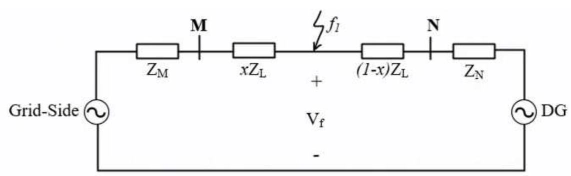


Fig. 1. Pre-fault Network

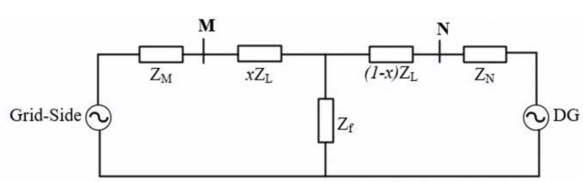


Fig. 2. Faulted Network

The superimposed quantities, voltage ($\Delta V$) and current ($\Delta I$), are therefore incremental quantities obtained by comparing the pre-fault and faulted quantities, as given by (1) and (2):

$$V_{fault} = V_{pre-fault} + \Delta V \tag{1}$$

$$I_{fault} = I_{pre-fault} + \Delta I \tag{2}$$

Similarly, the symmetrical components of the superimposed phase quantities can be obtained. Let us consider $I_a, I_b, I_c$ to be pre-fault phase currents in phases A, B and C, and $I_a{}', I_b{}', I_c{}'$ to be the corresponding faulted quantities. Then the pre-fault positive sequence quantities can be obtained as,

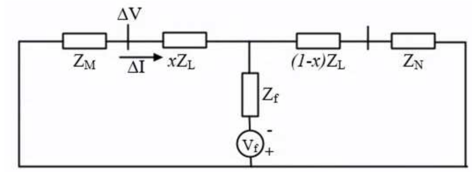


Fig. 3. Pure Fault Network

$$I_1 = \frac{1}{3}(I_a + a^2 I_b + a I_c) \tag{3}$$

Also, the fault-state positive sequence component $I_1{}'$, can be obtained from the phase currents $I_a{}', I_b{}', I_c{}'$:

$$I_1' = \frac{1}{3}(I_a' + a^2 I_b' + a I_c') \tag{4}$$

From (2), superimposed positive sequence current $\Delta I_1$, can be obtained from the phase quantities by:

$$\Delta I_1 = I_1' - I_1 = \frac{1}{3}(\Delta I_a + a^2 \Delta I_b + a \Delta I_c) \tag{5}$$

Similar analysis could be used to obtain superimposed negative sequence current $\Delta I_2$, positive sequence voltage $\Delta V_1$ and negative sequence voltage $\Delta V_2$. The superimposed sequence impedance ($\Delta Z$) and admittance ($\Delta Y$) could be found using $\Delta V$ and $\Delta I$.

Modern microprocessor-based relays are able to derive these quantities with the use of memory, together with faster sampling rates.

## III. Application of Superimposed Sequence Quantities

Many solutions for microgrid protection involve modification of conventional schemes, considering the unique characteristics of such microgrids. One such modification is the application of superimposed quantities as the quantities used to determine protection criteria. A description of various applications incorporating superimposed quantities methods in conventional schemes are presented in this section.

### A. Adaptive Protection Schemes

A common method employed to deal with the unique challenges of microgrid protection is adaptive protection. The adaptive protection method is an early approach initially used in transmission networks to modify protection settings in response to changes in the network conditions [20]. This approach is therefore extensively applied in microgrids considering the changing conditions in microgrids. This way, the schemes are applicable in both islanded and grid-connected modes and with changing network topology. Superimposed components have been deployed together with adaptive techniques in various schemes to provide distinct measuring quantities to help achieve the required selectivity and sensitivity of the protection system.

For instance, in [21], an adaptive overcurrent scheme was developed for protection coordination in a microgrid with both IIDGs and rotation type DGs (RTDGs.) Using $|\Delta I_1|$

and $|\Delta I_2|$, an impact factor is developed depending on the microgrid mode of operation and the type of DGs connected in the network at a particular time. This impact factor is then used to compute an adaptive fault current. A limitation to this solution is that it uses a simple signaling method to determine topology by using existing breaker status indications in the distribution network. However, for distribution networks with high penetration of DGs and continuously varying network conditions, additional methods such as directional scheme, as in [22] (discussed in part C below), should be included to improve protection selectivity [23].

