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A NEW METHOD TO ENHANCE THE DIFFERENTIAL PROTECTION OF THE MICROGRID BY SELF-BACKUP PROTECTION

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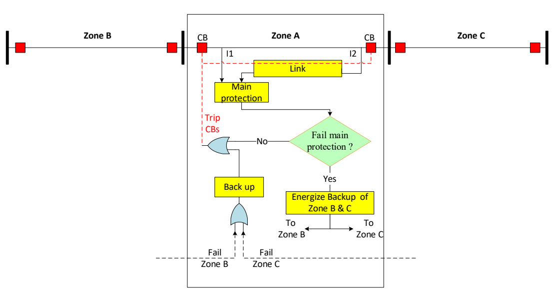
Graphical abstract



Abstract

Although the differential protection schemes consider as one of the effective types to protect the microgrid, this method may result in inaccurate performance because of the loss of communication link connecting the two ends of the line or other reasons. Therefore, the use of backup protection can lead to more accurate results. In this paper, self-backup protection is presented to cover the mal-operation of main protection. In this scheme, a new R-ratio method is defined based on the summation of the three-phase currents and the minimum of the three-phase voltages to overcome the low fault current during the islanded microgrid. The proposed scheme can detect all fault types during both operation modes of microgrid, grid-connected and islanded for radial and loop configuration. The validation of the proposed scheme is performed using PSCAD/EMTDC software. The simulation results proved that the proposed scheme could provide adequate protection against various fault types in grid-connected and islanded operation modes for a radial and loop configuration.

Keywords: Distribution system protection, Microgrid protection, Distributed generation, Distributed energy resources, Renewable energy sources, Differential relay.

1.0 INTRODUCTION

Nowadays, there has been a significant growth of distributed generators (DGs) that are installed into the distribution networks creating an autonomous distribution system, or microgrid [1]. Most DGs are renewable energy sources such as solar photovoltaic (PV) plants and wind turbine generators which are usually connected to the distribution system using power electronic devices, so it was called inverter-based DGs (IBDGs) [2]. The microgrid contributes to reducing transmission losses, improving efficiency, increasing reliability and mitigating overload problems from utility [3].

However, protection challenges have increased, and conventional overcurrent devices were no longer adequate due to fault current levels significantly decreasing when the microgrid be isolated [4]–[9]. Therefore, an appropriate protection scheme for microgrid should be designed to protect a microgrid against all types of faults for both grid-connected and islanded mode for radial and loop configuration.

Despite the continuing published research on microgrid protection, an effective protection scheme for microgrids has not been performed. It has seen conventional power systems protection relays found on the transmission and distribution systems were suggested for microgrids such as distance, directional overcurrent, and differential relays [10].

The differential protection schemes have been acknowledged as one of the most effective types for this purpose because of their high sensitivity, adequate selectivity and high-speed tripping, and a unit protection type that does not require coordination with other protective devices [11,12].

However, it may fail due to any reason, especially communication failure; therefore, backup protection is necessary [13].

The current schemes that have used differential protection are varied. Some of them are content with the main protection and ignore the backup protection such as papers [14]–[19]. In contrast, the authors of [20] proposed a multi-level scheme based on differential protection to ensure more secure protection for a meshed microgrid. The backup protection is once the connection between the two ends is broken, the line is isolated, and this is considered a malfunction where even if there is no fault in the line, any communication interruption for any reason leads to line isolation. Current differential protection was used in [21] to overcome the challenges of meshed microgrid protection resulting in varying fault current and bidirectional power flow due to penetration of DGs. The proposed scheme used an overcurrent relay with one set as backup protection that is not suitable for both modes of microgrid operation.

The protection scheme in [22] used two collections of differential functions independently as a machine-learning model input vector. For main protection, the functions are compared between the nearest faulted feeder's buses. While, for backup protection, the functions are compared between the remote faulted feeder's buses. The drawback of this scheme is the main and backup protections are differential where there is a contact between converging ends and diverging ends, which means the use of extended communication networks.

A comprehensive digital relay has been introduced in [2] for the protection of microgrids. The presented method utilized one-slope differential relay characteristic for protection feeders based on current data in both sides of the protected feeder is amassed, and fault occurrence is distinguished based on their variation. Also, a digital relay is utilized as a backup. This relay is fixed at the beginning of feeders and consists of two modules: the first module used a directional OC, and the second was used to detect faults by negative sequence component.

