A Microgrid Protection Scheme Using Differential and Adaptive Overcurrent Relays

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Abstract— **This paper proposes a hybrid adaptive overcurrent and differential protection scheme to deal with the drastic changes in microgrid short circuit current characteristics following shifts between grid and islanded operational modes. The scheme proposes using adaptive overcurrent relays to protect individual load points or feeders while using differential relays to protect load buses or backbone feeders in order to reduce infrastructure upgrade requirements and setting computation complexity. In the context of this paper, multiple time-domain simulations are conducted to determine the efficiency of the proposed scheme in protecting a microgrid network while operating in grid or islanded modes. Time domain simulations for validation purposes have been conducted using a typical microgrid test network in the EMTP-RV software environment.**

Index Terms — **Adaptive overcurrent protection, differential current protection, Microgrid.**

I. Introduction

In the context of grid modernization through the integration of distributed generation (DG) sources, microgrids have become a particular focus. A microgrid can be defined as a low or medium voltage network containing a cluster of local loads with DG sources [1]. A microgrid has the capacity to operate in two distinct operation types: grid connected and islanded mode. Adaption to each of these options will depend on the condition of the presence of a utility connection. The close source generation by DG sources in the microgrid context has numerous advantages, including loss reduction and prevention of network congestion. Additionally, local DG sources reduce the probability of supply interruption due to the capability of the islanded mode of the microgrid [2].

Although microgrids offer solutions, they also introduce operational and protection challenges. Traditionally, distribution networks are designed on the basis of large short circuit currents with a radial (unidirectional) power flow. In the standalone or microgrid context, the introduction of DG sources yields potential degradation of common characteristics prevalent in classical networks [3].

A key issue related to the topological changes of microgrids lies in the short circuit behavioral changes when switching between grid and islanded conditions. A microgrid is said to be in an islanded condition when the utility (grid) supply is disconnected following a disturbance (or planned disconnection) and the DG sources continue to supply the local load [1]. Once islanding has occurred, there is a strong potential for short circuit levels to reduce significantly due to the absence of the utility as a source of fault current. Additionally, power flow within the microgrid may become bi-directional, contradicting existing unidirectional characteristics. This can result in existing overcurrent protection infrastructure based on high short circuit currents becoming inadequate. This is particularly prevalent in microgrids dominated by inverter based DG sources, as they are equipped with current limiting devices to prevent overload currents on individual components [4].

Although research into microgrid protection schemes capable of negotiating the inherent changes in short circuit levels when operating in grid connected or islanded modes is in its infancy, some proposed methods have been offered:

It is apparent from Reference [5], in which the field of adaptive protection schemes is reviewed, that the inclusion of adaptive protective devices presents difficulties. Advanced technology is required for practical application, and there is a requirement for the capability of self-monitoring and computing in multiple scenarios. In addition the relays require complex integration of hardware and software units. Further complicating the integration process is that adaptive relays frequently require the implementation of fast relaying in addition to communication interface integration [5]. It follows that significant upgrades are required to existing infrastructure to make it “smart ready” [5]. Reference [6] addresses the need for an off-line analysis methodology into which suitable tripping characteristic individual relays can be programmed to allow for every possible state that the network/microgrid will encounter. This method requires substantial knowledge of the existing network and microgrid configuration in order to determine that every possible state has, in fact, been programmed: should the system encounter

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an unprogrammed state, the relay will operate incorrectly or will not operate at all.

Reference [7] presents a differential protection scheme with consideration to high impedance faults in radial and meshed networks. It is based on relays with communicative overlays. Such differential protection methods in the microgrid context require a communicative infrastructure, since failure will yield an unprotected operational grid. Additionally, synchronized measurements are required by the relays, and imbalance in system phases can yield mis-operation of protective schemes.

In reference [8] a differential protection scheme is proposed using current differential relays in conjunction with a communication channel. The scheme is shown to be effective in protecting a microgrid in both grid and islanded modes under varying fault impedances. A key requirement with this scheme is the requirement for relays at each line end, in addition to extensive communication infrastructure.

As evident in the literature, microgrid protection is a difficult technical field to negotiate [4] due to changes in short circuit levels when shifting between topologies, and due to balancing excessive additional relay implementation. In this paper, a hybrid differential and adaptive overcurrent protection scheme is presented. The scheme utilizes differential relays to protect microgrid feeders and interconnecting buses between individual DG sources, load points and the backbone feeder. In addition, adaptive overcurrent relays are employed to protect individual load points.