### *B. Wide Area Protection Schemes*

Many of the solutions proposed for microgrid protection take advantage of communication infrastructure in the distribution network for information sharing among various agents (intelligent electronic devices – IEDs, computing devices, and switching devices). This, therefore, enables the implementation of wide-area protection schemes in ADNs.

For instance, to identify the faulted section in a microgrid, the solution proposed in [24] divided the network into intentional islands bounded by intelligent circuit breakers (CBs). These CBs can communicate the $\Delta I_f$ flow with each other and to a central protection and control system. Thus the effect of the fault current quantities used are unaffected by the loads in different sections of the wide area. A determination is then made for the fault region by comparing the magnitudes and phase difference of $\Delta I_f$ in two adjacent CBs. The protection center uses different criteria to determine bus and transformer faults and faults outside or inside an intentional island.

Similarly, an integrated wide area protection scheme was proposed in [11]. The distribution network is divided into integrated protection units, which communicate directly with the main protection center. The protection center analyzes the phase difference of $\Delta I_1$ between the main and slave feeders to identify the faulted section.

An effective use of superimposed quantities to improve the sensitivity and dependability of fault detection in such wide-area schemes is as a starting criterion. This helps prevent unwanted action as a result of non-fault conditions in the wide network. For example, the scheme in [11] uses $(\Delta I_2 + \Delta I_0)/\Delta I_1$ as a starting criterion for the protection algorithm.

### *C. Directional Protection Schemes*

Another widely used method employed to overcome the challenge of bi-directional fault current flow is directional protection. An evaluation of directional protection algorithms for ADNs using fault-state and superimposed sequence quantities was carried out in [25]. The results revealed that the superimposed quantity applications provide the most effective applicable measuring quantities and thus have the best performance in detecting fault direction for all types of faults accurately. As in transmission networks [26]–[28], these superimposed sequence quantity applications can use both the phase difference and magnitude of an evaluated quantity to determine fault incidence and direction.

One advantage of directional protection is that it can provide a non-communication-assisted method to determine the direction of a fault. The solution proposed in [25] only used the phase difference between $\Delta I_1$ and $\Delta V_1$ to develop a criterion for detecting symmetrical fault direction. This simple application takes advantage of the absence of loads in the fault component to develop criteria limited to balanced faults. A negative sequence-based scheme was proposed for all other faults.

The direction of fault is determined in [22] by observing the phase difference between the pre-fault negative sequence current, $I_{2pre}$, and $\Delta I_2$. The negative sequence currents have the advantage of being present in all asymmetric faults; thus, an additional condition would be required for balanced faults. However, in [29], the amplitude change between $I_{1pre}$ and $\Delta I_1$ is deployed in a directional scheme to determine the fault direction. It is, therefore, applicable for all fault types.

As an improvement to the traditional T32Q element implemented in [30], the solution in [31], proposed a new directional element for unbalanced fault direction detection using both magnitude and angle of $\Delta Z_2$. For symmetrical faults, $\Delta Z_1$ was proposed for direction detection. This way, the challenges of the T32Q element (security of the protection when reactive current is generated by the inverter and sensitivity issues during the forward unbalanced faults) were eliminated. As discussed in [32], the performance of this scheme is affected for faults that lead to the absence of power frequency and subsequent weak output of the power generator.

Although directional schemes may be implemented without communication, some methods take advantage of communication infrastructure to improve the schemes. In [33], $|\Delta I_1|$ is observed to be highest in the faulted feeder of a microgrid. With the help of communication between relays, fault direction is established when both local and remote relays of the protected line determine that the higher $|\Delta I_1|$ is in the forward direction. This particular technique is simple but is not applicable for medium to high impedance faults (MIFs and HIFs) since fault component currents are significantly impacted under these conditions.

