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Microgrid Protection Using a Designed Relay Based on Symmetrical Components

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Abstract: Microgrid technology is increasing developing for efficient utilization of distributed generation (DG) sources in line with reliability and power quality improvement. Changes in power flow as well as in short circuit levels of network points in the case of fault event at grid connected or islanded modes, leads to problems in coordination among protection devices of traditional distribution networks. The problems necessitate application of new techniques for microgrid protection. The paper presents a directional digital over-current relay sensitive to symmetrical components for the purpose of microgrid protection against all fault types. The designed digital relay is operational despite of small amounts of symmetrical component quantities in fault conditions; It is also able to provide the possibility of fault locating more quickly and accurately. The paper, furthermore, proposes a protection algorithm through the designed digital relay, communication links and Micro Grid Central Controller (MGCC) for microgrid protection. The communication links are only required for sending signals based on relay operation not for fault electrical quantities. Thus, a narrow bandwidth communication channel is sufficient and there is no need to a wide bandwidth channel. The protection algorithm is simulated on a test system. This system is simulated using DIgSILENT Power Factory establish the claims made in this paper.

Key words: Microgrid protection % Digital relay % Distribution communication % Distributed generation % Symmetrical component

INTRODUCTION

Since the traditional distribution networks are utilized radially, designing protection scheme for them is not so complicated. In recent decade, there has been great attention to microgrids that utilization of them has been caused some challenges in distribution networks.

A microgrid is defined as a low to medium voltage network of small load clusters with DG sources and storage [1].

The microgrids in distribution network has brought many advantages including environmental pollution reduction, economic frugality related to development of transmission lines and power plants, improvement of power quality to costumers, increase of reliability, reduction of Energy Not Supply (ENS), etc.

Wind turbines, fuel cells, photo-voltaic cells and micro-turbines are considered as the most important sources used in microgrids.

Microgrids can either operate connected to the grid, or in the case of grid fault, in an islanded mode [2]. Thus, the proposed protection schemes need to be so applicable for each operation modes and so selective that can improve reliability and availability of its sources. The presence of microgrid has created many problems in distribution networks. Generally, the problems arising from [3-8].

- Short circuit capacity in different point of network due to the change of Thevenin impedance at fault location arising from the operation mode switch of microgrid from grid connected to islanded mode.
- Low capacity of fault current is less than half of rated current in some condition and switch from grid connected into islanded operation mode will cause considerable reduction in short circuit level of microgrid.
- Bidirectional flow of feeders due to microgrids feeding from main network and DG sources.
- The load balance of three phases in the network will be broken by the single-phase grid-connected microgrid.
- The relay protection constant setting may become invalid because of unpredictable dynamic output power characteristics of DG.

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Recent developments in distribution technology have drawn attentions to microgrid inclusion in distribution system. Hence, it is essential to propose a microgrid protection algorithm capable of detection and isolation of fault fast opening of Static Switch (SS) during fault event is an effective solution presented in the paper.

The protection philosophy is that microgrids are connected to main network in normal condition; but in the case of any disturbance, the protection system will immediately switch microgrids into islanded mode through SS. Therefore, the protection consists of two steps: First, fault detection in grid connected mode and quick change of microgrid to island mode; and second, having occurred any fault in microgrid, the protection scheme locates fault by the designed digital relay and MGCC and clears it before microgrid reconnection into the main network. Obviously, SS is open till fault isolation. When microgrid is connected to the main network, DG sources should feed local loads in order to reduce power flow through main network; DG sources should also satisfy microgrid load demands, in the case of islanded operation, in order to avoid overload in the system.

The purpose of protection scheme in microgrid is to detect and isolated faulted zone from other network so that utilizing DG sources in islanded mode, system reliability can be increased. Therefore, several solutions have already presented for microgrid protection. In [9], output voltage of generation sources has been analyzed and transformed from abc reference frame into dq0 reference frame. In this way, any disturbance in the output of generation source due to fault event is transformed to dq0 reference frame; this transformation system is used for fault detection in network. Then analyzing measurements conducted in different points, a relationship between the position of fault and disturbances in generation sources is extracted.