II. The Approach

A. System Under Study

A typical microgrid setup is depicted in Fig. 1 and is utilized for investigations conducted in this paper. The microgrid is an adaptation of the model depicted in reference [1]. The microgrid is connected to the main utility rated at 13.8 kV at the point of common coupling (PCC) through an interconnecting line. It has six main buses each with a load and DG source. Loads 1, 2, 4 and 5 are operating at 0.2 MW while loads 3 and 6 are operating at 0.1 MW with all at a power factor of 0.9. During regular operation the microgrid has two radial feeders with a tie line existing between bus 3 and 6 that is normally open (this tie line can be closed when required). For each load there is a protective breaker. Each bus has three breakers and each line has a breaker on each line end. It should be noted that the breaker protecting the load point is also used for the load bus (i.e. it can be tripped due to a fault on the load or on the load bus). Conductor data is available in the Appendix.

B. Adaptive Overcurrent Protection

In a typical distribution network, utilities use devices such as relays, reclosers and fuses to protect individual feeders and lateral taps. Reclosers are set to operate within a fractional timeframe to allow for fault self-clearing in the event of a temporary fault. After the recloser has performed a set number of operations, the switching time slows to allow for downstream fuses to clear permanent faults: essentially a fuse-saving scheme [9]. The key issue with this traditional technique in the context of microgrids is related to short circuit levels. Traditional fuse-saving schemes rely on high levels of short circuit current to allow for coordination between downstream and upstream devices [9]. Microgrids need to be able to operate in both grid and islanded modes, each with vastly different short circuit characteristics, which limits the suitability of traditional overcurrent protection devices. One such way to overcome this difficulty is through the use of adaptive overcurrent protection.

Adaptive overcurrent protection utilizes relays that allow for modification of characteristics and settings in response to grid conditions [4]. This modification usually occurs after inputs are received from external communication devices. The inherent inefficiency in this practice is the requirement for every topology of the microgrid to be known and programmed into the relay. This can be difficult, especially in complex networks, since the relay is vulnerable to malfunction when a situation occurs that was not preprogrammed. Additionally, all existing infrastructure (reclosers, fuses) are required to be replaced for the scheme to work [4].

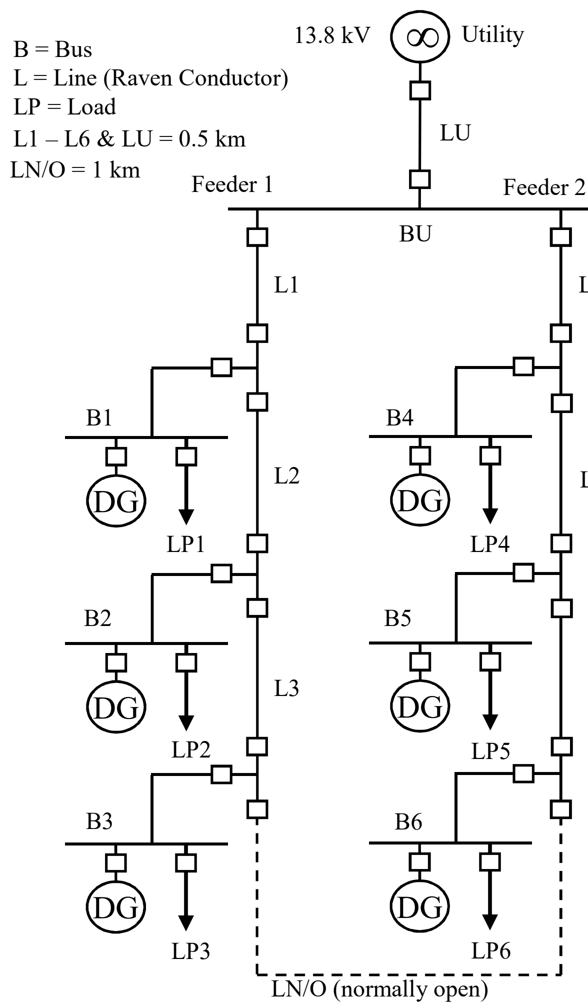

Fig. 1. Single line diagram of the microgrid under study.