The solution proposed in [34] for detecting faults in microgrids, monitors $\Delta I_1$ at the two terminals of the protected line. A curve, each with a minimum limit threshold, is developed based on the variation of $\Delta I_1$ along the line, as observed by each smart terminal unit (STU). Using peer-to-peer communication, a blocking pilot scheme is developed such that a fault is determined to be in the forward direction when at least one of the STUs communicates an action signal to the other. Otherwise, a blocking signal is continuously sent. The method fails, however, to deal with single-line-to-ground faults, considering the significant impact of fault resistance on the characteristic curve for $\Delta I_1$ observed by the STUs.

In the grid-connected mode of operation, the main grid with its higher short circuit power contributes to the fault current, rendering it much higher than a similar fault in islanded microgrid mode. This is a major influence on the protection schemes in the grid-connected mode [35]- [36]. To deal with the loss of selectivity, particularly in grid-connected mode, a directional scheme was developed in [37]. It compares the phase difference between $\Delta I_1$, one period just before and one period after the fault. The phase difference value is significantly influenced by the main grid's fault current contribution. This method employs the conventional overcurrent protection and the new directional method described. Hence, it has the practical advantage of being applicable to some existing technology.

### *D. Differential Schemes*

Differential protection schemes are known to achieve good sensitivity results. Also, as a unit protection scheme, it is inherently selective in identifying faulted zones. Superimposed quantities are applied in differential protection schemes to provide a quantity that limits the challenges faced by traditional differential schemes.

To determine fault direction, a differential method is introduced in [38], using $\Delta I_1$. For a fault within the protected line with local terminal $M$ and remote terminal $N$, the operate quantity is $|\Delta I_{1M} + I_{1N}| \geq I_{set}$, where $\Delta I_{1M}$ and $\Delta I_{1N}$ are the superimposed positive sequence currents measured at M and N, and $I_{set}$ is the pre-determined threshold. The criterion also includes a restraint coefficient to account for errors that may occur due to external faults.

The solution in [39] uses the phase difference of the $\Delta I_1$ flowing into a main substation bus and the remote feeder bus to develop a criterion for fault location. This improves the reliability during external faults since the current phases at the main bus and the remote bus are the same only for the faulted feeder. Similarly, the phase difference is used to distinguish between bus faults and feeder faults.

Superimposed quantities also improve sensitivity of starting elements in differential schemes. For instance, an impedance differential method proposed in [40], uses the $\Delta I_1$ to determine fault incidence before beginning fault detection algorithm. Furthermore, the main criterion for fault location uses $\Delta V_1$ and $\Delta I_1$ values to calculate the differential impedance $\Delta Z_{diff}$ and restraint impedance $\Delta Z_{res}$ of the line. An internal fault occurs when $|\Delta Z_{diff}| \leq 0.9\,|\Delta Z_{res}|$.

A major challenge faced by the differential schemes but not considered in the solutions above is data synchronization. Many modern solutions rely on sophisticated data synchronization infrastructure that increases the cost. To deal with data synchronization issues in communication networks used for differential protection, the impedance differential solution in [10] uses the superimposed positive sequence current as a fault-instance-based synchronization method. Here, the instance of the fault, identified by $\Delta I_1$, provides a time reference for the exchanged data. This is a simple alternative to using sophisticated data synchronization infrastructure.

### *E. Applications Based on LVRT Considerations*

IIDGs are required to have a Low Voltage Ride-Through (LVRT) capability and remain connected to the grid when the voltage sags to a certain level. This is achieved by providing a reactive output current to support the voltage during voltage sag [41]. This has an influence on the quantities used in fault detection. In [8], it was demonstrated that fault characteristics of IIDGs with LVRT are not to be based on equivalent constant current or power source. Similarly, studies conducted in [32] and [42] reveal that the magnitude and angle of the equivalent positive and negative superimposed impedances of IIDGs are affected by the control strategies of the inverter to achieve LVRT.

By analyzing LVRT characteristics of IIDGs, a fault detection method was proposed in [8] using the phase difference between $\Delta V_1$ of the bus and $\Delta I_1$ of the feeders. Also, $(\Delta I_2 + \Delta I_0)/\Delta I_1$ is compared to imbalance due to regular sequence components, and used as a starting criterion for the fault point detection algorithm. This way, the method is independent of fault resistance and applicable to high and low impedance faults.