Although some of the protection schemes mentioned above used a backup, it was expensive, as this protection is independent of the main protection, which requires to use of its equipment such as CT, VT, Battery, etc.

On the other hand, the proposed protection should not be limited to one operation mode (grid-connected or islanded) but rather to protect the microgrid in both modes for radial and loop configuration against different fault types.

This paper proposed self-backup protection that uses the same main protection equipment; thus, the cost is reduced. The proposed scheme defines a new R-ratio method between the summation of the three-phase currents and the minimum of the three-phase voltages. This method enabled the scheme to overcome the low fault current during the islanded microgrid in addition to the grid-connected mode. Fortunately, this scheme does not require time coordination where it uses a short link with the adjacent lines to send a signal when the main protection fail. The main contributions of this paper are as follows:

- The proposed scheme can detect all fault types during both operation modes of microgrid, grid-connected and islanded for radial and loop configuration.
- It can detect the low fault currents during islanded operation mode as a result of using IBDG.
- It does not require time coordination of the protective devices.
- It has been proposed without independent elements, which mean reducing the cost.

2.0 BACKUP PROTECTION

The function of protective devices is to detect and clear faults as soon as possible to reduce the risk of equipment damage and service interruption by isolating only the faulty zone from the health system. Sometimes the protection devices cannot do this due to a malfunction of any of the circuit components, e.g. the trip mechanism for the CB, the connection wiring or d.c supplies to the devices [23]; therefore, backup protection is necessary to avoid the risk of continual fault.

The conventional backup protection in the radial distribution network is based on the graded time principle, where the protective devices are coordinated to determine the precedence of separation of the faulted zone then the farthest and farthest. Overcurrent devices are usually used to fulfil that. The following example in Figure 1 illustrates how to coordinate protection devices in the radial distribution network.

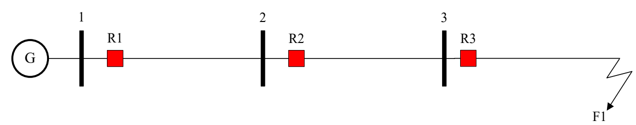


Figure1 Protection devices coordination

For fault at F1, R3 should operate first to clear the fault; R2 has a time setting higher than R3 to trip if it can. In the same way, R1 has a delay time higher than R2; R1 does not trip unless R2 and R3 did not trip. If the fault occurs between R2 and R3, there is no current flow in the R3 and therefore will not operate; R2 provide a trip signal to isolate the fault because it has a faster operating time from R1. Similarly, when the fault is between R1 and R2, then R1 will be clear a fault.

When the fault occurs in the distribution networks, the current magnitude increases obviously; therefore, protection systems have widely relied on this quantity for fault detection. For the microgrid, the fault current differs between the islanded mode of operation and grid-connected mode, where the current magnitude is small during the islanded mode.

This paper proposed self-backup protection to avoid the use of additional protective devices with its elements (CT, VT, batteries, ... etc.). Self-backup protection has been proposed without independent elements. Each main protection has been equipped with backup protection of an adjacent line beside the main function.

Also does not require time coordination of the protective devices but rather depend on the transmitted signal from the adjacent devices. The scheme is divided into two main parts, including fault identification and direction unit.

3.0 THE PROPOSED R-RATIO METHOD PROTECTION

In the proposed scheme, the differential current is used as the main protection for the microgrid feeder. Additionally, the R ratio method is considered as backup protection. Each zone in the microgrid has both protection (main and backup) that are collected in the same digital relay. The relays of the adjacent zones are connected by a short communication link. Figure 2 shows the schematic diagram of the proposed scheme; when the main protection fails then it sends a signal to the adjacent relays to energize the backup protection, which in turn will disconnect the adjacent lines to prevent the fault from continuing. For example, if a fault occurs in zone A in Figure 2, if the main protection fails, the backup relays of zone B and C will be energized after a certain time to examine the network health.