C. Differential Protection

Differential protection is based on comparative measurements of current entering and leaving a protected "zone". This is conceptualized visually in Fig. 2 using a line segment from a feeder as an example [10].

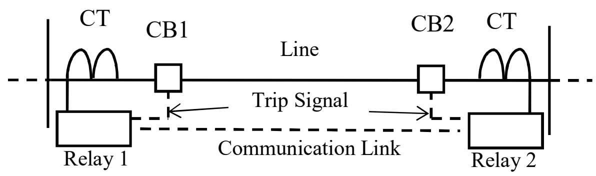

Fig. 2. Differential protection of a line.

As shown, each line end has a local current transformer (CT) in addition to a circuit breaker. The secondary output of the CT is connected to a relay (e.g. relay 1) which communicates with the second relay at the other end of the line (e.g. relay 2). When the difference between the measured current outputs of the CTs exceeds a predetermined value, the protection device operates to clear the fault [10]. Differential protection schemes are particularly effective at overcoming the changing short circuit characteristic of microgrids when converting between grid and islanded modes. This is due to reliance on comparisons between current levels as opposed to magnitudes. Although effective, differential protective devices require relays to be placed at either end of their protective zone, which can be a significant cost addition when upgrading an entire network [4].

D. The Proposed Microgrid Protection Scheme

Although adaptive overcurrent and differential protection schemes have been shown to be effective, practical implementation is limited by technical and cost-related challenges. In this paper, a hybrid approach is employed utilizing both adaptive overcurrent and differential protection in order to mitigate individual inefficiencies. The proposed scheme addresses the requirement for detection and isolation of all abnormal conditions in the microgrid, to allow for continual operation of the remaining un-faulted sections. In the proposed scheme, differential relays are used to protected individual lines and interconnecting load buses. This is visually represented in Figs. 2 and 3 [10].

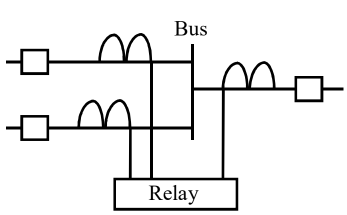

Fig. 3. Differential protection of a bus.

This model requires a communication channel between the ends of each protection zone. Adaptive overcurrent relays are used to protect each individual load point and settings are adjusted to the mode of the microgrid. The mode of the microgrid is transmitted to the relays through the use of a communication channel between the interconnecting breaker (between the utility and the microgrid) and each load point relay. The key advantage of this scheme is that it is scalable. In this lies the key difference from current proposals of individual differential and adaptive overcurrent protection schemes, which require significant changes to the relay infrastructure within the microgrid. Additionally, the proposed scheme can have the differential protection implemented on both a large or small scale depending on the application and size of the microgrid, whereas existing the schemes are prone to failure if not completed in their entirety. The adaptive overcurrent protection can also be implemented in a variety of contexts. It can be made to coordinate with downstream load point recloser/fuses or be utilized as an instantaneous relay. This means that excessive infrastructure upgrades can be mitigated. Additionally, the adaptive overcurrent and differential protection do not require coordination. This is attributed to the utilization of different tripping algorithms in these schemes.

1- Sequence of Operation:

For a line or a load bus, the CTs at each line/bus end measure the current. The secondary of the CT then connects to a relay which transmits/receives the value(s) to/from the relay(s) at the other end(s) of the line/bus. If the difference between the currents exceeds a specified value then the line/bus is deemed to be short-circuited and the breakers open to segment the faulted section. If the difference is not above the specified value, then a short circuit is present outside the zone of protection so the relay will not trip.

In the case of each load point, the input signal is read by the adaptive relay from the interconnecting breaker to determine if the microgrid is in a grid or islanded mode. The CT feeds the secondary current to the adaptive relay. When a fault occurs downstream within the load (i.e. somewhere in the sub network of the load) then the value being fed by the CT secondary will exceed the pickup setting and will cause the breaker to open.

2- Determination of Settings:

Differential relays are set in a similar way to those outlined in [10]. A typical differential relay characteristic is illustrated in Fig. 4.

