Hardware-in-the-loop Testing of Direct Transfer Trip for Network Protector Units in the Presence of Distributed Energy Resources

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***Abstract*—This paper proposes a direct transfer trip (DTT) scheme for the protection of low voltage (LV) secondary spot networks. The conventional protection on secondary networks is based on network protector units (NPU). NPUs play a critical role in the effective isolation of faults by disconnecting the secondary side of service transformers and avoiding the flow of fault currents through alternative paths in LV spot networks. The proposed approach improves the performance of conventional NPU logic and addresses two major challenges. It is shown that the proposed approach can effectively isolate ground faults on the primary system for which the conventional NPUs can fail to detect when the service transformer has a Delta winding on the high voltage side. Moreover, the proposed approach can allow for the reverse power flow caused by the Distributed Energy Resources located in the secondary LV networks. The performance of the proposed approach is validated using a hardware-in-the-loop testbed that runs a LV spot network in Opal-RT real-time digital simulator.**

***Index Terms*—Direct Transfer Trip, Hardware-in-the-loop testing, Network Protector Units, Secondary Networks**

I. Introduction

Secondary networks play a crucial role in various facilities and locations, often functioning unnoticed by individuals. Whether faced with adverse weather conditions or incidents such as a vehicle collision with a utility pole, the high reliability of secondary networks becomes essential for supplying power to loads (such as facilities or areas). It is imperative to continuously research and develop protective measures to enhance the reliability and resilience of these power systems. The conventional protection of secondary networks is based on network protector units (NPU). An NPU is a device in the secondary system that can disconnect its associated service transformer when it senses a reverse power flow from the secondary system back to the primary system. To ensure a reliable source of power to critical customers, spot networks are equipped with two or more service transformers connected to a single customer. Figure 1 illustrates the test system that is used in this paper with two spot networks. However, the challenge is that when a fault occurs on the primary system (e.g., on one of the primary feeders) and the substation breaker opens to de-energize that feeder, there is still a path for fault current to flow from the other primary feeder through the low voltage (LV) spot network and back up to the fault location. Therefore, to fully isolate the fault, NPUs are required to disconnect service transformers when such a reverse flow condition occurs [1]–[4].

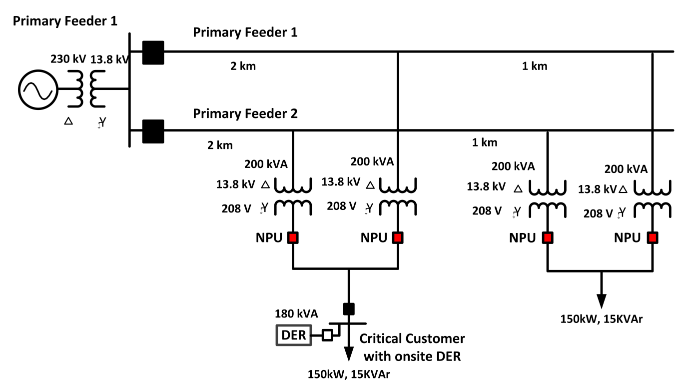

Fig. 1. Test system with two spot networks and DER.

There are two major challenges with the conventional NPU logic. The first challenge is that when the service transformer connecting LV spot network has a Delta winding on the high voltage side, the NPU may fail to detect the ground faults on the primary network. On the other hand, in the absence of distributed energy resources (DERs), it is true that the conventional logic of the NPU works well to isolate faults in the upstream grid, but, the same logic prevents the reverse power flow caused by DERs. Assume that the critical customer (e.g., hospital, community center, etc.) has an onsite DER installed for emergency backup generation when the source of power to this customer from the upstream power grid is interrupted. However, during normal operating conditions with a conventional protection scheme, the NPU would falsely trip if the DER were to inject power back into the upstream grid. So, all DER generation must always be immediately consumed or stored locally, which significantly limits its benefits [5]–[8].