Similarly, to eliminate the effect of the LVRT current during fault location, a negative sequence current direction scheme was developed in [43] to detect asymmetrical faults. This is due to the fact that no negative sequence ride-through current is contributed by the main grid or the IIDG. On the other hand, in [44], by including the characteristics of the LVRT current of the IIDG, the ratio of $\Delta I_1$ at the grid and DG side is used to develop a criterion for fault location. In addition, the phase difference of this ratio is used to set a threshold that ensures the sensitivity of the scheme.

A summary of the different superimposed quantities proposed in the various schemes has been provided in Table I.

TABLE I
APPLICATIONS OF SUPERIMPOSED QUANTITIES: SUMMARY

| Applications | Proposed Solution | Operation Mode: GC or B | Superimposed Quantities Used | Comm: Y, N |
|---|---|---|---|---|
| Adaptive | [21], [22] | B | $\Delta I_1, \Delta I_2$ | Y |
| Wide Area | [24] | B | $\Delta I_1$ | Y |
| | [11] | B | $\Delta I_0, \Delta I_1, \Delta I_2$ | Y |
| Directional | [22] | B | $\Delta I_1, \Delta I_2$ | Y |
| | [25] | B | $\Delta I_1$, $\Delta V_1$ | Y |
| | [33], [34] | B | $\Delta I_1$ | Y |
| | [29] | B | $\Delta I_1$ | N |
| | [31] | B | $\Delta Z_1$, $\Delta Z_2$ | N |
| | [37] | GC | $\Delta I_1$ | N |
| | [8] | GC | $\Delta I_0, \Delta I_1, \Delta I_2, \Delta V_1$ | Y |
| | [43] | GC | $\Delta I_1, \Delta I_2$ | Y |
| | [44] | GC | $\Delta I_1$ | Y |
| Differential | [10], [38], [39] | B | $\Delta I_1$ | Y |
| | [40] | B | $\Delta I_1, \Delta V_1, \Delta Z$ | Y |

GC = Grid-Connected, B = Both; Comm = Communication; Y = Yes, N = No

## IV. NEGATIVE SEQUENCE ADMITTANCE BASED SUPERIMPOSED QUANTITY

### *A. Methodology*

A superimposed negative sequence admittance method, $\Delta Y_2$, proposed in [45], is considered in this paper to demonstrate the application of such quantities for microgrid protection. Negative sequence quantities are known to be present in significant quantities in unbalanced faults which form about 95% of all faults in power systems [46]. This element shows high magnitude to fault incidence during forward faults and provides a good distinction from normal operation. The direction of the fault is determined by the phase angle. The element is evaluated by the equation

$$\Delta Y_2 = \frac{I_{2fault} - I_{2pre}}{V_{2fault} - V_{2pre}} = \frac{\Delta I_2}{\Delta V_2}. \tag{6}$$

The phase angle, $\arg\{\frac{\Delta I_2}{\Delta V_2}\}$, for forward faults is determined to be (7) and for reverse faults to be (8)

$$0^\circ + \phi < \arg\{\Delta Y_2\} < 180^\circ + \phi \tag{7}$$

$$180^\circ + \phi < \arg\{\Delta Y_2\} < 360^\circ + \phi \tag{8}$$

where $\phi$ is the compensation for the angle of the protected line.

To discriminate fault conditions from normal imbalance in the network, a ratio factor $\alpha = |I_2/I_1|$ can be used as a starting criterion for fault detection as employed in other methods, [31]. $\alpha$ is often set to about 0.1 as minimum threshold for unbalanced shunt fault. Additionally, to improve the sensitivity of the element during high impedance faults, another factor, $\beta = |I_0/I_2|$ can be implemented in the starting criterion. Since it is expected that negative sequence and zero sequence currents measured at the fault point will be close in value, $\beta$ will be close to 1.

