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Communication-assisted Impedance-based Microgrid Protection Scheme

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Abstract—**Development of efficient non-overcurrent based protection schemes is a prerequisite for significantly increasing microgrids renewable energy penetration. In this paper a novel communication-assisted impedance-based protection scheme is proposed. For the sake of protection design, we partition microgrids into protection zones based on the availability of fault interruption devices. The proposed scheme depends on monitoring impedance trajectories at different feeder relays to detect the occurrence of faults and utilizes directional elements to determine the direction of faults. Communications between feeder relays are utilized to exchange permissive and blocking signals in order to locate the fault and trip the least part of the microgrid to clear the fault. Simulation results are presented to demonstrate the effectiveness of the proposed scheme.**

I. INTRODUCTION

Since the introduction of the microgrid concept in [1], it was realized that designing efficient protection schemes for microgrids would be challenging and would require advancing the state-of-the-art of protective relaying. The main challenge facing the development of *standardized* microgrid protection originates from the fact that microgrids differ in their topology, generation mix, feeder sizes and fault interruption devices types and locations. Additionally, fault current levels could change drastically between grid-connected and islanded modes of operation which makes it very difficult, or even impossible in some cases, to maintain overcurrent protection coordination for both cases. Moreover, in the islanded mode of operation, fault currents could change significantly with generation dispatch which complicates protection coordination design. Further, for microgrids with significant inverter-interfaced generation, renewable generation for example, fault currents could be very limited as a result of inverter current-limiting control functions which typically limit fault contribution to as low as 1.1 per unit. For this particular case, overcurrent protection could fail completely to pick up the fault in the first place.

Extensive research has been directed toward designing efficient protection schemes for microgrids. The challenge of maintaining proper overcurrent protection coordination in microgrids, and more generally for distribution systems, with significant DGs have been discussed extensively in literature, see [2], [3] and references therein for example. Adaptive overcurrent protection schemes were discussed in several works, [4], [5], [6], [7]. These schemes rely on a central protection unit and communication infrastructure to determine and continuously adjust the settings of different protection relays in the microgrid to maintain proper coordination under changing microgrid operation modes and generation dispatch. Adaptive overcurrent protection schemes, however, are difficult to apply to inverter-dominated microgrids specially in islanded mode of operation since fault current could be too low to be detected by overcurrent protection.

Several protection schemes were introduced for inverter-dominated low-fault current microgrids. Voltage based protection schemes were discussed in [8]. The method is based on the fact that during faults, voltage levels dips across the microgrid. However, discriminating between faults and other events, such as capacitor tripping, is hard to achieve using voltage measurements. Additionally, in a typical microgrid, the magnitude of voltage dip during faults would be the same in different locations, therefore; determining fault location based on voltage measurements is very difficult. Reference [9] used voltage-based protection in combination with directional elements to develop protection scheme for low fault low voltage radial microgrids. Communication-assisted voltage-based protection for radial medium-voltage microgrids was proposed in [10].

Differential protection for low fault microgrids was proposed in [11]. That scheme is based on installing fault interrupting devices and differential relays at both ends of each feeder segment of the microgrid. Additionally, the scheme requires communication channel for each protection zone and it rely on synchronized measurements of currents at both ends of each line segment. As a result, a robust transmission-grade protection scheme is built but at a very high cost. Therefore, unless the particular application of a microgrid justify the cost, it is hard to see that scheme used widely for typical microgrids. A differential sequence component protection scheme was proposed in [12] which assumes protection zone granularity similar to [11] but it requires more processing time and more extensive communication infrastructure without a noticeable improvement in protection robustness.

The application of traditional distance protection for microgrids, and generally for distribution systems, was discussed in [13]. However, conventional distance protection is not typically efficient when applied to tapped feeders since it will cause the relay to underreach and thus complicates coordination between different relays.

Several protection methods based on transient behavior of faults was discussed in literature. In [14], a travelling wave based protection scheme was presented. The scheme is based on measuring timing and polarity of the initial waves at both side of the protected line after the occurrence of the fault. For a typical microgrid it is very hard to discriminate between incident waves travelling timing to different locations due to the relatively small feeders lengths compared with travelling waves speed. Moreover, the method require protection zone granularity similar to differential protection proposed in [11], however, differential protection is way more robust. Protection schemes based on wavelet analysis of fault currents was presented in [15] and [16]. These papers only discussed faults at the terminals of DGs and the method was not extended to feeder faults. Additionally, as for other transient based methods, there is no general proof that the transient signature used in the proposed protection is universal and does not depend on the microgrid configuration or generation dispatch.