In [10], LL and SLG faults are detected using symmetrical components through zoning microgrid applying relay for each source. This scheme works without the use of communication system. In method presented in [11], DG sources are isolated immediately after fault occurrence and before other relays trip, leading to a decrease in system reliability. All the above mentioned schemes are not completely effective against high impedance faults; additionally, they are tested on small scale networks with few buses.

In [12], dynamic strategy has been presented to control and protect distribution system with DG sources. The focus of the paper [12] is to verify effectiveness of DSP in online evaluation of network control and protection operation and to emphasize modern telecommunication technology in online analysis of distribution system and information transmission.

In [13], fault position is determined in network by applying S transformation on current signals and bus voltage. This method has not been studied over networks with several buses and equipped with voltage transformers with problems in high frequencies.

Concerning the above mentioned problems and regarding the importance of a more secure and selective protection, the present paper proposes a protection scheme through the design of directional digital relay sensitive to symmetrical component in contribution with communication links.

Having measured the positive and negative sequence impedance, the scheme is reliably and quickly detects the asymmetrical and symmetrical faults, respectively. In addition, the proposed scheme, unlike differential protection in which the measured fault current is transmitted through communication channels, makes use of a signal based on relay operation and needs no of fault electrical quantities. Therefore, the high-speed operation will increase due to signal application and the costs will decrease due to the application of limited bandwidth communication links.

Protection Scheme

The Case for a New Protection Paradigm: Power flow directional in distribution networks is typically from higher voltage levels to lower voltage levels, i.e. from transmission system to distribution system. Traditional distribution systems are radial in nature fed by a power supply. Protection of these systems typically is by fuses, reclosers and over-current relays. The presence of microgrid will lead to power flowing in opposite direction, i.e. from distribution system to transmission system. Also, power flow in different parts of the network will change, leading to mis-coordination among protection relays. In addition, the presence of power electronic devices and reduction of short circuit current during fault occurrence will make traditional-based protection practically impossible.

High-speed fault clearing and fast protection are essential in microgrids and make possible the use of DG sources preserve of stability and optimal power quality. Since microgrids are equipped generators known as DGs, high-speed fault clearing is required to prevent dynamic instability of network. Furthermore, considering the modern costumers with special features such as computer and electronic devices high-speed protection has been required. These costumers are highly sensitive to voltage sag arising from fault occurrence. Regarding the technological developments, facilitating the use of digital communication links as signals path, the use of communication-assisted digital relays is the best solution to microgrid protection.

The Overall Profile of Proposed Scheme: The proposed protection scheme has been implemented by the design of a directional digital relay sensitive to symmetrical components. Capabilities provided by digital relays are considerably greater than electronic and static models. High accuracy and more settings are among these capabilities. In addition, digital relays provide direct or indirect (through communication channels) link to computers. They are also self–metering and have oscillographic event report [14].

Each protection scheme can be implemented by programmable information processors. In the proposed protection scheme, as shown in Figure 1, digital relays are installed between two terminals in the same line. The relays are connected to MGCC using communication channels and are able to identify with adequate security fault occurrence in reverse and forward regions by means of symmetrical components.

Regarding EPRI studies in 1980, only 2 percent of faults in distribution systems are allocated to symmetrical three-phase type [15]. It can be said that asymmetrical faults such as SLG, LL, LLG and other asymmetrical faults have highest percentage of faults at distribution voltage level. However, protection against all fault types is essential for microgrids. On the other hand, analysis and calculation of asymmetrical faults are difficult due to their entity.

Symmetrical components method, introduced by C.L. Fortescue, is one of the most effective methods dealing with unbalance multi-phase circuits [16]. When asymmetrical faults occur due to lose of network symmetry, positive, negative, or zero sequence will be created in network depending on fault type. Table 1 indicates the presence of symmetrical components in different fault types and percentage of their occurrence in EPRI studies. Considering Table 1, negative sequence is the only component appears in all asymmetrical fault types. Positive sequence is also the only component appears in network during three-phase symmetrical fault occurrence.

