

# Microgrid Protection

H. Nikkhajoei, *Member, IEEE*, R. H. Lasseter, *Fellow*,

## Abstract

*In general, a microgrid can operate in both the grid-connected mode and the islanded mode where the microgrid is interfaced to the main power system by a fast semiconductor switch called static switch, (SS). It is essential to protect a microgrid in both the grid-connected and the islanded modes of operation against all types of faults. The major issue arises in island operation with inverter-based sources. Inverter fault currents are limited by the ratings of the silicon devices to around 2 p.u. rated current. Fault currents in islanded inverter based microgrids may not have adequate magnitudes to use traditional over-current protection techniques. The philosophy for protection is to have the same protection strategies for both islanded and grid-connected operation. The static switch is designed to open for all faults.*

*Index Terms*—Microgrid, protection, inverter, DER

## I. MICROGRID CONCEPT

CERTS Microgrid has two critical components, the static switch and the microsource. The static switch has the ability to autonomously island the microgrid from disturbances such as faults, IEEE 1547 events or power quality events. After islanding, the reconnection of the microgrid is achieved autonomously after the tripping event is no longer present. This synchronization is achieved by using the frequency difference between the islanded microgrid and the utility grid insuring a transient free operation without having to match frequency and phase angles at the connection point. Each microsource can seamlessly balance the power on the islanded microgrid using a power vs. frequency droop controller. This frequency droop also insures that the microgrid frequency is different from the grid frequency to facilitate reconnection to the utility.

To enhance reliability, a peer-to-peer and plug-and-play model is used for each component of the microgrid. The peer-to-peer concept insures that there are no components, such as a master controller or central storage unit that is critical for operation of the microgrid. This implies that the microgrid can continue operating with loss of any component or generator. With one additional source,

(N+1), we can insure complete functionality with the loss of any source. Plug-and-play implies that a unit can be placed at any point on the electrical system without re-engineering the controls thereby reducing the chance for engineering errors. The plug-and-play model facilitates placing generators near the heat loads thereby allowing more effective use of waste heat without complex heat distribution systems such as steam and chilled water pipes.

Peer-to-peer and plug-and-play concepts also impact the protection design. The peer-to-peer concept insures that there are no protection components, such as a master coordinator or communication system critical to the protection of the microgrid. Plug-and-play implies that a unit can be placed at any point on the electrical system without re-engineering the protection thereby reducing the chance for engineering errors. This implies that microgrid protection is part of each source.

## II. BASIC PROTECTION ISSUES

In general, a microgrid can operate in both the grid-connected mode and the islanded mode where the microgrid is interfaced to the main power system by a fast semiconductor switch called static switch, (SS). It is essential to protect a microgrid in both the grid-connected and the islanded modes of operation against all types of faults. The major issue arises in island operation with inverter-based sources. Inverter fault currents are limited by the ratings of the silicon devices to around 2 p.u. rated current. Fault currents in islanded inverter based microgrids may not have adequate magnitudes to use traditional over-current protection techniques. This possibility requires an expanded protection strategy.

The philosophy for protection is to have the same protection strategies for both islanded and grid-connected operation. The static switch is designed to open for all faults. With the static switch open, faults within the microgrid need to be cleared with techniques that do not rely on high fault currents. Fig. 1 shows a simple microgrid. The SS (static switch) separates the utility from the microgrid. The islanded part contains two loads and the inverter based sources. The microgrid assumes that the sources have adequate ratings to meet the load demands while in island mode. This example shows two sources in series with impedances between the sources using a four-wire configuration with a common ground point and one source in parallel.

In this example, we assume four protection zones with circuit breakers between Zone 2 and Zone 3, Zone 3 and Zone 4 and between Zone 2 and Zone 5. The system could

---

The work described in this paper was coordinated by the Consortium for Electric Reliability Technology Solutions with funding support from the California Energy Commission, Public Interest Energy Research Program, under contract #500-03-024.

Dr. H. Nikkhajoei and Professor R. H. Lasseter are affiliated with the Department of Electrical and Computer Engineering, University of Wisconsin, Madison

be designed without these circuit breakers but the protection zones remain the same. In either case, sources feeding the fault must shut down without communications. For example, for a fault in Zone 2 we would expect the SS in Zone 2 to open in  $\frac{1}{2}$  to 2 cycles, the circuit breakers between Zones 2-3, 3-4 and 2-5 to open with the inverter-based sources in all Zones shutting down. If the fault was in Zone 4, ideally the SS would open and the circuit breaker between Zones 3 and 4 would open but the breaker between Zones 2 and 3 would not. The source in Zone 4 would also shut down. This would result in Zone 2, Zone 3 and Zone 5 operating as an island.