It is evident from this literature survey that there is a need to fill the gap between low-cost low-reliability schemes like overcurrent protection and high-cost high-reliability schemes like differential protection. In this paper, we propose a new protection scheme for low-fault microgrids that utilizes impedance and directional elements to detect the occurrence of faults. Additionally, permissive and blocking signals are exchanged between feeder relays to locate the fault. The proposed scheme does not assume specific locations for fault interrupting devices and only low bandwidth communication is required. Thus the proposed scheme represents a protection solution that is more reliable than overcurrent protection for low-fault microgrids and less expensive than differential protection.

II. Microgrid Protection Zones

In order to design a rather general protection scheme for Microgrids that does not depend on fault interrupting devices locations, we define microgrid protection zones as: *a part of the microgrid bordered by a set of fault interrupting devices*. Fig. 1 shows examples of microgrid protection zones. If a fault was to occur in a certain protection zone, the *least disruptive way* to clear the fault would be to open all fault interrupting devices surrounding that particular zone. In other words, for protection purposes any microgrid could be split into a group of protection zones and there is a one-to-one mapping that maps every protection zone to a unique set of fault interrupting devices. Thus, when a fault occur, the function of the protection system will be to determine the faulty zone and to trip fault interrupting devices associated with that particular zone.

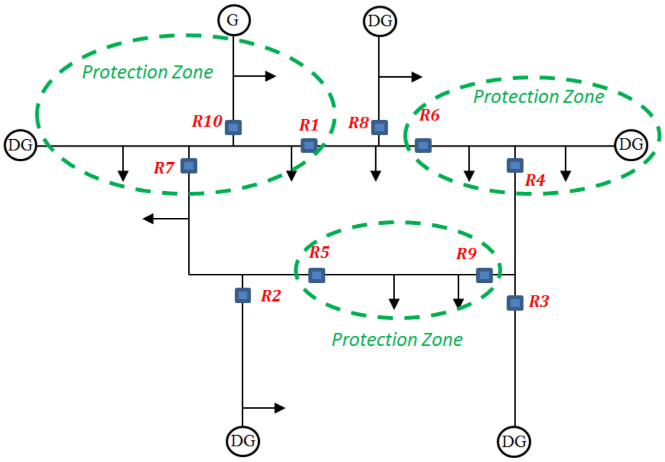

Fig. 1. General Microgrid Protection Zones

III. Impedance-based Microgrid Protection

It is important to notice that the low fault current contribution of inverters is mainly due to inverter's controller and not because of network impedance. As a matter of fact, the impedance of the microgrid, as defined by the impedance bus matrix for instance, would change due to the presence of the fault regardless of the attributes of the electrical source. However, the presence of the fault would not result in high fault current from the inverter-interfaced source, the way it typically would for a conventional source, due to the control actions of the inverter. As a result, the voltage at the terminals of the inverter would typically decrease more than it would for a conventional source. Based on that, a more robust way to detect faults in low-fault microgrids is to monitor impedance changes instead of current changes. To design an impedance-based protection for a given microgrid, protection zones will have to be constructed as discussed in section II. Then, several faults would have to be applied to each zone to determine impedance threshold values which will be used to indicate the occurrence of faults for different feeder relays. Then, a fault is declared by a relay whenever its measured impedance falls below its impedance threshold value. In determining the impedance threshold values for a general configuration microgrid with arbitrary relays locations, it is conceivable that relays would have to pick up out-of-zone fault based on their impedance threshold values. As a matter of fact, establishing exclusive impedance threshold values for each relay corresponding to particular zones could be impossible in general due to the relatively small feeder lengths of microgrids and the assumed arbitrary locations of feeder relays.

To overcome this problem, we propose a pilot scheme to exchange permissive/blocking signals between feeder relays to ensure that only relays associated with the faulty zone are tripped.

A. Impedance-based Pilot Protection Scheme

The proposed protection scheme is based on communication between adjacent relays, or in general between relays of the same protection zone, to locate the fault. Each feeder relay will be equipped with an impedance element to detect fault occurrence and a directional element to determine the direction of the fault. The particular design of the impedance and directional element is not critical to the implementation of the proposed protection scheme. Thus, the vast literature and extensive existing experience in designing impedance and directional elements could be utilized in designing these protection elements [17], [18]. Different pilot protection logic could be used to determine the location of the fault. For example, a pilot protection logic based on permissive and blocking signals could be implemented as follows:

1) Any relay that detects a fault in its forward zone will:
    - send a block signal to its reverse zone breakers.
    - send a permissive signal to its forward zone breaker.
2) Any relay that receives a permissive signal will:
    - if it has detected a fault in its forward zone and the signal is from one of its reverse zone breakers, ignore the signal.
    - if it has detected a fault in its forward zone and the signal is from one of its forward zone breakers, issue a trip signal to the breaker (fault is located in the forward zone).
    - if it has not detected a fault, send back a permissive signal and issue a trip signal to the breaker (fault is located in the zone shared by the breaker which sent the original permissive signal).