Table 1 also shows that zero sequence will be appeared during the occurrence of ground faults. Since, some designs consider microgrids ungrounded, the use of

Table 1: Presence of Symmetrical Components in Different Fault Types and Percentage of Their Occurrence

Fault Type	Zero Sequence	Negative Sequence	Positive Sequence	Percentage
Single Phase to Neutral	Yes	Yes	Yes	63%
Line to Line	No	Yes	Yes	11%
Line to Line to Neutral	Yes	Yes	Yes	2%
Three Phase	No	No	Yes	2%
Single Phase to Ground	Yes	Yes	Yes	15%
Line to Line to Ground	Yes	Yes	Yes	2%
Three Phase to Ground	Yes	Yes	Yes	1%
Others	-	-	-	4%

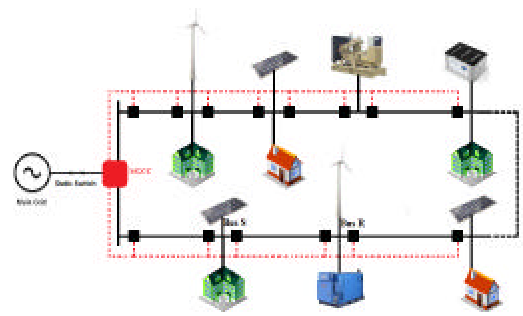

Fig. 1: Position of relays in the proposed protection scheme

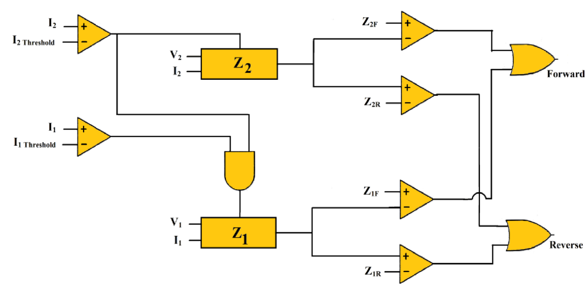

Fig. 2: The designed relay based on symmetrical components

the zero sequence is not recommended in identification of ground faults. Therefore, with availability of voltage and current symmetrical components, the designed relay in Figure 2 makes use of negative sequence and positive sequence to protect microgrid against asymmetrical and symmetrical three-phase faults, respectively.

According to Figure 2, the designed relay makes use of negative sequence current to detect asymmetrical faults and negative sequence current and voltage to locate of asymmetrical faults. In other words, when the negative sequence current is more than negative sequence unbalanced current value in normal condition, asymmetrical fault occurrence is identified. Then, applying the following relationship and calculating scalar quantity Z_2, forward or reverse faults can be located [17]:

Fig. 3: SLG fault occurrence between buses R and S in Figure 1

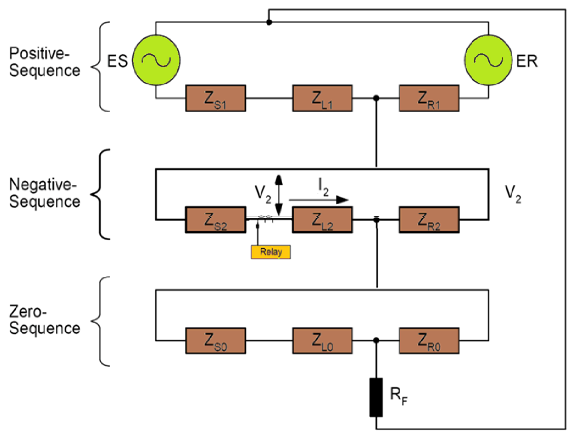

Fig. 4: Sequence network equivalent circuit

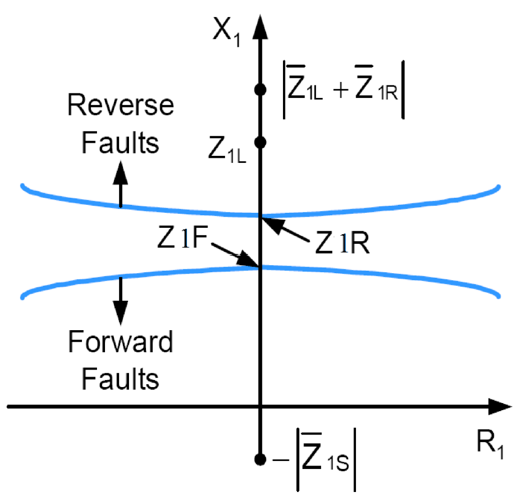

Fig. 5: The operating characteristic of the designed relay for a symmetrical fault

$$Z_2 = \frac{\mathrm{Re}\left[\vec{V}_2 \times \left(\vec{I}_2 \times 1\angle Z_{1L}\right)^*\right]}{|I_2|^2} \quad (1)$$