3.1 Fault Identification

Conventional overcurrent devices were used previously in distribution networks with time coordination, but this coordination becomes difficult with installing the IBDG. Furthermore, a large difference in fault current level between the islanded mode and grid-connected mode. Thus, the traditional overcurrent protection is insufficient for the protection of islanded microgrids.

The protection scheme of each line has been connected with the adjacent lines via a short link to send a continuous signal as a sign that the main communication link is healthy. When the signal is lost, the backup protection has been energized. Loss of signal does not necessarily mean the fault occurrence in the system, but it might happen for other reasons, such as failure in the communication system. Therefore, the line whether must be examined if there is a fault or not. When the fault was detected, then a trip signal was sent to local and remote CBs. The remote CB receive the tripping signal via the main communication link. Figure 3 shows the procedures of the proposed protection scheme.

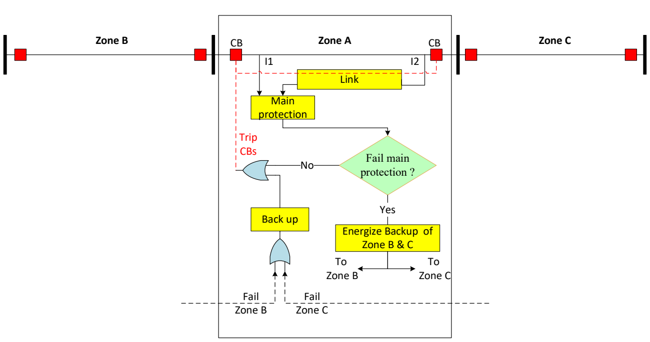


Figure 2 Schematic diagram of the proposed scheme

The proposed scheme in this work defines a new R-ratio method to overcome the low fault current problem of IBDG in the islanded mode. R-ratio represents the ratio of the summation of three-phase currents magnitude in per unit to the minimum voltage magnitude of the three phases voltage in per unit, also as in 1. So that if the increase of current is slight, R-ratio will be high due to the voltage decreases during the fault.

$$R = \frac{I_a + I_b + I_c}{\min(V_a, V_b, V_c)} \qquad (1)$$

where I_a, I_b and I_c are the magnitude of three-phases currents in per unit, V_a, V_b and V_c are the magnitude of three-phases voltages in per unit.

Equations (2) to (4) are used to convert the currents and voltages to per unit,

$$V_{pu} = \frac{V_m}{V_B} \qquad (2)$$

$$I_{pu} = \frac{I_m}{I_B} \qquad (3)$$

$$I_B = \frac{S_B}{\sqrt{3} V_B} \qquad (4)$$

where, V_{pu} and I_{pu} are the per-unit voltage and current, respectively. V_m and I_m are the measured voltage and current, respectively. V_B and I_B are the base value of voltage (v) and current (A), respectively. S_B is the base value of apparent power (VA).

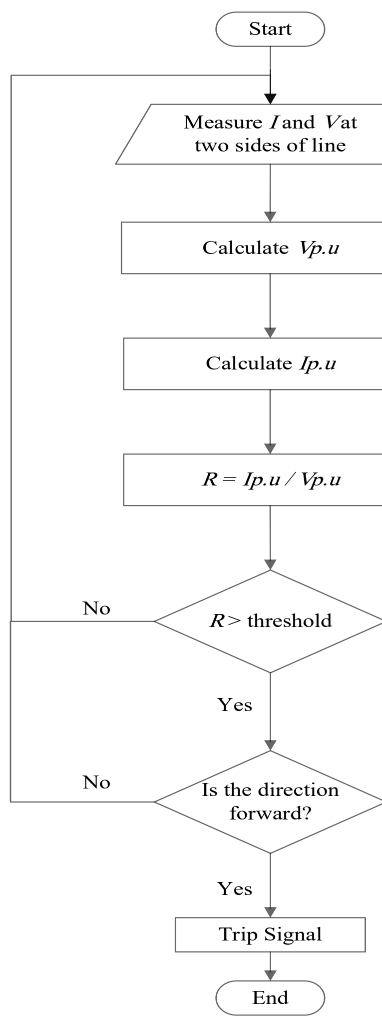


Figure 3 Flowchart of the proposed scheme protection

To find the threshold value R-ratio of the proposed scheme for the protected line, the fault study will do to determine the minimum fault current of the protected line for three-phase A, B and C and minimum voltage to ensure pickup in all fault cases. Minimum fault currents can be computed by applying the fault at the end of the protected line. The threshold value depend on network size and configuration. The threshold value R-ratio is calculated from Equation (1) based on the minimum fault current, when the R-value exceed the threshold value; the scheme sends a trip signal to a certain CBS.