One approach to allow reverse power flow caused by DERs is desensitizing the settings of NPUs. However, with desensitizing, (i) the NPU may allow reverse flow of current caused by high impedance faults (reliability issue), (ii) NPU may allow reverse current flow during maintenance work which is a safety issue, and (iii) NPU still may fail to detect ground faults when the secondary network transformer has a Delta winding on the primary network side. To overcome these issues the direct transfer trip (DTT) from the upstream relay on the primary feeder can be used to help NPU effectively distinguish between a fault and non-fault scenario. In this paper, to overcome the above challenges, a DTT scheme for the operation of NPUs is proposed. This paper proposes that NPU mainly relies on the DTT signal received from the upstream primary feeder relay to make a decision about the faults on the primary feeder. As a backup, the NPU's conventional protection logic can also take action if no transfer trip signal is received from the upstream relay. However, in the presence of DERs in the LV network, the NPU's logic will utilize desensitized settings that are higher than the service transformer's current rating. Doing so, the NPU not only allows for the reverse power flow caused by DERs in the LV network but also its desensitized element can detect phase faults on the primary network that result in high fault currents. When there is no DER in the LV network, the NPU's conventional logic with normal settings will be utilized as the backup of the DTT scheme. This paper verifies the performance of the DTT scheme under different scenarios in a hardware-in-the-loop (HIL) platform.

II. Desensitizing NPUs for DER Integration

The conventional protection logic of NPUs accommodates one instantaneous (insensitive) and one delayed (sensitive) tripping element. The insensitive element has a higher pickup current value and is associated with a 5 cycle delay to ensure that NPU does not trip instantaneously for transients. On the other hand, the delayed element has a lower pickup current with a 10 sec delay to avoid tripping of NPU for transients that result in lower reverse current flow. A typical NPU Watt-VAr trip characteristic diagram is shown in Fig. 2. In this diagram, the area above the blue line shows the normal operating region (this area allows for some amount of reverse current flow caused by DERs). The area below the blue line shows the trip region. If the current magnitude falls between the blue and orange lines, the NU trips with a delay. If the current magnitude falls is greater than the orange threshold,

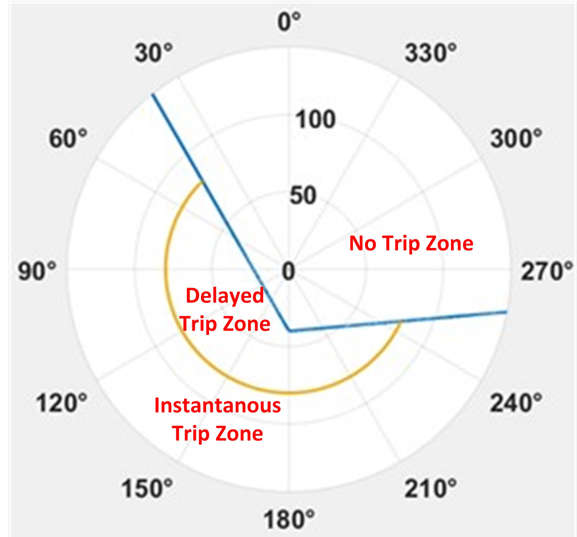

Fig. 2. NPU Watt-VAr characteristic based on current magnitude and angle.

the NPU trips instantaneously. The NPU calculates the phase angle difference between the positive sequence current and voltage phasors. The angle settings of the NPU will ensure that the NPU properly distinguishes between the forward and reverse flow of current concerning the voltage phasor. The conventional protection logic of the NPUs does not allow for the reverse power flow caused by DERs installed on the LV network. During normal operating conditions with a conventional protection scheme, the NPU would falsely trip if the DER were to inject power back into the upstream grid. This forces all DER generation to be immediately consumed or stored locally, which significantly limits its benefits for increasing grid resilience.

One approach for the Network Protector Unit (NPU) to distinguish between a fault and reverse power flow caused by downstream DERs is desensitizing the NPU unit by increasing the pickup currents. This will allow the low-magnitude reverse power flows caused by DERs. Desensitizing NPU means that higher pickup current settings are introduced to ensure that NPU does not mistakenly operate for reverse currents with low magnitude. This high pickup current should be typically around the current rating of the service transformer. There are three issues associated with NPU desensitizing: (i) NPU may allow reverse flow of current caused by high impedance faults (reliability issue), (ii) NPU may allow reverse current flow during maintenance work (safety issue), and (iii) NPU still may fail to detect ground faults when the secondary network transformer has a Delta winding on the primary network side.