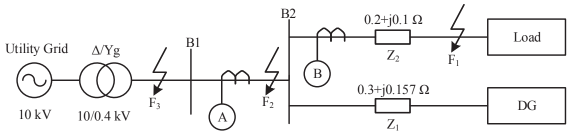


Fig. 4. Test system

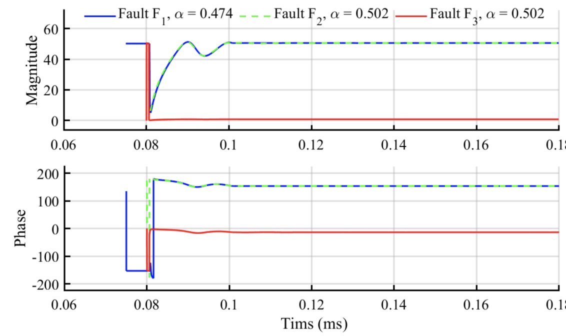


Fig. 5. $\Delta Y_2$ evaluated by Relay A

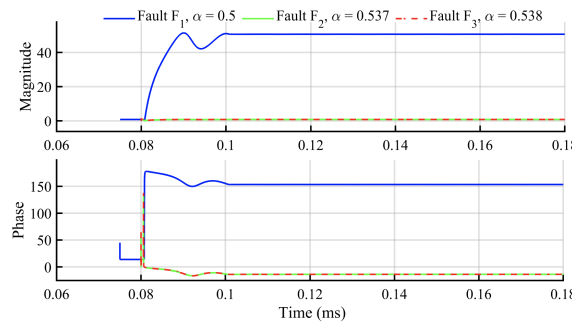


Fig. 6. $\Delta Y_2$ evaluated by Relay B

### *B. Simulation Results*

Simulation studies were carried out on the test system in Fig. 4 to demonstrate the performance of the $\Delta Y_2$ method for detecting usually elusive open-phase faults. The system is a simple 10/0.4kV microgrid that connects a $13.2 + j3.14\Omega$ load and a $0.01 + j0.01$MVA IIDG to the main grid. The DG response is simulated using PQ control as modeled in [47]. Relays A and B are positioned at Buses B1 and B2. Open-phase faults are applied at $F_1$ (load side), $F_2$ (Bus B2) and $F_3$ (Bus B1) at t=0.08s in each case. Considering the normal operation for this network $|\Delta Y_2|$ setting can be set to be not less than 30 for a faulted case. This allows a significant margin for normal operation. To compensate for the the protected line, $\phi$ is set at $14°$ for relay B and $27.5°$ for relay A.

A commonly used method of identifying an open-phase is the amount of current imbalance [48]. It is shown in [46], by analyzing the sequence networks of a one-phase open-fault, that for a system grounded at both sides of the open-phase, $|I_2|$ will be about 50% to 100% of $|I_1|$, depending on the zero sequence impedance, $Z_0$. In the case where one side of the open-phase is ungrounded, $|I_2|$ will be almost equal to $|I_1|$ since $I_0$ will be zero. Thus, for this demonstration $\alpha = |I_2/I_1|$ is the starting criterion for the open-phase detection and it has a setting of 0.2.

Fig.5 and Fig.6 show the operation of the relays A and B respectively in response to the series faults. As it can be seen, both relays correctly detect the direction of faults in all cases. $|\Delta Y_2|$ is about 50.6 for forward faults. But reverse faults has a smaller magnitude of about 0.82. The phase angle, $\arg\{\Delta Y_2\}$ provides an even clearer distinction between the forward and reverse faults, with about $154°$ in the forward direction and $-13°$ in the reverse. The starting criteria, $\alpha$, operates correctly in all cases with a value of between 0.47 and 0.54.

To observe the influence of the infeed by the DG, the results obtained when the DG is disconnected were also considered. Simulation results show values of 50.6 and $153.4°$ for $|\Delta Y_2|$ and $\arg\{\Delta Y_2\}$ respectively. Thus it can be realized from the results in the previous paragraph, that in this case, the infeed does not affect the performance of the element.

## V. Disadvantages of Superimposed Sequence Quantities

Although different superimposed quantities applications reveal great potential for resolving microgrid protection challenges, some literature also shows limitations when these quantities are applied. These limitations are mainly due to the effects of the control strategy of IIDGs.

As described in Section III, IIDGs provide both active and reactive current to support voltage sag during fault. Analysis conducted in [42] shows that this requirement leads to non-linearity in the output current during faults, and this is influenced by the level of the voltage sag and the fault resistance. Hence, solutions whose criteria depend on magnitude ratio or phase difference of superimposed voltage and current may not have a reliable constant value as a threshold for protection elements [49], [50].

The angular characteristics of superimposed fault components were also studied in [32]. It was observed that the phase angles of superimposed impedances vary with fault positions, affecting the performance of superimposed component-based directional solutions.