3.2 Direction Unit

The overcurrent protection is appropriate for radial distribution systems with a single source, but it does not suitable for the distribution network with multiple sources or single-source network with parallel paths. Therefore, the network which has multiple current paths require relays at both ends with a directional unit. To illustrate the need for directionality in this type of distribution network, consider Figure 4.

If the fault occurs at F1, then it is the responsibility of R3 and R4 to open. While the fault at F2, the relays R1 and R2 which should trip the line. However, it is quite likely that for fault F2, R3 may trip before R2 opens to disconnect feed from the source S2 because that both relays are subjected to the same fault current magnitude. In other words, R3 competes with R2 to clear a fault. Opening of R3 unnecessarily causes loss of service to load at bus 3, and it should be classified as the wrong operation.

The wide expansion of the microgrid makes the coordination of the protection devices impossible since the microgrid operates in more than one state, i.e. grid-connected and islanded modes. In addition to the main problem of the main protection when the communication link is lost. Therefore, a backup protection scheme should be developed.

When a fault occurs on a power line, the protection device located at the ends of the line senses the fault. The protection device of other lines might sense the fault as well; therefore, the correct decision must be taken only by the protective device of the faulted line to achieve the reliability of the protection system. This can be done using the fault direction feature.

Directional unit is usually used for the protection of lines having infeed from both sides (e.g. loop systems, parallel lines). In these cases, the unit must be made operable only for a certain direction of fault current.

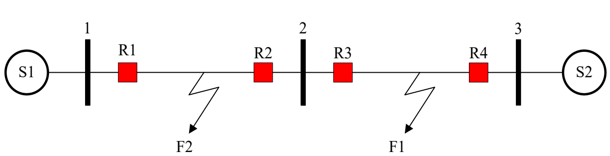


Figure 4 A distribution network with multiple sources

The voltage polarised directional unit respond to the differences in the relative phase angle between the voltage signal and current signal. Now, if it is defined:

$$\delta = \angle V - \angle I \tag{5}$$

where δ is the phase angle between V and I, V and I measured by R23 for forward and reverse fault. Since lines are usually inductive for forwarding line faults, so I lags V by the fault impedance angle δ, for a reverse fault on the adjacent line, the current is reversed compared to the current that flows during a fault in the forward direction, it seems to be rotated by about 180°.

4.0 RESULTS AND DISCUSSION

To evaluate the validity of the proposed scheme, several simulations have been implemented by using PSCAD/EMTDC software.

4.1 Microgrid Test System

The single line diagram of the microgrid test system is illustrated in Figure 5. The voltage level of the studied system was 24.9 kV, and the operating frequency was maintained at 50 Hz. As shown in this figure, the microgrid is connected to the main grid by a 69 kV/24.9 kV Dyn transformer. It contains two photovoltaic systems (640 KVA) and one wind turbine (500 KVA) that are connected with the power network through a power electronic inverter circuit in addition to one synchronous generator (300 MVA). Each DG source is interfaced through a 0.4/24.9 kV transformer. Radial and loop configuration can be achieved when the circuit breakers of L7 are opened or closed. The basic structure, networks, the information of transformer and loads are taken from [24] - [26].