III. Direct Transfer Trip Scheme and HIL Testbed

To further increase the reliability and sensitivity of the NPU, we will utilize direct transfer trips (DTT) communicated from the upstream relays on the primary network at the NPU. We have created and implemented the following logic on a Raspberry Pi (RP). To overcome these issues the direct transfer

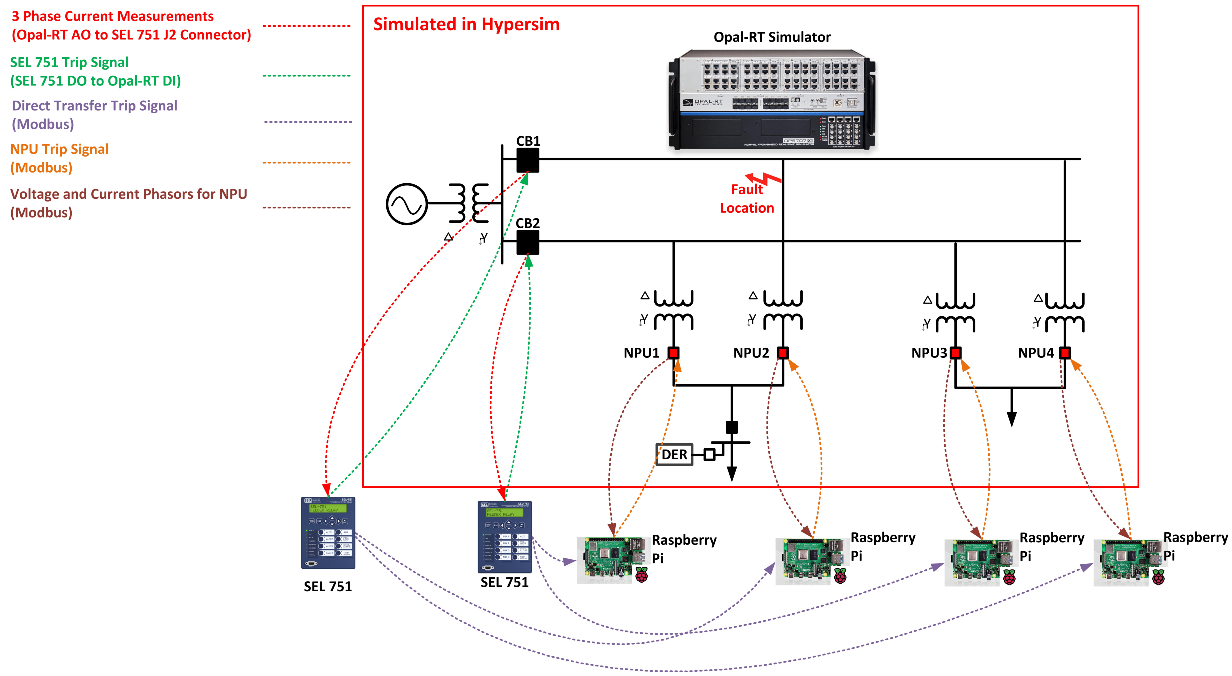

Fig. 3. HIL testbed diagram for the implementation of DTT scheme.