Where, V_2 and I_2 are, respectively, the voltage and current negative sequences. Z_{1L} is line positive sequence impedance angle which is equal to line negative sequence impedance angle. The directional relay compares negative sequence line impedance with two thresholds for asymmetrical faults; the relay detects forward faults if Z_2 is below than forward threshold (Z_{2F}) and reverse faults if Z_2 is above than reverse threshold (Z_{2R}). Figure 3 shows a SLG fault occurrence between the buses R and S of Figure 1. Its sequence network equivalent circuit will be according to Figure 4.

According to Figure 4, if the relay measures I_2 negative sequence current, the relay measured voltage is equal to $V_2 = -I_2 \cdot Z_{2S}$. If the negative impedance source angle $\left(\angle\vec{Z}_{2S}\right)$ equals the setting angle (Z_{1L}), the calculated scalar quantity is $Z_2 = -\left|\vec{Z}_{2S}\right|$. For any location of the forward fault, the directional element measurement corresponds to the negative-sequence impedance of the equivalent system behind the relay. A similar analysis shows that for all reverse faults, the scalar quantity $Z_2 = \left|\vec{Z}_{2L} + \vec{Z}_{2R}\right|$, corresponding to the negative-sequence impedance of the equivalent system in front of the relay.

As shown in Figure 2, the designed relay utilizes different strategies to detect symmetrical faults. Having occurred any symmetrical three-phase fault, positive sequence current will identify fault occurrence. The location of symmetrical fault is determined by following relationship using positive sequence current and voltage:

$$Z_1 = \frac{\mathrm{Re}\left[\vec{V}_1 \times \left(\vec{I}_1 \times 1\angle Z_{1L}\right)^*\right]}{|I_1|^2} \quad (2)$$

Where, V_1 is positive sequence voltage, I_1 is positive sequence current and Z_{1L} is line positive sequence impedance. Calculation of scalar quantity in symmetrical fault is the same as that of asymmetrical one, with the only difference that relay settings will be based on Z_{1F} and Z_{1R}. Figure 5 shows the operating characteristic of the designed relay for a symmetrical fault. In the Figure, the calculated impedances at forward and reverse faults are separated regarding line impedances. Value setting for Z_{1F} and Z_{1R} is the same as that of Z_{2F} and Z_{2R}. For simplicity in the figure design, the network has been assumed purely inductive and the line positive sequence impedance angle has been set in 90 degree. It is worth mentioning, in the designed relay, forward and reverse regions can be freely set depending on different protection schemes.

Fault Location Algorithm: As shown in Figure 6, relays are installed at the two terminals of microgrid lines and numbered in order to implement the proposed algorithm after setting the reverse and forward thresholds. The relays are connected to MGCC through narrow bandwidth communication channels only to send relay signals. It should be noted that the algorithm is applicable for each network configuration.

The philosophy of the protection system presented in the paper, as mentioned before, is that microgrid is connected to main network in normal conditions. Having occurred any disturbance, the protection system will immediately switch the microgrid into islanded mode via SS. In the case of fault occurrence in the microgrid, the protection scheme will locate the fault using digital relays and MGCC and will connect the microgrid to main network only after fault clearing. Fault location in relays is based on right-side trip signals.

Having occurred a fault in any segment, a trip signal is sent to MGCC by the relay after seeing the fault in its right side. It is obvious that for some relays, the right signal is forward signal and for some others, the reverse signal. Considering the right-side signals, fault in any segment is modeled as a binary. For fault location analysis, the obtained binary values are transformed into decimal values in MGCC. Table.2 indicates the binary and decimal values obtained from MGCC.