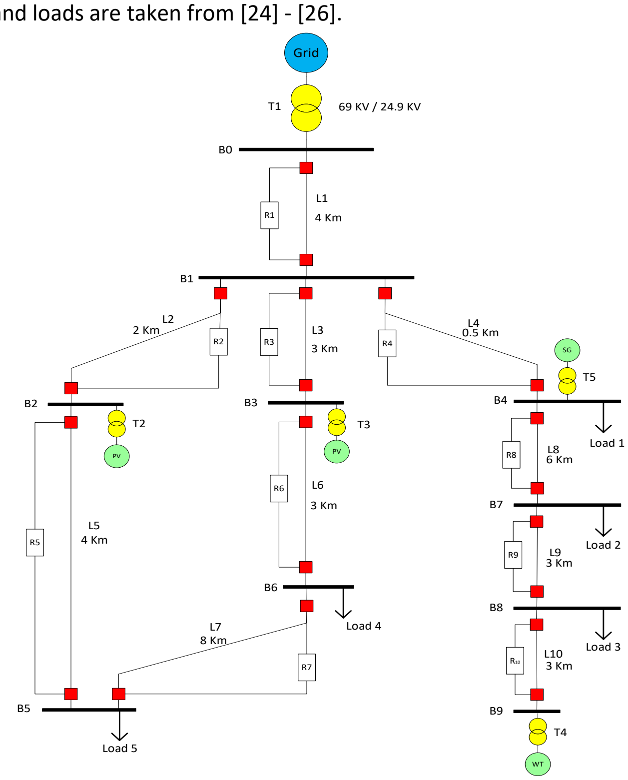


Figure5 Microgrid test system

4.2 Case Studies

A complete fault analysis for all locations in the microgrid test system is carried out. The fault types considered in this study include single line-to-ground (SLG) faults, line-to-line faults (LL), double-line-to ground faults (DLG), and three-phase to ground faults. All situations of circuit breaker and main protection failures are also simulated to validate the effectiveness of backup protection. The tests are performed under two different scenarios: grid-connected mode and islanded mode. In addition, the looped case is developed by simulating the fault on Line L7 of the studied microgrid. The communication delay is taken as 10 ms and the time delay specified for backup protection is 0.1 s [27].

All types of faults were applied to the test system at the time t = 0.2 s for different locations in both islanded and grid-connected operation modes. To calculate the ratio R, SB and VB were chosen 1 MVA and 24.9 kV, respectively. R is calculated based on (1), where it is monitored simultaneously. When the main protection has failed, this ratio exceeds the threshold. The following subsections show the simulation results of the backup protection scheme during different kinds of faults for different locations inside the microgrid.

4.2.1 Case Study 1: Grid-Connected Operation Mode

The objective of this case study is to verify the effectiveness of the proposed main protection scheme during the grid-connected operation mode for radial and loop configurations of the microgrid with balance and unbalance load. The primary protection relays detect all faults and send the trip signal to relevant circuit breakers to isolate the faulty section from the rest of the microgrid. In this case, it is assumed that the main protection scheme has failed to clear the fault; therefore, the fault should be clear by the backup protection. The backup protection scheme detects all types of faults and sends the trip signal to relevant circuit breakers.

For SLG fault that was assumed to have occurred on line L5. In this zone, R5 is the main protection scheme that has failed to clear the fault, so the backup scheme R2 and R7 are responsible for protecting the L5 zone for loop configuration and only R2 for radial configuration.

Figure 6(a) shows the current magnitude of the faulted phase in the faulted line L5 and the adjacent lines L2 and L7 for the radial and loop configuration. As a result of the current increases and the decreasing of the phase voltage, the R ratio of relays R2 and R7 exceeded the threshold, as shown in Figure 6(b). Also, the power flow direction at R2 is forward while at R7 is reversed, so the trip signal is sent to the CBS to isolate the fault, as can be seen from Figure 6(c). As can be seen from the figure, that trip time is less than 108.5 ms after the fault incident at time 0.2 s. while the total clearing time is 111.5 ms, as shown in Figure 6(d), this time includes operating times of the relay, communication delay time, CB opening time and the delay time of the backup protection.

The Unbalanced load without a synchronous generator is also considered. In this case, an unbalanced load was taken into consideration. Also, the synchronous generator disconnects from bus 4 to test the system with IBDG only. The proposed scheme is based on the positive current component to fit with this issue.

All types of fault were tested, but only a three-phase fault was presented because it is more severe in the power system. A three-phase fault was assumed to occur on line L5. Figure 7(a) shows the current magnitude of the faulted phase a in the faulted line L5 and the adjacent lines L2 and L7 for the radial and loop configuration. As a result of the current increases and the decreasing of the phase voltage, the R ratio of relays R2 and R7 exceeded the threshold as shown in Figure 7(b).