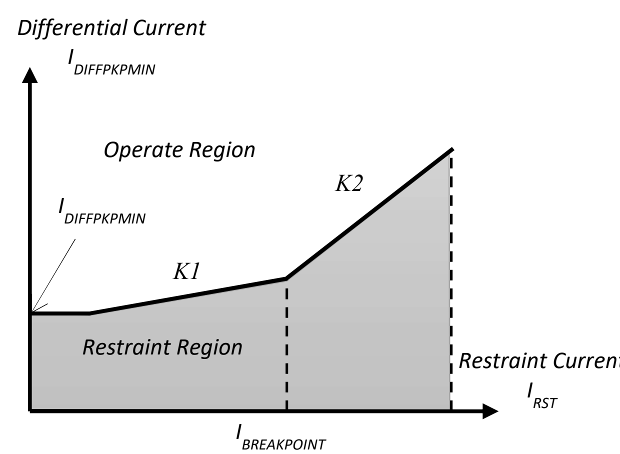

Fig. 4. Differential relay current characteristic.

The restraint and differential pickup currents are the two key values that define the relay operating and restraint regions. The pickup current can be defined as:

$$I_{DIFFPKP} = |I_1| - |I_2| \quad (1)$$

Where I_1 and I_2 are the secondary CT phasor currents from each relay. The restraint current can be defined as [10]:

$$I_{RST} = 0.5|I_1 + I_2| \quad (2)$$

During normal steady state conditions, the differential current should theoretically be equal to zero. Due to line charging, CT saturation and inaccuracies in the CT mismatch, this is rarely the case in practical scenarios [8]. In response to these mismatches, a typical minimum pickup setting used for differential based relays is 0.25 A on the secondary [10].

K1 and *K2* can be defined as the slope of the percentage differential characteristic [10]. This is generally expressed in a percentage value. These slopes cause the pickup setting to increase proportionally as the fault level increases: defined in (3) [10].

$$I_{PKP} \geq KI_{RST} \quad (3)$$

Typical values of *K1* and *K2* are 20% and 98% respectively [11]. The breakpoint is the last setting that is required. This is the setting that separates the *K1* and *K2* slopes. A typical setting is 5 A [10].

Adaptive overcurrent relays on the loads are set such that the pickup settings are greater than double the normal load current, but less than one third of the minimum fault current [12]. These settings will be required for both phase and ground faults in grid connected and islanded modes. The pickup setting of each mode is determined through the use of (4):

$$I_{PKP} = \frac{1}{3} I_{fminx} \quad (4)$$

where I_{fminx} is the minimum phase or ground fault level experienced by the relay in mode x (grid or islanded mode). If (4) results in a setting that is less than the normal load current then the pickup setting will be taken as twice the magnitude of the normal load current.

The settings used in this paper are provided in the Appendix. It should be noted that for simplification the adaptive overcurrent relays are considered instantaneous, however use of TCC characteristics are also possible.

III. THE EFFECT OF FAULT IMPEDANCE ON DG INTEGRATION IN THE CONTEXT OF DISTRIBUTION OVERCURRENT PROTECTION COORDINATION

This section presents the feasibility of using the proposed microgrid protection scheme for both grid and islanded modes.

A. Case Studies

TABLE I: CASE STUDIES

	Case Study-1	Case Study-2
Fault type	Sustained three-phase-G	Sustained three-phase-G
Fault location	Line 1	Load 1
Fault inception	At time = 1 second	

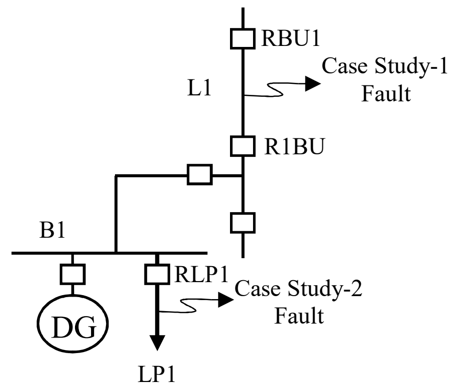

Fig. 5. Fault applied at line 1/load 1 Case Study-1/2

Due to space limitation, two case studies are selected for presentation in this section, namely Case Study-1 and Case Study-2. Specifics of these studies are provided in Table I and are shown in Fig. 5. The first case study demonstrates the effectiveness of the differential relays in separating a line when a fault occurs within its zone of protection. The second case study demonstrates the effectiveness of an adaptive overcurrent relay in protecting a load point when a fault occurs. It also demonstrates that differential line/bus relays do not operate when a fault is outside their protection zone.