Considering Table.2 and the decimal values calculated by MGCC, a geometric progression will be created for fault in different segments. The n-th term of the progression indicates the fault occurring between n and n+1 relays. Therefore, faulted segment is located by determining the n-th term of the progression and disconnection command is sent to (n) and (n+1) circuit breakers. The n-th term of the geometric progression is calculated by equation (3).

$$t_n = a \times q^{n-1} \quad (3)$$

Where a, q and n are scale factor, common ratio and number of terms, respectively. Regarding the geometric progression obtained from Table.2, the scale factor is equal to 1 and the common ratio is 2. Substituting the values in equation (3), n value is calculated:

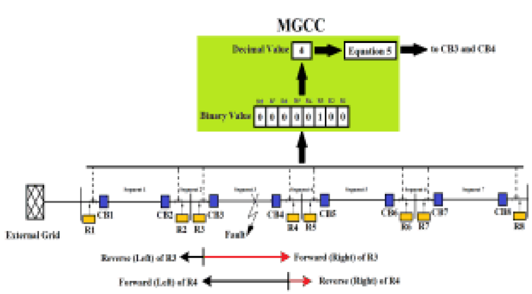

Fig. 6: Fault occurrence at segment 3

Table 2: The Binary and Decimal Values Obtained from Mgcc

Right Signals	Fault Segments: Segment 1	Segment 2	Segment 3	Segment 4	Segment 5	Segment 6	Segment 7
Relay 1	1	0	0	0	0	0	0
Relay 2	0	1	0	0	0	0	0
Relay 3	0	0	1	0	0	0	0
Relay 4	0	0	0	1	0	0	0
Relay 5	0	0	0	0	1	0	0
Relay 6	0	0	0	0	0	1	0
Relay 7	0	0	0	0	0	0	1
Relay 8	0	0	0	0	0	0	0
Binary Equivalent	00000001	00000010	000000100	00001000	00010000	00100000	01000000
Decimal Equivalent	1	2	4	8	16	32	64

Table 3: Length of the Feeders Branches

Branch	Length	Branch	Length
L1	1.00	L7	1.00
L2	0.50	L8	1.00
L3	0.80	L9	0.50
L4	1.00	L10	0.70
L5	0.80	L11	1.00
L6	0.50	L12	0.50

Table 4: Generators Units Characteristics

	Nominal Voltage (KV)	Rated Apparent Power (MVA)
Synchronous Machine	0.4	1.4
Synchronous Machine 1	0.4	2.1
Synchronous Machine 2	0.4	2.8
Asynchronous Machine	0.4	0.7

$$t_n = (1) \times (2)^{n-1} \quad (4)$$

$$n = \log_2(t_n) + 1 \quad (5)$$

Determination of n value through equation (5) will help to locate the faulted segment independent of fault type and consequently, MGCC will send disconnection command to (n) and (n+1) circuit breakers. For example, having occurred a fault at segment 3 of Figure 6, the fault is sensed in right side of relay3. After MGCC analyzing, disconnection commands are sent to CB3 and CB4. So, the appropriate protection in all segments will be provided through communication lines and therefore, reliability will be increased.

Microgrid Application System: Simulations have been performed for a LV distribution network with a nominal voltage of 0.4 kV and an apparent power of the MV/LV transformer equal to 15 MVA. The studied network has been shown in Figure 7. The microgrid is connected to the main network at the Point of Common Coupling (PCC) and