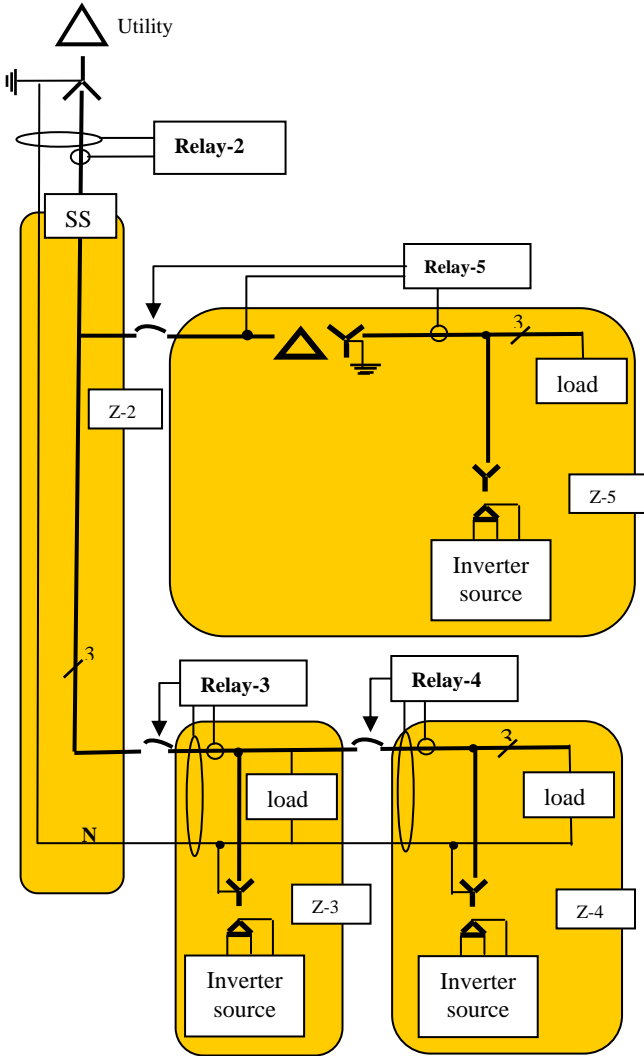


Figure 1. Simple microgrid with sources in series

### Single Line-to-Ground (SLG) Faults

The basic fault sensors for each zone are; a current sensors for each phase and a current sensor summing the three phases and the neutral in zones 2, 3 and 40. It was initially thought that a microgrid could be protected, at least for SLG faults, based on differential component of current  $I_d$ ,

( $I_d = \sum_{k=a,b,c,n} |I_k|$ ) for any number of sources in series. For

example, in Fig.1, a SLG fault in Zone 4 would generate a non-zero differential current in zones 2, 3 and 4. This would result in Relay-2 opening the SS in  $\frac{1}{2}$  - 2 cycles followed by Relay-4 opening its circuit breaker and shutting down the source in Zone 4. Using a delay in Relay-3 would allow the section(s) of the microgrid upstream of the fault to remain operating. This section could then reconnect to the utility autonomously since the faulted section is no longer connected. The problem with this concept is that any zones down-stream of the fault will not see the effect of ground currents. The  $I_d$ , sum of the three phase currents and neutral current, will be zero.

For example a SLG fault in Zone 3 will create differential current signals for the SS and Relay-3 to open and shut down the source in Zone 3, but the Zone 4 relay will not see the fault. The fault's ground current does not pass through Zone 4 and therefore, the differential current component detected by the Relay-4 is zero. This would leave Zones 3 and 4 energized as a faulted sub-island. For the case of a microgrid, which does not have breakers between zones, the SS would open and source in Zone 3 would be shut down but the source in Zone 4 would not shut down. It would continue to operate and feed the fault. If the fault were of high impedance, such back-up detection methods as over current and  $I^2t$  would not trip the source in Zone 4. Under-voltage protection could possible provide some back up, but again this would have problems. This problem requires using zero-sequence current detection for SLG faults. In this case, this is defined as the vector sum of the three phase currents.