Case studies are conducted with Photovoltaic (PV) DG sources at each load point. The PV DG's are sized to operate at 0.2 MW with a power factor of 0.9. All values of the currents are stated in RMS unless otherwise specified. Additionally each case study is conducted for the grid and islanded modes of the microgrid. Case studies are conducted in time-domain using the EMTP-RV simulation software.

Case Study-1: Figs. 6 and 7 illustrate the time domain simulation results for Case Study-1. According to these results, the following observations are worth noting:

- Where the microgrid is operating in the grid connected mode (Fig. 6), the differential relay protecting line 1 trips the line after 0.00745 seconds. Through observations, it can be determined that the peak current experienced by the relay is 2075 A. Additionally, the differential current is 12.5 per unit while the restraint current is 12.98 per unit. This results in a successful disconnection of the faulted line from the network.
- Where the microgrid is operating in islanded mode (Fig. 7) the differential relay operates in 0.00735 seconds with a corresponding peak relay current of 40 A. Additionally, the differential current experienced by the relay is 0.18 per unit with a corresponding restraint current of 0.05 per unit. Again, this relay results in a successful disconnection of the faulted line from the network.

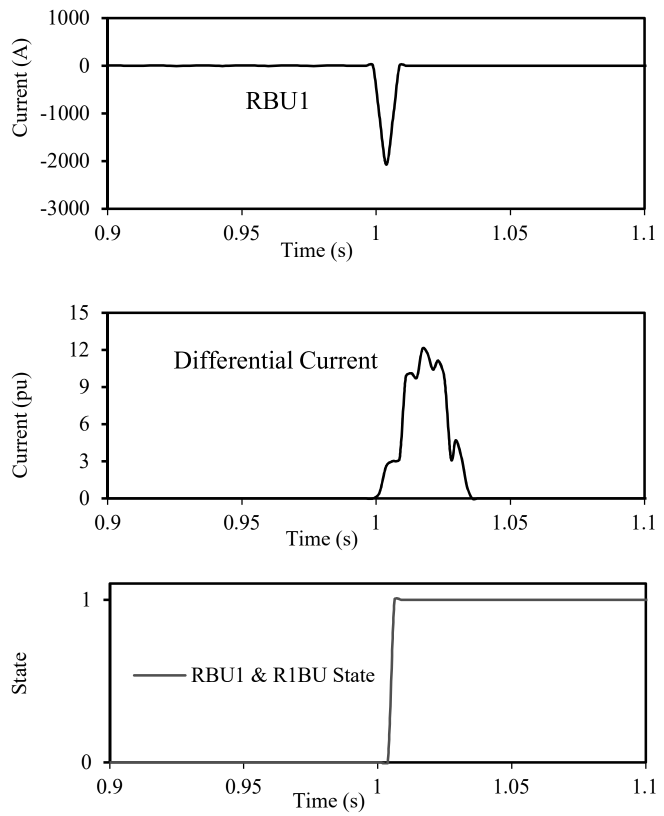

Fig. 6. Case Study-1 during grid connected mode: RBU1 current, RBU1 & B1BU differential current, RBU1 & R1BU state signals.