Similar logic could be applied if the fault is detected in the reverse zone. In essence, the criteria for tripping is the fulfilment of *one* of the following two conditions:

1) Fault detection no blocking signal and, optionally, receiving permissive signal.
2) No fault detection, no blocking signal and receiving a permissive signal.

Note that in the above pilot protection logic, the blocking signal increase the security of the scheme but it could also work well based on permissive signals only.

To illustrate the basic operation of the proposed scheme, consider Fig. 2. Assume a fault occurred on the line segment between $B1$ and $B2$. Additionally, assume that impedance-elements at all three relays ,$B1, B2$ and $B3$, detected a drop in their measured impedances below the detection threshold and thus declared a fault. Directional elements of the three relays will identify the direction of the fault as shown in Fig. 2.

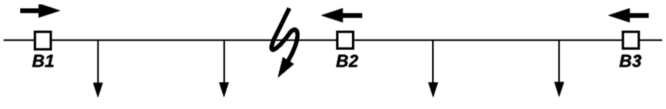

Fig. 2. Impedance-based pilot protection scheme illustration

Based on the pilot protection logic mentioned above, relay $B1$ will send a permissive signal to relay $B2$ and a block signal to its reverse zone relays (not shown in Fig. 2), relay $B2$ will send a permissive signal to relay $B1$ and a blocking signal to relay $B3$ and, similarly, relay $B3$ will send a permissive signal to relay $B2$ and a block signal to its reverse zone relays (not shown in Fig. 2). As a result, relays $B1$ and $B2$, having detected the fault and received permissive signals, will trip their associated breakers to clear the fault.

In general, all relays of the same protection zone will have to be able to communicate with each other. For example, for the part of the microgrid depicted in Fig. 3, assume that $B7$ was the only relay that detected the fault $F1$ based on drop of the measured impedance at $B7$. According to the above pilot logic, $B7$ should send permissive signals to $B1, B2, B4$ and $B8$. This task could be achieved based on peer-to-peer communication by sending the permissive signal from $B7$ to $B2$ and requesting that $B2$ transfer the permissive signal to $B4$ and so on. It is important to notice, however, that while microgrid configurations like the one depicted in Fig. 3 is quite complicated from protection perspective, they are rather uncommon in practice today.

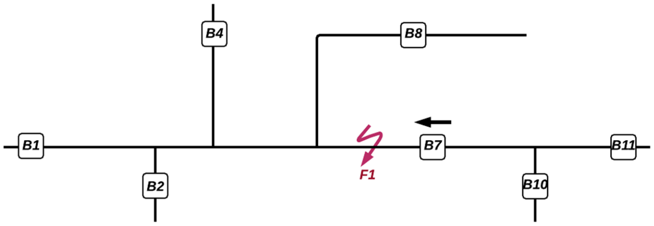

Fig. 3. Impedance-based pilot protection scheme illustration

B. Communications

Implementation of the proposed protection scheme require only low bandwidth communications since only permissive and blocking signals will be transferred between relays in the pilot scheme. Unlike the schemes described in [11], [10], [14], the proposed impedance-based protection scheme does not require relay measurements to be synchronized regardless of the distances between relays.

C. Weak Infeed Issues

The weak infeed problem is a well-known issue in transmission distance protection literature [19],[20]. Weak infeed was particularly problematic for electromechanical relays where a minimum current is needed to produce enough torque to operate the relay. Implementation of the proposed impedance-based scheme using numerical relays should largely provide immunity against weak infeed issues for the islanded mode of operation. The case of a fault on the grid during grid-connected mode should be carefully considered though. For a very weak microgrid connected to a relatively strong distribution feeder, the fault current contribution from the microgrid could be difficult to detect. That case could be covered by an undervoltage element combined with a directional element at the PCC of the microgrid or by a transfer trip signal from the utility breaker.