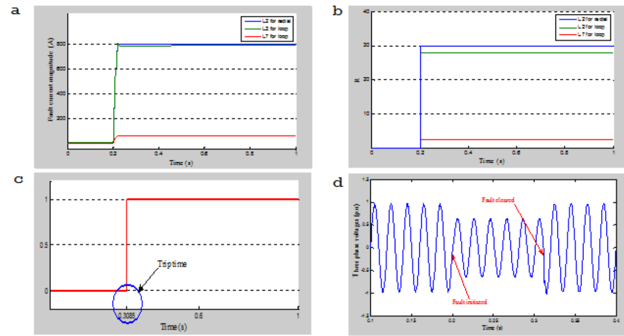


Figure 6 Results of SLG fault on line L5 for grid-connected mode
(a) Fault current magnitude of phase a on lines L2, L5 and L7 (b) R ratio for L2 and L7 for SLG on L5 (c) Trip signal of R2 (d) Voltage of phase a at bus 2

Also, the power flow direction at R2 is forward while at R7 is reversed, so the trip signal is sent to the CBS to isolate the fault as can be seen from Figure8(c). As can be seen from the figure that trip time is less than 108.5 ms after the fault incident at time 0.2 s. while the total clearing time is 111.5 ms as shown in Figure8(d), this time includes operating times of the relay, communication delay time, CB opening time and the delay time of the backup protection.

In summary, this section presents the results of the backup protection scheme. The results showed the efficiency of this scheme for all types of fault during the grid-connected operation mode for radial and loop configurations of the microgrid with balance and unbalance load. The results also showed that the scheme is characterized by high reliability and accuracy, in addition to fast operation speed that was less than 115.5 ms.

4.2.2 Case Study 2: Islanded Operation Mode

In this case, the scheme is simulated for all types of faults in the islanded mode, for both radial and looped topologies.

A LL fault on L6 was tested in the islanded mode, where it was assumed that the fault occurred at time 0.2 s, the main protection scheme (R6) has been assumed to have failed to clear the fault, so the backup scheme R3 and R7 are responsible to protect the L6 zone for loop configuration and only R3 for radial configuration.

Figure 8(a) shows the fault current magnitude in the faulted line L6 and the adjacent lines L3 and L7 for the radial and loop configuration. As a result of the current increases and the decreasing of the phase voltage, the R ratio of relays R3 and R7 exceeded the threshold as shown in Figure 8(b).

Also, the power flow direction at R3 is forward while at R7 is reversed, so the trip signal is sent to the CBs to isolate the fault as can be seen from Figure 8(c). As can be seen from the figure that trip time is less than 108.5 ms after the fault incident at time 0.2 s. while the total clearing time is 130 ms as shown in Figure 8(d), this time includes operating times of the relay, communication delay time, CB opening time and the delay time of the backup protection.

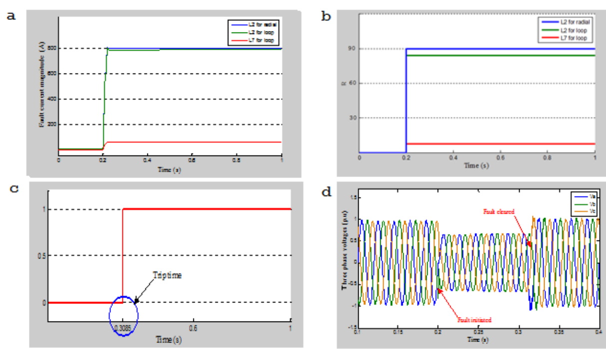


Figure 7 Results of three-phase fault on line L5 for grid-connected mode with unbalance load (a) Fault current magnitude (b) R ratio for L2 and L7 (c) Trip signal of R2 (d) three-phase voltage at bus 2

In this case, also unbalanced load was taken into consideration and the synchronous generator disconnects from bus 4 to test the system with IBDG only. The proposed scheme is based on the positive current component to fit with this issue.

All types of fault were tested, but only a three-phase fault was presented because it is more severe in the power system. A three-phase fault was assumed to occur on line L5. Figure 9(a) shows the current magnitude of the faulted phase a in the faulted line L5 and the adjacent lines L2 and L7 for the radial and loop configuration. As a result of the current increases and the decreasing of the phase voltage, the R ratio of relays R2 and R7 exceeded the threshold as shown in Figure 9(b).