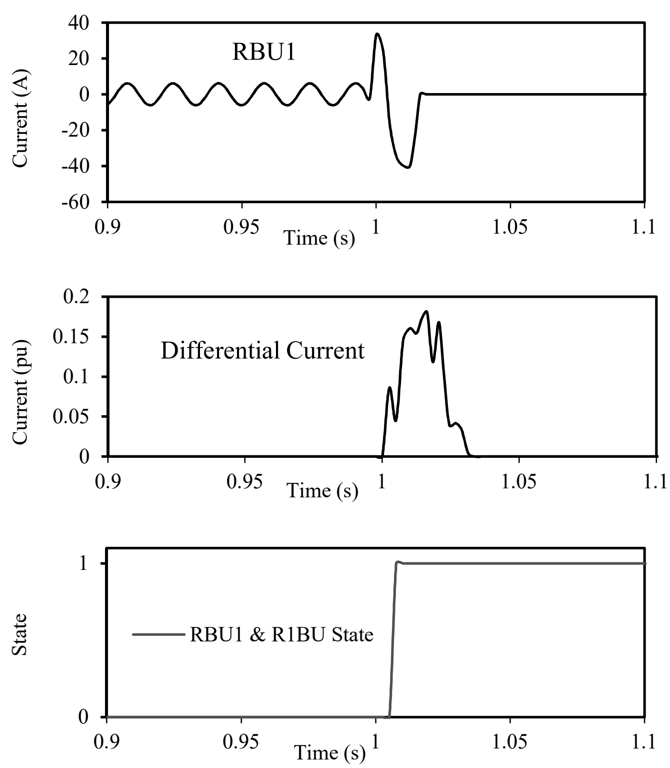

Fig. 7. Case Study-1 during islanded mode: RBU1 current, RBU1 & B1BU differential current, RBU1 & R1BU state signals.

Case Study-2: Figs. 8 and 9 illustrate the time domain simulation results for Case Study-2. According to these results, the following observations are worth noting:

- Where the microgrid is operating in the grid connected mode (Fig. 8), the adaptive overcurrent relay protecting load 1 trips after 0.051 seconds. Observations determine that the peak current experienced by the relay is 1660 A. Observation of the line 1 differential relay shows that the differential current experienced by the relay is 0.000576 per unit with a corresponding restraint current of 11.3 per unit. Additionally the differential relay protecting line 1 did not trip, as the fault is outside the zone of protection. Since the adaptive overcurrent relay trips while the differential relay does not, it is apparent that the protection scheme is effective in the grid connected case.

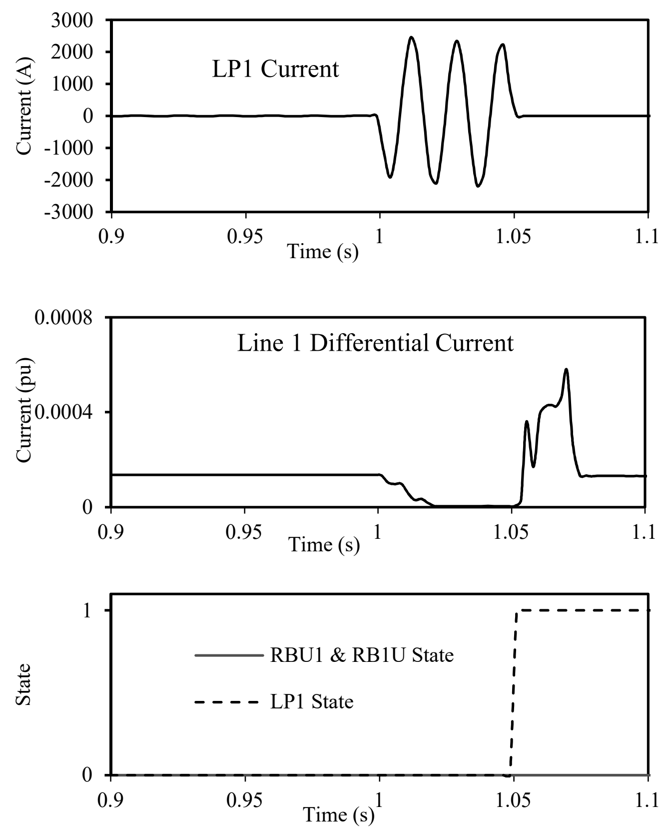

Fig. 8. Case Study-2 during grid connected mode: LP1 current, RBU1 & B1BU differential current, RBU1 & R1BU state signals.

- In the case where the microgrid is operating in islanded mode, (Fig. 9) the adaptive overcurrent relay protecting load 1 operates after 0.0457 seconds with a corresponding peak current of 55 A. Additionally, differential current of 0.000576 per unit with a corresponding restraint current of 1.77 per unit is experienced by the line 1 differential relay. Again, the differential relay does not operate for the fault outside of the zone of protection, while the adaptive overcurrent relay successfully trips the faulted load. This makes it apparent that the protection scheme is effective in the islanded mode case.