IV. SIMULATION RESULTS

The proposed impedance-based protection scheme was tested on several microgrids with variety of configurations. Due to space limitation, only simulation results for the test microgrid shown in Fig. 4, which is based on a real microgrid design [2], is presented in this section. MATLAB/SimPowerSystems was used to run all time-domain simulations. Inverter-interfaced generators are modelled as current-controlled inverters with a real/reactive-power control outer loop in the $dq-$frame. Inverters are modelled using averaged three phase voltage-source converter models as depicted in Fig. 5, see [21] for modelling details.

Feeders are modelled using 336ACSR with positive sequence impedance of $0.27974 + j0.6388\ \Omega/mile$ and zero sequence impedance of $0.57118 + j1.80198\ \Omega/mile$. Feeder lengths are shown in Fig. 4. Fault detection impedance threshold for all relays is set as a circle centered at the origin with a radius of 10 Ω. This circle is shown on the impedance trajectory plots for reference.

Three fault scenarios are presented in this section. For each scenario, a fault is applied at $t = 0.3sec$ and removed at $t = 0.45sec$. Fig. 6 shows the impedances measured by different relays prior to applying any fault to the microgrid.

Impedance trajectories for fault $F1$, are shown in Fig. 7. It is clear from these figures that relays $R2, R3$ and $R4$ detected the fault. For this particular microgrid, $R2$ is designed such that it will trip for any fault in its downstream zone since that is the only zone downstream of $R2$. Following the pilot protection logic of section III-A, $R3$ and $R4$ would have to wait for a permissive signal before tripping. However, since in this particular case the fault will be cleared by $R2$ instantaneously, $R3$ and $R4$ will see their impedance trajectory change and their fault detection flags will reset automatically, hence no communication is needed. Simulation results for fault $F2$ is shown in Fig. 8 and is cleared by relays $R1$ in a similar fashion as $F1$ was cleared by $R2$ without a need for communications.

Fault $F4$ was simulated with the microgrid operating in an islanded modes of operation. Fig. 9 shows the impedance trajectories after $F4$ was applied. It is clear that in this case relays, $R1$,$R2$ and $R3$, have detected the fault. Following the pilot protection logic of section III-A, all three relays will eventually receive permissive signals and trip to clear the fault.

It is also interesting to notice that, fault $F4$ could be cleared without need for communications, if all relays are programmed to trip after a suitable delay if the fault could still be detected. The intentional delay will, for example, prevent $R3$ and $R4$ from tripping for $F1$ to allow $R2$ to clear the fault. Thus an intentional delay could provide a suitable way to discriminate between faults for this particular microgrid. In conclusion, while communications is needed in general to implement the proposed pilot protection scheme, there are cases where good coordination between relays could be achieved without the need for communications based on the particular design of the microgrid.

V. CONCLUSIONS

Currently, the main protection solutions available for microgrids are overcurrent and differential schemes. Therefore, there is a need to develop microgrid-specific protection schemes which are non-overcurrent based to ensure efficient operation for inverter-dominated microgrids but also are not element-based to minimize the associated cost. This paper discussed the challenges facing efficient microgrid protection design and proposed a communication-assisted impedance-based protection scheme for inverter-dominated microgrids. The proposed scheme depends on monitoring impedance trajectories at different feeder relays to detect the occurrence of faults and utilizes directional elements and pilot signals to locate the fault. Future work includes conducting hardware-in-the-loop tests for the proposed protection scheme to validate its performance under different microgrid configurations.

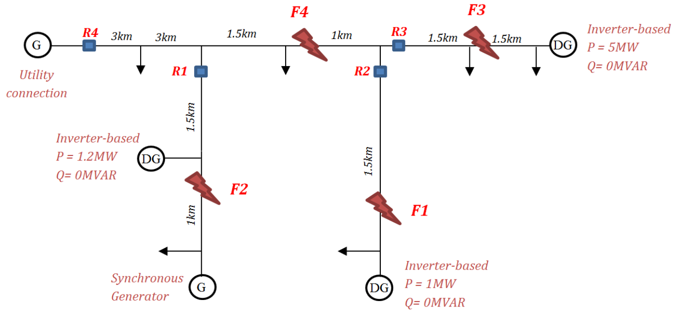

Fig. 4. Microgrid used for $Case1$ study

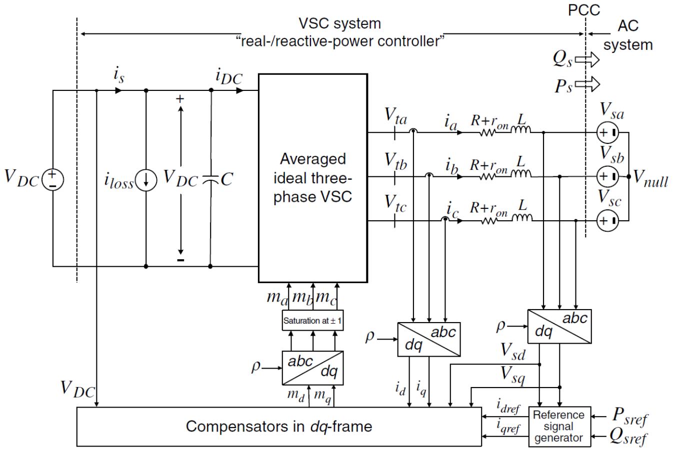

Fig. 5. Inverter and controller modelling [21]