## VI. Conclusion

The goals of achieving large scale integration of DGs and reliable operation of microgrids require protection systems that can adequately address the new challenges DGs pose to distribution network protection. A review of different proposed protection schemes based on superimposed quantities is carried out in this paper. It has been established that these quantities can be applied to both conventional and novel schemes to improve selectivity, sensitivity and security of the protection. These applications have varying limitations in terms of specific fault types or modes of operation. Ongoing research also shows that the efficacy of these quantities are significantly affected by the inverter control strategies of IIDGs.

## References


[1] O. Dharmapandit, R. Patnaik, and P. Dash, “A fast time-frequency response based differential spectral energy protection of ac microgrids including fault location,” *Protection and Control of Modern Power Systems*, vol. 2, no. 1, p. 30, 2017.

[2] H. J. Laaksonen, “Protection principles for future microgrids,” *IEEE Transactions on Power Electronics*, vol. 25, no. 12, pp. 2910–2918, 2010.

[3] H. Nikkhajoei and R. H. Lasseter, “Microgrid protection,” in *2007 IEEE Power Engineering Society General Meeting*. IEEE, 2007, pp. 1–6.

[4] M. R. Miveh, M. Gandomkar, S. Mirsaeidi, and M. R. Gharibdoost, “A review on protection challenges in microgrids,” in *2012 Proceedings of 17th Conference on Electrical Power Distribution*. IEEE, 2012, pp. 1–5.

[5] Y. Bansal and R. Sodhi, "Microgrid fault detection methods: Reviews, issues and future trends," in *2018 IEEE Innovative Smart Grid Technologies-Asia (ISGT Asia)*. IEEE, 2018, pp. 401–406.

[6] "Ieee standard for interconnection and interoperability of distributed energy resources with associated electric power systems interfaces," *IEEE Std 1547-2018 (Revision of IEEE Std 1547-2003)*, pp. 1–138, 2018.

[7] M. E. Baran and I. El-Markaby, "Fault analysis on distribution feeders with distributed generators," *IEEE Transactions on Power Systems*, vol. 20, no. 4, pp. 1757–1764, 2005.

[8] F. Zhang and L. Mu, "A fault detection method of microgrids with grid-connected inverter interfaced distributed generators based on the pq control strategy," *IEEE Transactions on Smart Grid*, vol. 10, no. 5, pp. 4816–4826, 2019.

[9] S. Mirsaeidi, D. M. Said, M. W. Mustafa, and M. H. Habibuddin, "A protection strategy for micro-grids based on positive-sequence component," *IET Renewable Power Generation*, vol. 9, no. 6, pp. 600–609, 2015.

[10] W. Huang, T. Nengling, X. Zheng, C. Fan, X. Yang, and B. J. Kirby, "An impedance protection scheme for feeders of active distribution networks," *IEEE Transactions on Power Delivery*, vol. 29, no. 4, pp. 1591–1602, 2014.

[11] F. Zhang, L. Mu, and W. Guo, "An integrated wide-area protection scheme for active distribution networks based on fault components principle," *IEEE Transactions on Smart Grid*, vol. 10, no. 1, pp. 392–402, 2019.

[12] X. Li, A. Dyśko, and G. M. Burt, "Traveling wave-based protection scheme for inverter-dominated microgrid using mathematical morphology," *IEEE Transactions on Smart Grid*, vol. 5, no. 5, pp. 2211–2218, 2014.

[13] S. M. Brahma and A. A. Girgis, "Development of adaptive protection scheme for distribution systems with high penetration of distributed generation," *IEEE Transactions on Power Delivery*, vol. 19, no. 1, pp. 56–63, 2004.

[14] S. I. Gkavanoudis, D. Tampakis, K. N. D. Malamaki, G. C. Kryonidis, E. O. Kontis, K. O. Oureilidis, J. M. Maza-Ortega, and C. S. Demoulias, "Protection philosophy in low short-circuit capacity distribution grids with high penetration of converter-interfaced distributed renewable energy sources," *IET Generation, Transmission Distribution*, vol. 14, no. 22, pp. 4978–4988, 2020.