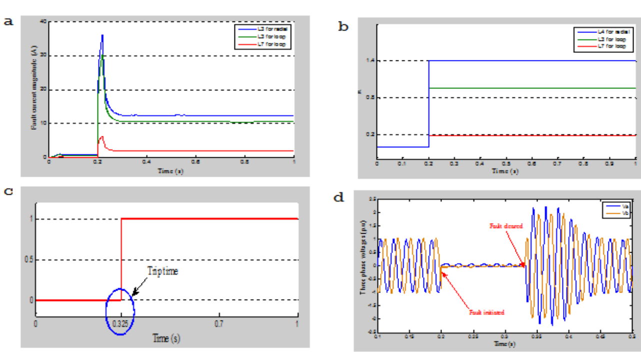


Figure 8 Results of LL fault on line L6 for islanded mode (a) Fault current magnitude (b) R ratio for L3 and L7 (c) Trip signal of R3 (d) voltages at bus 3

Also, the power flow direction at R2 is forward while at R7 is reversed, so the trip signal is sent to the CBs to isolate the fault as can be seen from Figure 9(c). As can be seen from the figure that trip time is less than 108.5 ms after the fault incident at time 0.2 s. while the total clearing time is 111.5 ms as shown in Figure10(d), this time includes operating times of the relay, communication delay time, CB opening time and the delay time of the backup protection.

In order to validate the performance of the proposed scheme, it is compared with work in [2] in terms of the operation speed of the protection scheme. Where the maximum operation time in [2] is 372.3 ms, while the proposed scheme has a fast operation speed that was less than 130 ms. Also, the results showed the efficiency of this scheme for all types of fault during the islanded operation mode for radial and loop configurations of the microgrid with balance and unbalance load. The results also showed that the scheme is characterized by high reliability and accuracy.

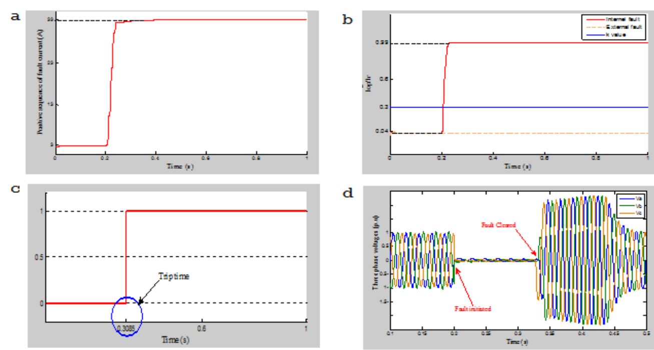


Figure 9 Results of three-phase fault on line L5 for islanded mode with unbalance load (a) Fault current magnitude (b) R ratio for L2 and L7 (c) Trip signal of R2 (d) three-phase voltage at bus 2

5.0 CONCLUSION

Although the differential protection schemes consider as one of the effective types to protect the microgrid, this method may result in inaccurate performance because of the loss of communication link connecting the two ends of the line or other reasons. Therefore, the use of backup protection can lead to more accurate results. In this paper, self-backup protection is presented to cover the mal-operation of main protection. In this scheme, a new R-ratio method is defined based on the summation of the three-phase currents and the minimum of the three-phase voltages to overcome the low fault current during the islanded microgrid. When this ratio is above pickup and the power direction is appropriate, then the trip coil is energized and CB tripping is ensured. To evaluate the validity of the proposed scheme, several simulations have been implemented by using PSCAD/EMTDC software. The simulation results proved that the proposed scheme could protect the microgrid with inverter-based DG against all types of fault for both operation modes, grid-connected and islanded, for radial and loop configuration.

The proposed scheme has been verified the selectivity where only the faulty zone is isolated when a fault occurs. Also, the speed of the protection scheme was demonstrated since the main protection scheme tripped CBs did not exceed 34 ms during the grid-connected and islanded modes, while the backup scheme tripped CBs in less than 130 ms with delay time. Furthermore, the proposed scheme reliability for the grid-connected and islanded mode was validated during where the main and backup protection tripped and did not trip as expected in all cases.

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