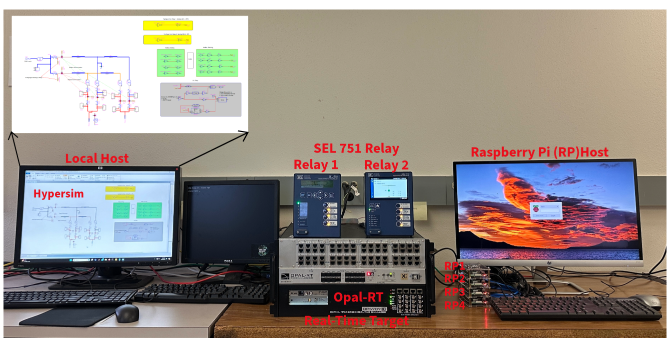

Fig. 4. The implemented HIL testbed at the University of New Mexico.

trip (DTT) from the upstream relay on the primary feeder can be used to help NPU effectively distinguish between a fault and non-fault scenario. In this paper, to overcome the above challenges, a DTT scheme for the operation of NPUs is proposed. This paper proposes that NPU mainly relies on the DTT signal received from the upstream primary feeder relay to make a decision about the faults on the primary feeder. As a backup, the NPU's conventional protection logic can also take action if no transfer trip signal is received from the upstream relay. However, in the presence of DERs in the LV network, the NPU's conventional logic will utilize desensitized settings that are higher than the secondary transformer's current rating. Doing so, NPU always allows for the reverse power flow caused by DERs in the LV network. Even though, the desensitized setting of NPU adopts high pickup values that do not let NPU trip for high impedance ground faults, the NPU still has a backup protection for phase faults which result in high reverse fault currents. When there is no DER in the LV network, the NPU's conventional logic with normal settings will be utilized as the backup of the DTT scheme. This will add an additional level of redundancy to the NPU's logic.

In order to verify the performance of the DTT, the hardware-in-the-loop (HIL) testbed that is illustrated in Figs. 3 and 4 is utilized. The specifications of the model are provided in Table I. This testbed includes a 13.8kV primary feeder with two LV spot networks that is simulated in Hypersim and runs in real time using Opal-rt real-time digital simulator. Each of the primary feeders are protected through an SEL 751 relay which is equipped with overcurrent protection. The primary feeders include two line segments with the length of 2km from substation to the first LV network and 1km between the first and second LV networks. The SEL 751 relay on the top feeder can trip CB1 circuit breaker and sends the DTT signal to NPU2 and NPU4. The SEL 751 relay on the bottom feeder can trip CB2 circuit breaker and sends the DTT signal to NPU1 and NPU3. The communication between SEL 751 relays and NPUs is performed through Modbus TCP/IP communication protocol over Ethernet. SEL 751 relays read the real-time measurements from Opal-RT using the Analog Output card of Opal-RT that is connected to the J2 connector of SEL 751 relay. The currents measured in Hypersim are down-scaled with the gain of 0.00011 to avoid damaging the J2 connector of SEL relay. To read correct currents in the relay, the CT ratio of 337 is used in the relay. Both relays have the same settings. For the instantaneous phase overcurrent element, the pickup current in secondary Amps is 5 A, while for ground one, the pickup current in secondary Amps is equal to 2 A. Utilizing instantaneous overcurrent elements for protecting distribution circuits against the faults on the primary feeders is a common practice according to the IEEE C37.108 standard [9]. On the other hand, the trip signal of SEL 751 is sent to its Digital Output card that is hardwired to the Digital Input card of Opal-RT to open the simulated breakers when SEL 751 relay detects a fault. Each NPU is implemented on a Raspberry Pi microprocessor. Each NPU also communicates to Opal-rt through Modbus TCP/IP communication protocol over Ethernet to not only read the real-time voltage and current phasors at the NPU location but also send a trip command to Opal-rt to open the corresponding breaker at the location of NPU. In order to avoid circulating fault currents, it is critical that each primary feeder relay sends DTT signals to all of the NPUs connected to that feeder. For example, in Fig. 3, the SEL 751 relay located on the top feeder sends the DTT signal to both NPU2 and NPU4.

The DTT scheme has some advantages compared to other communication-assisted schemes that use phasor measurement unit (PMU) data to assist NPUs. The PMU-based approaches would require additional hardware setup line GPS clocks in addition to the communication system which adds to the cost and complexity of the system.