[15] K. Liu and Y. Li, "Study on solutions for active distribution grid protection," in *Proceedings of the CSEE*, vol. 34, no. 16, 2014, pp. 2584–2590.

[16] A. Ukil, B. Deck, and V. H. Shah, "Current-only directional overcurrent relay," *IEEE sensors journal*, vol. 11, no. 6, pp. 1403–1404, 2010.

[17] A. Ukil, B. Deck, and V. H. Shah, "Current-only directional overcurrent protection for distribution automation: Challenges and solutions," *IEEE Transactions on Smart Grid*, vol. 3, no. 4, pp. 1687–1694, 2012.

[18] N. Rezaei and M.-R. Haghifam, "Protection scheme for a distribution system with distributed generation using neural networks," *International Journal of Electrical Power & Energy Systems*, vol. 30, no. 4, pp. 235–241, 2008.

[19] M. El Khatib, J. Hernandez-Alvidrez, and A. Ellis, "Fault analysis and detection in microgrids with high pv penetration," *Sandia National Laboratories (SNL-NM), Albuquerque, NM (United States)*, 2017.

[20] G. D. Rockefeller, C. L. Wagner, J. R. Linders, K. L. Hicks, and D. T. Rizy, "Adaptive transmission relaying concepts for improved performance," *IEEE Transactions on Power Delivery*, vol. 3, no. 4, pp. 1446–1458, 1988.

[21] H. Muda and P. Jena, "Real time simulation of new adaptive overcurrent technique for microgrid protection," in *2016 National Power Systems Conference (NPSC)*, 2016, pp. 1–6.

[22] H. Muda and P. Jena, "Superimposed adaptive sequence current based microgrid protection: a new technique," *IEEE Transactions on Power Delivery*, vol. 32, no. 2, pp. 757–767, 2016.

[23] D. Sampath Kumar, D. Srinivasan, A. Sharma, and T. Reindl, "Adaptive directional overcurrent relaying scheme for meshed distribution networks," *IET Generation, Transmission Distribution*, vol. 12, no. 13, pp. 3212–3220, 2018.

[24] M. Xu, T. Meng, G. Zou, J. Zhang, X. Lin, and J. Yang, "A centralized protection and control scheme for microgrid," in *2015 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC)*, 2015, pp. 1–5.

[25] D. Yuan, X. Dong, S. Chen, Z. Q. Bo, B. R. J. Caunce, and A. Klimek, "An new directional comparison scheme for distribution line protection," in *Proceedings of the 41st International Universities Power Engineering Conference*, vol. 3, 2006, pp. 881–885.

[26] H. Gao and P. A. Crossley, "Directional relay for ehv transmission lines using positive sequence fault components," in *2005 IEEE Russia Power Tech*. IEEE, 2005, pp. 1–5.

[27] G. Benmouyal and J. Roberts, "Superimposed quantities: Their true nature and application in relays," in *Proceedings of the 26th Annual Western Protective Relay Conference, Spokane, WA*, 1999.

[28] A. Sirisha and S. Bhide, "Incremental quantities based relays," in *2014 International Conference on Power, Automation and Communication (INPAC)*. IEEE, 2014, pp. 27–32.

[29] H. Muda and P. Jena, "Sequence currents based adaptive protection approach for dns with distributed energy resources," *IET Generation, Transmission Distribution*, vol. 11, no. 1, pp. 154–165, 2017.

[30] *SEL-221-16 Distance Relay/Fault Locator*, Schweitzer Engineering Laboratories, Pullman WA, USA. 2021. Available at https://selinc.com/.

[31] A. Hooshyar and R. Iravani, "A new directional element for microgrid protection," *IEEE Transactions on Smart Grid*, vol. 9, no. 6, pp. 6862–6876, 2018.

[32] K. Jia, Z. Yang, Y. Fang, T. Bi, and M. Sumner, "Influence of inverter-interfaced renewable energy generators on directional relay and an improved scheme," *IEEE Transactions on Power Electronics*, vol. 34, no. 12, pp. 11 843–11 855, 2019.

[33] W. Huang, N. Tai, Ke Li, X. Zheng, and Shi Chen, "Protection scheme for active distribution networks using positive-sequence components," in *2015 IEEE Power Energy Society General Meeting*, 2015, pp. 1–5.