As an example, consider the system in Fig.1 where the loads in all zones are 40 kW and the source in Zone 3 is dispatched at 40 kW and the Zones 4 and 5 are at 20 kW. The nominal line-to-line voltage is 480 volts. This implies that the grid provides 40 kW. When a high impedance SLG ( $\sim 28$  kW) fault is applied to phase A, in Zone 3, Relay-2 will see the fault,  $I_d > 0$ , and open the SS in 5-10 milliseconds. The resulting sequence voltages and currents seen by each relay are shown in Table I.

TABLE I: FAULT CURRENTS SEEN BY THE RELAYS FOR A SLG FAULT IN ZONE 3 AND SS OPEN

Signal	Relay 2	Relay 3	Relay 4
$ I_a (A)$	0	3.5	59.6
$ I_b (A)$	0	20.8	4.8
$ I_c (A)$	0	21.4	9.2
$I_d(A)$	0	<b>32.2</b>	0
$3 I_0 (A)$	0	0	<b>54.4</b>
$ V_+ (volts)$	391.6	392.1	391.2
$ V_- (volts)$	0	4.8	5

Relay-4 has a 3-cycle delay to insure that the SS will open first. Relay 3 has a 10-cycle delay to insure that Zone 4 will shut down first. From the table, we see that Relay-4's

differential current is zero but the zero sequence current provides the trip signal. Note that the voltage unbalance is small, (~1%) due to the local voltage control at each source. The usual relationship between the differential currents and the zero sequence currents is a function of the placement of the cts and the neutral conductors connection to the inverters' transformers.

Coordination between unbalanced loads and zero sequence currents is important. Unbalanced loads cause a zero sequence trip. The differential current detection does not see unbalanced loads.

#### Line-to-Line (L-to-L) Faults

Using  $I^2t$  protection for L-to-L faults is effective for low impedance faults but in many cases the time to trip will be long causing unnecessary disturbances to the loads and utility. High impedance fault current magnitudes will not be adequate to provide a trip. The our approach is to use negative sequence current to detect line-to-line faults.

TABLE II RELAY SETTINGS

Relay	Up-stream SLG faults	Down-stream SLG faults	Line-to-Line faults
2	$I_d > 15A$ delay=0 ms	$3 I_0  > 35A$ delay= 0 ms	$3 I_-  > 80A$ delay=0 ms
3	$I_d > 15A$ delay=167 ms	$3 I_0  > 35A$ delay=167 ms	$3 I_-  > 80A$ delay=50 ms
4	$I_d > 15A$ delay=50 ms	$3 I_0  > 35A$ delay=50 ms	$3 I_-  > 80A$ delay=50 ms
5	$I_d > 15A$ delay=50 ms	$3 I_0  > 35A$ delay=50 ms 50% voltage drop	$3 I_-  > 80A$ delay=50 ms
Relay	1 <sup>st</sup> back-up protection $I^2t$		
2	overload setting 480A delay 50 ms		
3	overload setting 225A delay 50 ms		
4	overload setting 125A delay 50 ms		
5	overload setting 125A delay 50 ms		
Relay	Voltage dips		
2	Voltage power quality CBEMA (2000 version)		
3	50% under voltage delay 30 cycles only when source in Zone-3 is active		
4	50% under voltage delay 20 cycles only when source in Zone-4 is active		
5	50% under voltage delay 20 cycles only when source in Zone-4 is active		

### III. PROTECTION: AEP CERTS MICROGRID

CERTS Microgrid test site at AEP is shown in Fig. 1. There are three sources and loads; two are in series using a four-wire conductor. The other source is in parallel with transformer isolation and a three-wire conductor. Zone 5 has a current sensor on each phase and a voltage sensor on the Zone 2 side of the transformer. This voltage measurement is important for SLG faults in Zone 2. In this case, the SS will open,  $I_d > 0$ , while Zones 3 and 4 will

isolate and shut down on zero sequence trips. Zone 5 will not see the fault except through under voltage at the transformer in Zone 5.