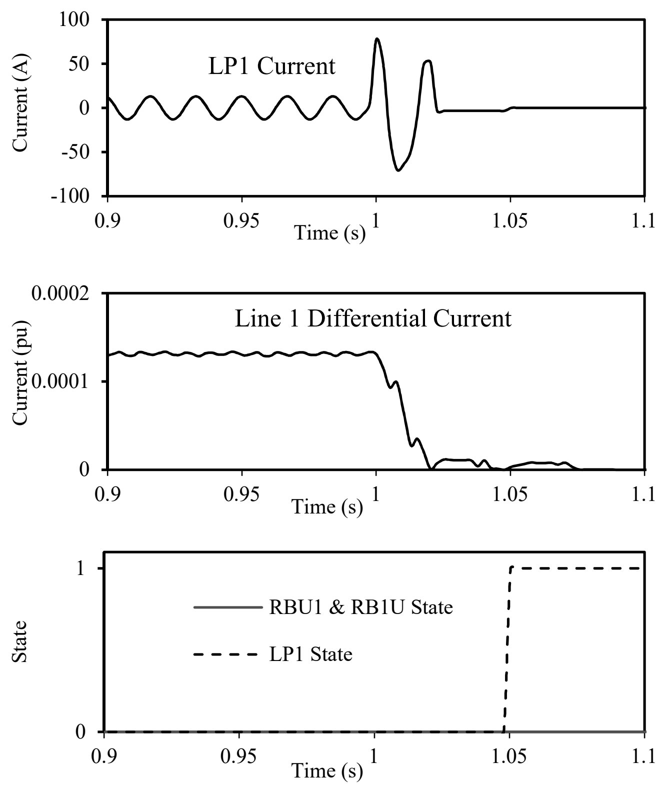

Fig. 9. Case Study-2 during islanded mode: LP1 current, RBU1 & B1BU differential current, RBU1 & R1BU state signals.

Comparison of results between the grid and islanded modes demonstrate that the adaptive overcurrent relay is effective in removing load faults regardless of the microgrid operation characteristic. In a traditional scheme a fuse would be used that is larger than the typical load current experienced. In the case of Load 1 (a 9 A steady-state load) a Kearney 20T fuse, which has a minimum melting current of 40 A, would be typical [9]. In the case of the islanded mode, the fuse would only experience 55A; resulting in a minimum melt time of approximately 15 seconds [13]. Many utilities require that a fault is removed from a system within 3 seconds [14], which means that the fuse would fail to meet requirements in an islanded mode, demonstrating the suitability for the load adaptive overcurrent relay. Similar results were obtained for faults on other loads, lines and buses.

IV. Conclusion

This paper investigates the feasibility of using a combined adaptive overcurrent and differential protection scheme to address the drastic changes in microgrid short circuit current characteristics following shifts between grid and islanded operational modes. Results obtained demonstrate the effectiveness of the proposed approach during three-phase faults, while validating that the scheme is effective when the microgrid is operating in either a grid or islanded mode. Additionally, this scheme requires significantly fewer infrastructure upgrades than pure differential or adaptive overcurrent protection schemes, whilst also simplifying the relay setting process.

Furthermore, results highlight the inefficiencies in traditional fuse protection for a load in a scenario where a network requires conversion to a microgrid. It is apparent that fuses are particularly prone to the significant changes in short circuit levels experienced by microgrids when converting between grid and islanded modes. This inefficiency is not present with the proposed adaptive overcurrent relays. Lastly, results demonstrate that in the proposed model, the adaptive overcurrent and differential relays do not require coordination, since upstream protection (differential relays) does not operate out of zone faults.

The results and considerations discussed in this paper offer significant practical value in the context of network expansion planning and microgrid integration feasibility.

Appendix A

TABLE A.I
CONDUCTOR DATA

Conductor	R_1 (Ω/km)	L_1 (Ω/km)	C_1 (µS/km)	R_0 (Ω/km)	L_0 (Ω/km)	C_0 (µS/km)
Raven	0.536	0.342	5.102	1.548	0.988	1.99

Protection settings:
Line & Bus Differential Relays: CT: 150/5, $I_{DIFFPKPMIN}$: 0.05 pu (0.25 A), $I_{Breakpoint}$: 1 pu (5 A), K1: 20%, K2: 98%. LP Relays: CT: 150/5, Grid Mode: Phase pickup: 477 A, Ground pickup: 735 A, Island Mode: Phase pickup: 18 A, Ground pickup: 29 A.

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