IV. HIL Testing Results

In order to verify the performance of the DTT-based scheme, the following test scenarios were performed:

- Scenario A: Three-phase to ground (THP) fault on the top feeder
- Scenario B: Single line to ground (SLG) fault on the top feeder
- Scenario C: No fault condition with high penetration of DER (See Table I for the DER size)

In the following studies, the conventional NPU's setpoints are as follows: The sensitive trip element's pickup is equal to 2 A. The insensitive trip pickup is equal to 80 A. The NPU's characteristic angles are set to 30 and 80 degrees. The delay of the insensitive element is 5 cycles while the delay of sensitive trip element is 10 sec.

A. Scenario A Results

In this scenario, it is assumed that a THP fault occurs at the location shown in Fig. 3 at 5 sec. When this fault occurs, the SEL 751 relay on the top primary feeder detects the fault through its insensitive overcurrent element and issues a trip command. This trip command is transferred to NPU2 and NPU4 and both of these units disconnect their corresponding breakers after receiving the DTT signal. In Fig. 5, the three phase currents of NPU2 are illustrated. As seen, the NPU2 disconnection occurs after receiving the DTT signal from the upstream SEL 751 relay. Due to the intrinsic communication delays in Raspberry Pi, the NPU2 disconnection occurs with some delay at around 5.09 sec. In Fig. 5, the tripping times of different NPU2 elements are also illustrated. As seen, the DTT element in NPU2 trips at around 5.09 sec while its insensitive element would trip at around 5.19 sec if there was no DTT available. The delay of insensitive element compared

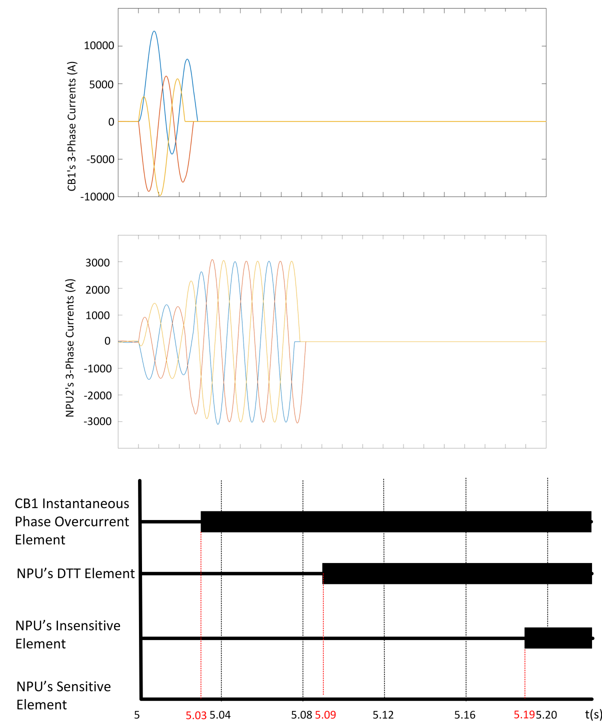

Fig. 5. Scenario A: CB1 and NPU2's three phase currents before and after the fault along with the tripping times of CB1 and NPU2's elements.

to the DTT element is due to the intentional 5 cycles delay applied to insensitive element. The NPU's current is plotted in the NPU2 characteristic plane in Fig. 6. As seen, the NPU's current moves from the non-tripping zone to the insensitive trip zone as the fault occurs.

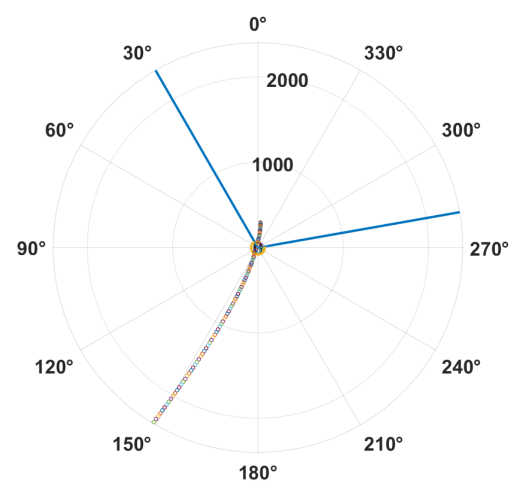

Fig. 6. Scenario A: NPU2's current and its characteristic when a THP fault occurs in the primary feeder. The NPU's current starts in the normal zone (prefault current is equal to 294∠-5° A) and moves to the insensitive trip zone.