The basic protection levels are shown in Table. II. For unbalance loads of 20% the values for zero and negative sequence currents are  $3|I_0| \leq 12A$  and  $3|I_-| \leq 26A$ . The basic trip values for zero and negative sequence should be at least three times the load unbalance value. The primary protection for SLG faults relies on the differential current for the zones up-stream of the faults while zero sequence current detection is used for zones-down stream of the fault. The primary protection for line-to-line faults is negative sequence current.

The primary back-up is  $I^2t$  for both SLG and line-to-line events. The activation level and trip time is sized based on the thermal properties of the conductors. In many islanded cases, the current will not be large enough to activate this protection. This protection does insure that damage to the cables is kept to a minimum. The under voltage protection will provide some backup, but again high impedance faults are a problem.

#### Example of SLG fault in Zone 4

Figure 2 shows plots for a single line to ground fault in Zone 4. The fault impedance is relative high, ~ 28 kW at rated voltage. Traces (a) and (b) are from Relay-2 on the utility side of the static switch. Fig 2(a) shows the half cycle interruption of the current from the grid while Fig 2(b) shows Relay-2 trip signals where the trip levels are normalized to 1 p.u. Note that both the differential current,  $I_{dss}$ , and zero sequence current,  $I_0$ , are above their trip levels.

The currents and trip signals for Relay-4 are shown in Figs 2(f) and (g) respectively. Note that the trip was delayed 50 ms plus the shunt breaker opening delay of 30 ms. This results in a 5 cycle delay after the fault is applied. Note that the differential current,  $I_d$ , and zero sequence current,  $I_0$ , are above their trip levels.

Relay-3, Fig 2(e), differential current,  $I_d$ , and zero sequence current,  $I_0$ , are above their trip levels, but the extra 117 ms delay for Relay-3 allows for Zone 4 to clear the fault allowing Zone 3 to continuing operating. Note that Zone 5, (Figs 2 (i) and (j)) did not have any trip signals above the threshold. The currents, seen by Relay-3 and Relay-5, shows transients (Figs 2 (d) and (i)), but the voltage does not. The voltage controller on the sources prevents expected transients. See Figs 2 (c) and (h). The resulting transients. See Figs 2 (c) and (h). The resulting state is that the fault in Zone 4 is cleared and the rest of the system is intact and can be re-connected to the utility.