[34] C. Zhou, G. Zou, J. Yang, and X. Lu, "Principle of pilot protection based on positive sequence fault component in distribution networks with inverter-interfaced distributed generators," in *2019 IEEE PES GTD Grand International Conference and Exposition Asia (GTD Asia)*, 2019, pp. 998–1003.

[35] L. Che, M. E. Khodayar, and M. Shahidehpour, "Adaptive protection system for microgrids: Protection practices of a functional microgrid system." *IEEE Electrification Magazine*, vol. 2, no. 1, pp. 66–80, 2014.

[36] P. Mahat, Z. Chen, B. Bak-Jensen, and C. L. Bak, "A simple adaptive overcurrent protection of distribution systems with distributed generation," *IEEE Transactions on Smart Grid*, vol. 2, no. 3, pp. 428–437, 2011.

[37] S. Tian, Y. Liu, and G. Mei, "New theory of directional current protection for the distribution network containing dg based on fault component," in *2011 International Conference on Advanced Power System Automation and Protection*, vol. 1, 2011, pp. 558–563.

[38] H. Gao, J. Li, and B. Xu, "Principle and implementation of current differential protection in distribution networks with high penetration of dgs," *IEEE Transactions on Power Delivery*, vol. 32, no. 1, pp. 565–574, 2017.

[39] G. Yang, W. Liu, D. Li, B. Liang, and Y. Liu, "Microgrid protection based on positive sequence fault component current," in *2019 4th International Conference on Power and Renewable Energy (ICPRE)*, 2019, pp. 1–6.

[40] G. Chen, Y. Liu, and Q. Yang, "Impedance differential protection for active distribution network," *IEEE Transactions on Power Delivery*, vol. 35, no. 1, pp. 25–36, 2020.

[41] Z. Dai, C. Li, and X. Chen, "Fault model of iidg considering lvrt and its application in fault analysis of active distribution networks," in *2016 IEEE Region 10 Conference (TENCON)*, 2016, pp. 3831–3834.

[42] Z. Yang, K. Jia, Z. Li, H. Zhao, Y. Fang, T. Feng, and B. Liu, "Adaptability analysis of the directional relay for the system with inverter-interfaced renewable energy generators," in *2019 IEEE 8th International Conference on Advanced Power System Automation and Protection (APAP)*, 2019, pp. 1611–1616.

[43] Y. Li, G. Zou, J. Yang, and H. Sui, "Faulty section location scheme for distribution grid with inverter interfaced distributed generation," in *2017 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe)*, 2017, pp. 1–6.

[44] J. Yang, C. Zhou, and G. Zou, "A protection scheme based on positive sequence fault component for active distribution networks," in *2018 2nd IEEE Conference on Energy Internet and Energy System Integration (EI2)*, 2018, pp. 1–5.

[45] K. Opoku, S. Pokharel, and A. Dimitrovski, "A negative sequence element for fault detection in inverter-interfaced microgrid," *Submitted for publication*, 2021.

[46] J. L. Blackburn and T. J. Domin, *Protective relaying: principles and applications*. CRC press, 2006.

[47] Z. Shuai, C. Shen, X. Yin, X. Liu, and Z. J. Shen, "Fault analysis of inverter-interfaced distributed generators with different control schemes," *IEEE Transactions on Power Delivery*, vol. 33, no. 3, pp. 1223–1235, 2018.

[48] T. Smith and B. Graves, "Detection of loss of voltage phase," in *Conference Record of 2013 Annual IEEE Pulp and Paper Industry Technical Conference (PPIC)*, 2013, pp. 165–169.

[49] Z. Wu, G. Wang, H. Li, G. Pan, and X. Gao, "Analysis on the distribution network with distributed generators under phase-to-phase short-circuit faults," in *Zhongguo Dianji Gongcheng Xuebao(Proceedings of the Chinese Society of Electrical Engineering)*, vol. 33, no. 1. Chinese Society for Electrical Engineering, 2013, pp. 130–136.

[50] M. Xu, G. Zou, C. Xu, W. Sun, and S. Mu, "Positive sequence differential impedance protection for distribution network with ibdgs," in *2016 IEEE International Conference on Power System Technology (POWERCON)*, 2016, pp. 1–5.