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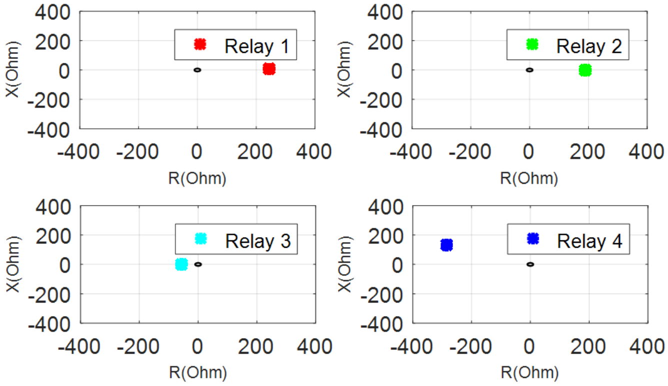

Fig. 6. Impedance measured by all relays prior to applying any fault

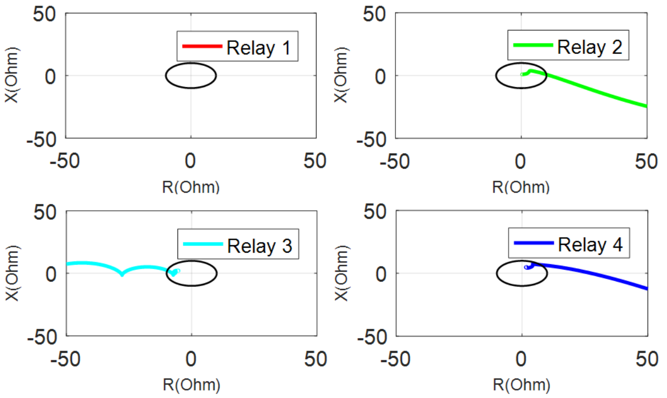

Fig. 7. Impedance trajectories during a three phase to ground fault at $F1$

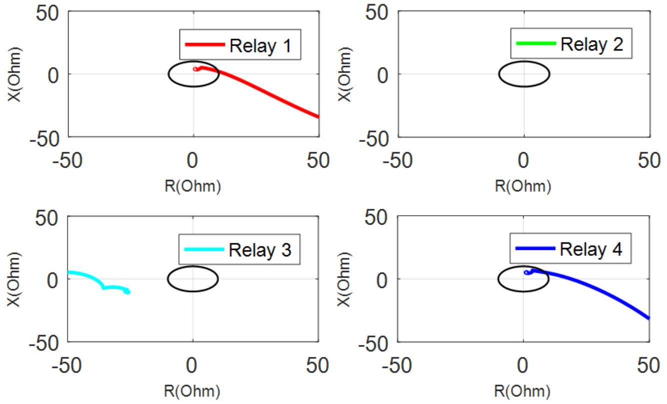

Fig. 8. Impedance trajectories during a phase A to ground fault at $F2$

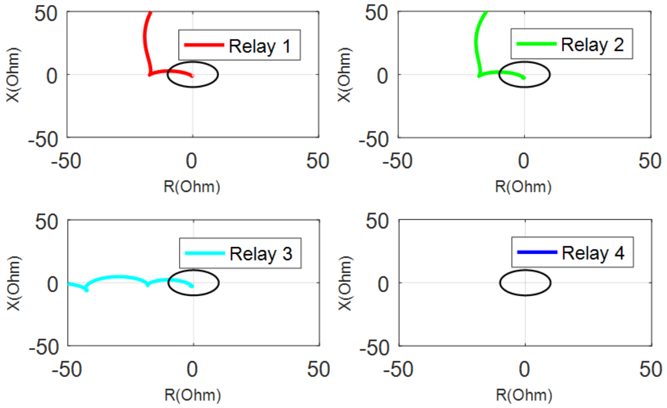

Fig. 9. Impedance trajectories during a three phase to ground fault $F4$ under islanded mode of operation

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