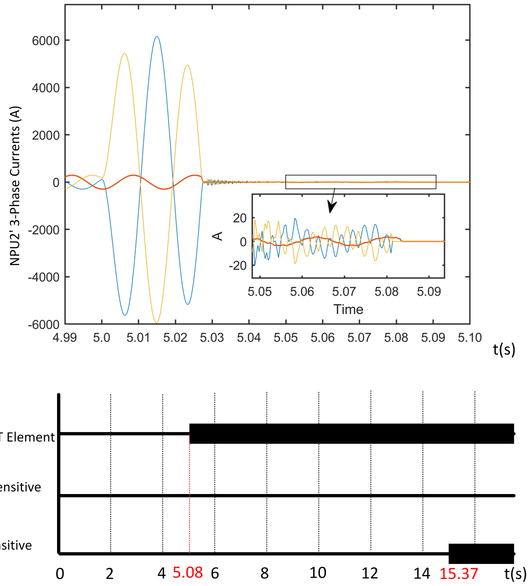

Fig. 7. Scenario B: NPU2's three phase currents before and after the fault along with the tripping time of NPU2's elements.

B. Scenario B Results

In this scenario, an SLG fault occurs at the location shown in Fig. 3 at 5 sec. When this fault occurs, the SEL 751 relay on the top primary feeder detects the fault through its instantaneous overcurrent element and issues a trip command. This trip command is transferred to NPU2 and NPU4 and both of these units disconnect their corresponding breakers after receiving the DTT signal. In Fig. 7, the three phase currents of NPU2 and the tripping time of different NPU2 elements are illustrated. As seen, the DTT element in NPU2 trips at around 5.08 sec. Due to the low reverse current after CB1 breaker on the primary feeder opens, the insensitive trip element is not triggered. However, the sensitive trip element is triggered and this element would trip with a round 10 sec delay at around 15.37 sec. The NPU's current is plotted in the NPU2 characteristic plane in Fig. 8. As seen, the NPU's current moves from the non-tripping zone to the insensitive trip zone after the fault occurs and quickly moves back to the sensitive trip zone after CB1 on the primary feeder opens. It should be noted that if the pickup value of the sensitive trip element is increased to 4, the NPU2's current will reside in the non-tripping zone and NPU2 would never trip for this fault. This is shown in Fig. 9 and highlights the importance of using DTT scheme for increasing the NPU's sensitivity and reliability of tripping for faults on the primary system.

C. Scenario C Results

This scenario shows the advantage of using DTT scheme for DER integration. As seen in Fig. 10, the DER is integrated at 5 sec, and NPU2 allows for the reverse power flow caused by the DER integration. The reason is that the NPU adopts desensitized settings in the presence of DER in the LV

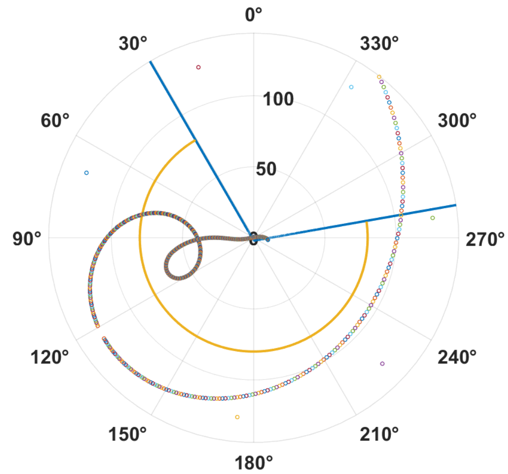

Fig. 8. Scenario B: NPU2's current and its characteristic when an SLG fault occurs in the primary feeder. The sensitive element pickup is 2 A. The NPU's current is $10\angle\text{-}98°$ A and rests in the sensitive trip zone.