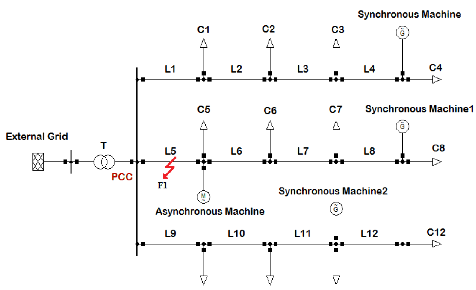

Fig. 7. The studied network

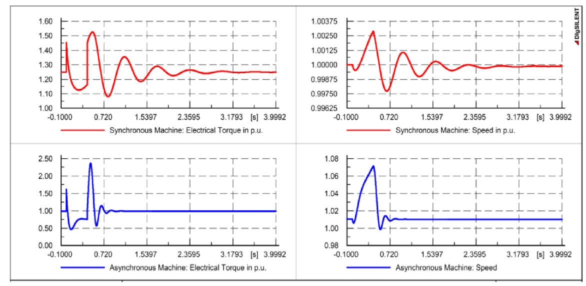

Fig. 8: Simulation results of a symmetrical three phase fault at L5

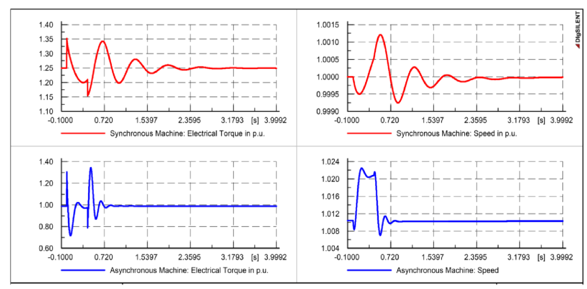

Fig. 9: Simulation results of a line to line fault at L5

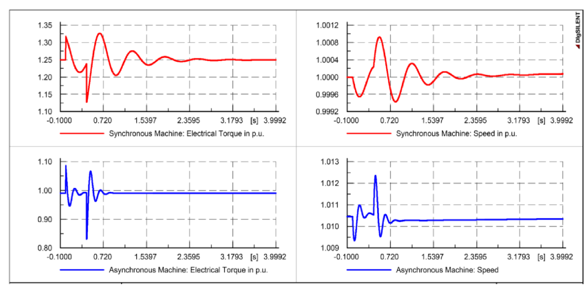

Fig. 10: Simulation results of a single line to ground fault at L5

can be supplied by four generators when operated as an island, e.g. following an external fault event. The feeders are cable lines (Cu) with a section of $3x(1x95)mm^2$.

The length of the feeders branches are listed in Table 3. The installed apparent power of the network loads is 0.4 MVA for loads C1, C2, C3, C4, C5, C6, C7, C8, C9, C10, C11 and C12. All loads have a power factor of 0.95. The generation units characteristics are summarized in Table 4. The designed relay used in the proposed scheme is modeled by DIgSILENT Simulation Language (DSL) in DIgSILENT PowerFactory software.

Simulation Results: In this study, the three major faults (single line to ground, line to line and three phase faults) are simulated in a test system by DigSILENT PowerFactory. We are interested in evaluating the stability of generators a fter fault clearing using the proposed protection scheme. For simplicity, only the most critical fault is considered in the simulations.

According to steady-state studies, when a fault is occurred in the closest point to the PCC, the fault current and voltage drop levels will be in their maximum values. The simulations result of a symmetrical three phase fault at L5 is shown in Figure 8. In the figure, the electrical torque and rotor speed of both synchronous machine and asynchronous machine are simulated during the fault occurrence. In the case, the occurred fault is cleared after 0.4 s by the proposed protection scheme.

According to Figure 8, it is obvious that this fault clearing time is adequate for maintaining of generators stability. Similar simulations are done for line to line and single line to ground faults that are depicted in Figure 9 and 10. The simulation results are indicated that the proposed protection scheme can effectively clear the fault without any instability in microgrid generators.

CONCLUSION

The paper presented a directional digital relay sensitive to symmetrical components to protect microgrid against all fault types. The designed relay makes use of negative and positive s equences to protect microgrid asymmetrical and symmetrical three-phase faults, respectively. The relay can detect fault occurrence in reverse and forward regions via calculation of negative and positive sequence impedances, respectively in asymmetrical and symmetrical faults despite of small amounts of currents and voltages.

A protection algorithm was also proposed using the designed digital relay and communication links together with MGCC for detecting fault and isolating faulted segment from the other segments. For the implementation of the algorithm, relays are located at the end of the lines and connected to MGCC. Having received and processed the information, the MGCC detects the faulted segment and sends disconnection command to respective circuit breakers. The protection algorithm is simulated on a test system. The simulation results indicated that the proposed protection scheme can effectively clear the fault without any instability in microgrid generators.

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