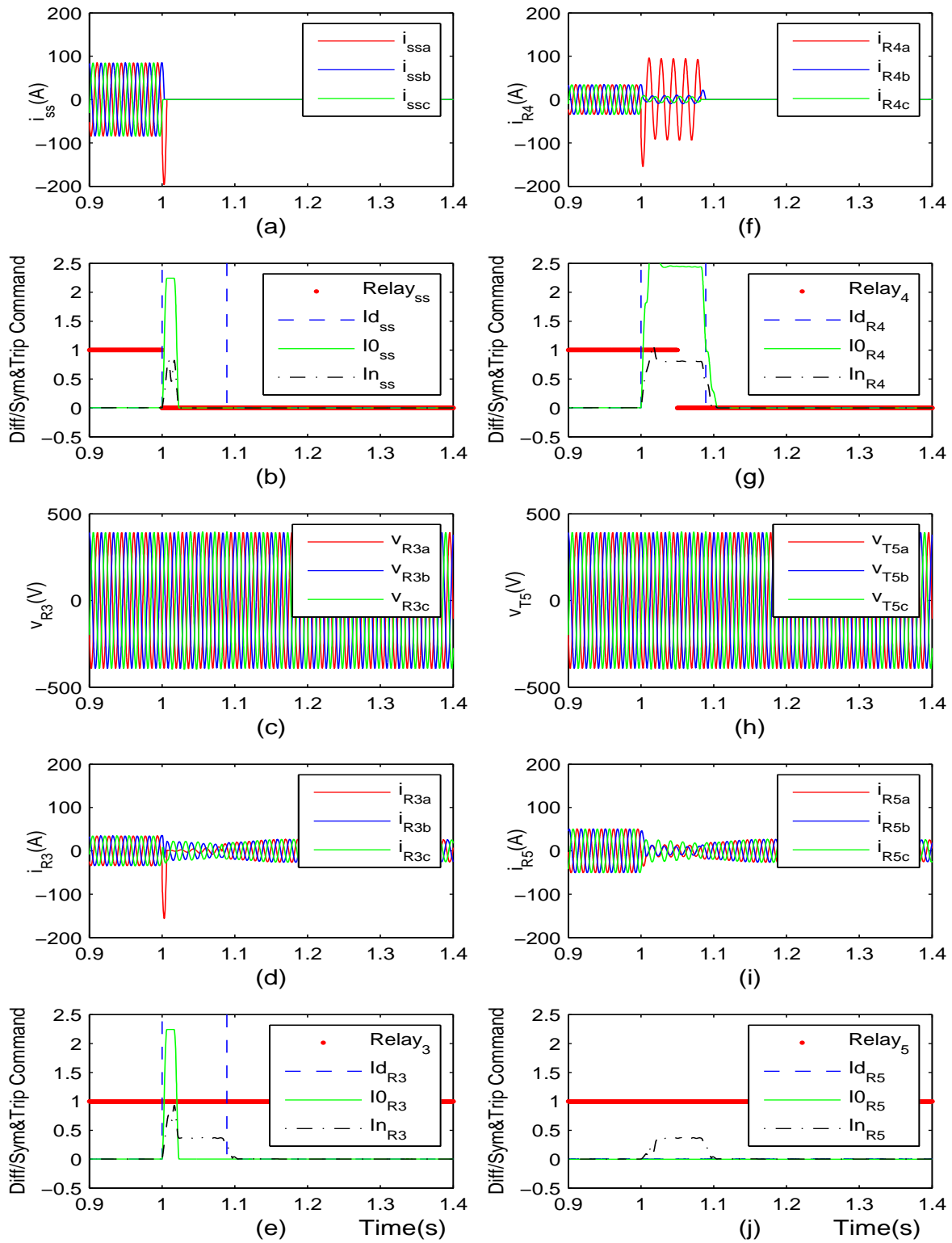


Figure 2: SLG Fault in Zone 4; (a), (b), Relay-2; (c), (d), (e), Relay-3; (f), (g), Relay-4; (h), (i), (j), Relay-5.