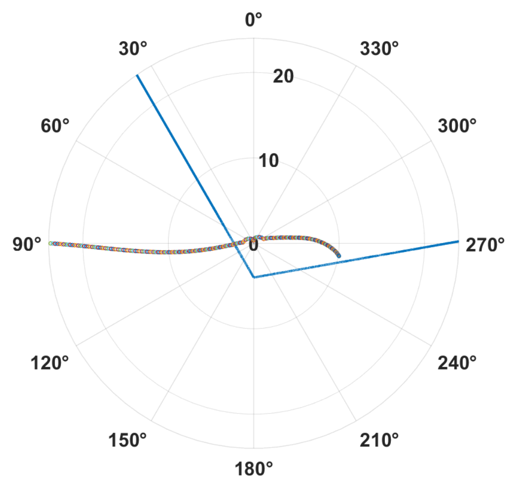

Fig. 9. Scenario B: NPU2's current and its characteristic when an SLG fault occurs in the primary feeder. The sensitive trip pickup is 4 A. The NPU's positive sequence current is $10\angle\text{-}98°$ A and rests in the no-trip zone.

network. The desensitized pickup is set to 300 A which is equal to the current rating of the service transformer of NPU. Fig. 10 also shows the tripping time of the different NPU elements under the DER integration. As seen, in the case of conventional NPU settings (i.e., 2 A and 80 A for the sensitive and insensitive elements), NPU does not allow large DER penetration and the insensitive element trips at around 5.19 sec after it senses the reverse current flow caused by DER integration.

V. Conclusion

In this paper, a new DTT scheme for improving the performance of NPUs in the LV spot networks is presented. The proposed approach has advantages compared to the conventional NPU's protection logic. First, it was shown that the proposed

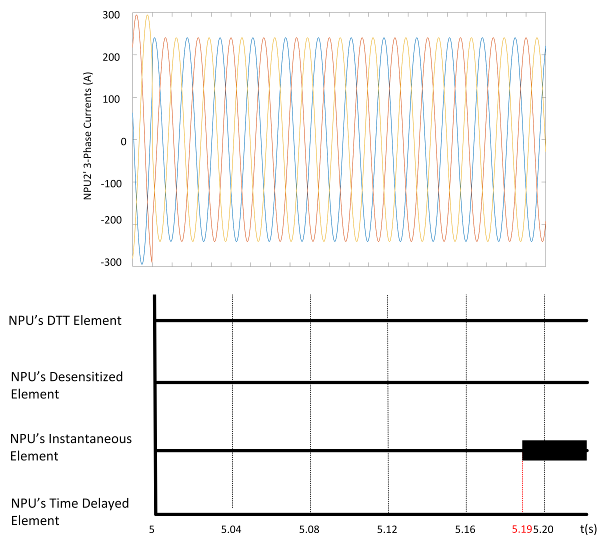

Fig. 10. Scenario C: NPU2's 3 phase current before and after the DER injection at t = 5 sec, demonstrating that the proposed DTT does not trip for reverse power even though a standard NPU instantaneous element would have.

TABLE I
HYPERSIM MODEL PARAMETERS

Substation Transformer	
Primary: Delta, 230 kV	Secondary: Grounded Y, 13.8 kv
R = 85.690E-3 $m\Omega$	L = 2.273E-3 μH
Primary Feeder Voltage and Frequency	
V = 13.8 Kv	f = 60 Hz
Lines	
Zero Seq.	Positive Seq.
R = 295.220E-3 Ω/km	R = 17.815E-3 Ω/km
L = 2.758E-3 H/km	L = 832.593E-6 H/km
C = 6.405E-9 F/km	C = 9.697E-9 F/km
Service Transformers	
Primary: Delta, 13.8 kV	Secondary: Grounded Y, 208 V
R = 216.000E-6 Ω	L = 5.730E-6 H
DER Size	
S = 180 kVA	Maximum Current = 500 A
Load	
P = 150 kW	Q = 15 kVAr

approach can help NPUs detect ground faults that occurred on the primary feeder in the case of having a Delta winding on the high voltage side of service transformers. Moreover, it is shown how the proposed approach can help with the integration and utilization of DERs in the LV spot networks.

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