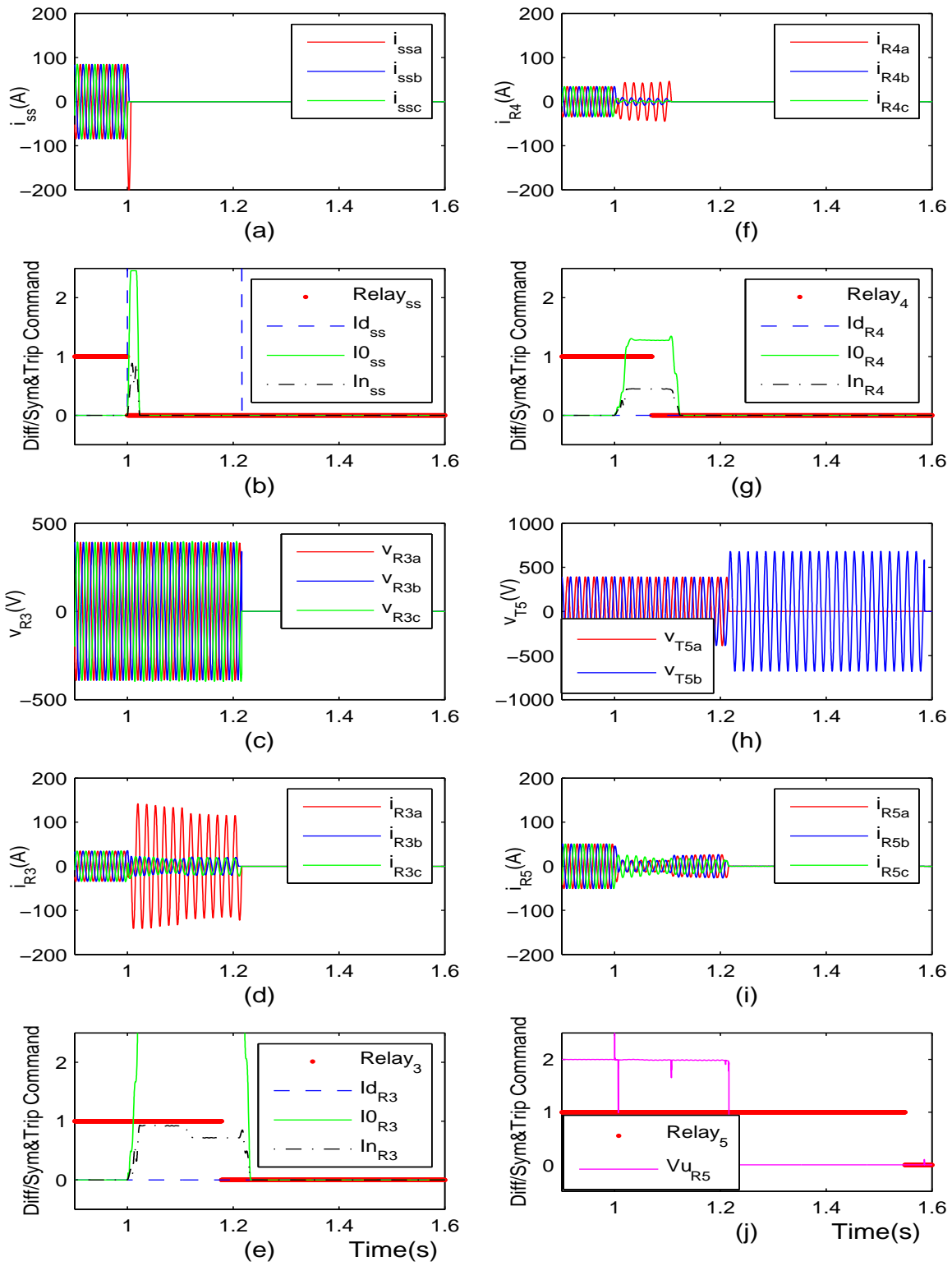


Figure 3: SLG Fault in Zone 2; (a), (b) Relay-2; (c), (d), (e) Relay-3; (f), (g), Relay-4; (h), (i), (j) Relay-5. (h),(i), (j)

### *Example of SLG fault in Zone 2*

A SLG fault in Zone 2 requires that all microgrid sources be shut down. In this example, the breakers associated with Relay-3, Relay-4 and Relay-5 will open and the sources in these zones will shut down. If the breakers were not present the relays still provide the trip for the sources insuring that all the microgrid sources are off. Of course, based on our basic philosophy, Relay-2 would open the static switch within a few milliseconds.

Figure 3 shows plots for a single line to ground fault in Zone 2. The fault impedance was relative high,  $\sim 28 \text{ kW}$  at rated voltage. Traces (a) and (b) are from Relay-2 on the utility side of the static switch. Fig 3(a) shows the half cycle interruption of the current from the grid while Fig 3(b) shows Relay-2 trip signals. Note that the differential current,  $I_d$ , and zero sequence current,  $I_0$ , were above their trip levels.

The currents and trip signals for Relay-4 are shown in Figs 3(f) and (g) respectively. Note that only the zero sequence current,  $3|I_0|$ , is above its trip level, but the differential current,  $I_d$ , is zero. Also the trip was delayed 50 ms plus the shunt breaker opening delay of 30 ms. This results in a 5 cycle delay after the fault is applied.

The fault is seen by Relay-3, Fig 3(e), but only the zero sequence current,  $3|I_0|$ , was above its trip levels. There is an extra 117 ms delay for Relay-3 to allow for Zone 4 to clear. During this delay time the voltage, Fig 3(c), is normal while the current seen by the Relay-3, Fig 3(d), is elevated but does not exceed the  $I_{2t}$  level of 225 A.

Zone 5, Figs 3(h), (i), (j), did not have adequate current levels to cause a trip. This is expected due to the presence of the transformer. At the point Zone 3 is shut down, ( $\sim 1.2$  seconds), the voltage on the Zone 2 side of the transformer changes, Fig 3(h). The faulted phase becomes zero. If the under-voltage protection was not present, Zone-5 would continue to operate provided there was adequate generation to meet the load demands in Zone 5. If the fault self extinguished after the fault current went to zero, Fig 3(i), the resulting system would consist of Zone 2 and Zone 5 which could be reconnected to the utility. If the fault did not clear, under voltage protection would trip the zone after a 20-cycle delay. This is seen in Figs 3(h) and (j).

## IV. CONCLUSION

The philosophy for protection is to have the same protection strategies for both islanded and grid-connected operation. The static switch is designed to open for all faults. With the static switch open, faults within the microgrid need to be cleared with techniques that do not rely on high fault currents. It is important that the protection functions are part of the microsource and have plug-and-play functionality. This work makes some progress in this direction, but further progress needs to be made.