Adaptive Protection for Meshed Secondary Networks using Network Protectors

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***Abstract*— Traditional secondary network protection schemes trip in response to reverse power flow to prevent back feed from the secondary network to the primary feeder. This protection philosophy enables fast, selective isolation of secondary networks from faulted primary feeders, but can limit the distributed energy resources (DER) hosting capacity of the secondary network. This paper details the design, testing, and implementation of an adaptive protection scheme in a commercially available network protector which uses instantaneous rate of change of real power (ROCOP) to enable limited reverse power flow, while supplemental logic is used to adaptively change the network protector closing parameters. The adaptive protection scheme was implemented in a commercially available protection relay to demonstrate that it can be implemented using off-the-shelf hardware. Hardware in the Loop (HIL) testing was used to evaluate the performance of the scheme for fault and non-fault disturbances. The test results highlight the improved efficacy of the network protector adaptive logic for higher DER penetration levels.**

***Index Terms*—Distributed Energy Resources, Network Protectors, Secondary meshed networks, RoCoP, Hardware-in-the-loop**

I. INTRODUCTION

Conventional secondary meshed network or low voltage grid network protection schemes are typically configured to trip in response to reverse power from the secondary network to the primary feeder. Network Protectors (NWPs) are typically installed on the LV side of secondary network transformers to perform this protection function [1], [2]. Although this protection scheme allows for simple yet effective isolation of secondary networks from faulted primary feeders, it can limit the addition of distributed energy resources (DER) and as such, the hosting capacity of the secondary network. The impact of such DER on general protection schemes of power distribution systems ([3]-[7]) as well as low voltage secondary network protection has been studied in the past ([8] - [13]). However, the impact on network protection while hosting significantly higher DER penetration levels has been less understood in the past. With certain utility networks aiming for more than 100% renewable penetration in future, understanding and coming up with practical solutions for robust adaptive protection (AP) schemes becomes extremely challenging. There are two key issues with respect to (DER) hosting capacity on meshed secondary distribution networks. The first issue relates to network protectors tripping when DER power output results in the reverse flow of power to the primary feeder during non-fault conditions. The second issue is that network protectors can fail to automatically close after re-energization of primary feeders because of elevated voltages on the secondary network due to DER. The network protector's reverse power pickup setting could be raised to allow limited reverse power flow due to DER, but this reduces protection sensitivity. This could prevent the relay from reliably detecting certain primary feeder breaker outages and faults on account of the reduced trip setting sensitivity.

In this paper, an adaptive protection scheme is proposed to solve the former issue. A possible solution is also proposed that could solve the latter issue too. The scheme design is presented and the experience of implementing and testing the scheme in a commercial network protector is detailed. The adaptive protection scheme uses instantaneous rate of change of real power (RoCoP) to enable limited reverse power flow, while supplemental logic is used to adaptively change the network protector closing parameters. The scheme enables limited reverse flow of power from the secondary network to the primary feeder, while still providing fast and coordinated protection tripping for primary-side feeder faults. The logic design can be used to supplement existing logic and can be customized based on site or grid-specific requirements.

The adaptive protection scheme was developed in conjunction with Consolidated Edison, Inc., a US-based electric utility with a focus on their LV secondary meshed system. The primary feeders were 33kV while the secondary networks were 480 V and 208 V. The secondary networks are supplied through delta/wye-ground connected network transformers. The adaptive protection scheme was implemented in a commercially available off-the-shelf protection relay to demonstrate its easy deployment and is also currently being evaluated in a network protector in conjunction with a commercial partner. Hardware in the Loop (HIL) testing was used to evaluate the performance of the scheme for fault and non-fault disturbances. Several scenarios of secondary network faults, primary feeder faults as well as other back feed energization cases were simulated on the utility distribution model in Open Distribution System Simulator program (OpenDSS for phasor domain simulations) as well as Electromagnetic Transients Program (EMTP for EMT simulations). Thereafter, COMTRADE files were generated to be replayed in the protective devices housing the adaptive protection logic. The test results highlight the improved efficacy of the proposed protection scheme for higher DER penetration (up-to 200% of loading in the system) scenarios.

The rest of the paper is structured as follows: Section II discusses the proposed adaptive protection design overview. Section III outlines the various considerations and scenarios considered for the pre-deployment testing phase of the adaptive protection scheme. Section IV illustrates the various test results that were carried out using HIL lab testing. Finally, the conclusions, ongoing, as well as future work are summarized in Section V.

II. ADAPTIVE PROTECTION DESIGN

A. Adaptive protection success criteria

While designing the scheme, it is imperative to define some important success merits to correctly identify key design aspects of the scheme. The success of the adaptive protection logic design for use on secondary networks can be evaluated by the following measures. These success merits were translated to specific simulations and lab tests to validate the scheme.

- A de-centralized adaptive protection design that permits reverse power flows through the network protector or bulk supply point and thus enables increased penetration of DER on secondary networks without compromising sensitivity to credible faults.
- A scheme which can be readily deployed to common protection and controller equipment already in use by distribution grid utilities.
- A protection scheme that does not interfere with the operation of protective devices responsible for clearing all manner of credible faults on the secondary network in line with existing utility protection practices and requirements.
- Protection that does not trip when cumulative DER installed capacity on the secondary network results in the reverse flow of power through the network protector under nominal conditions where there is no fault, or the primary breaker is not open.
- A design that permits closing of network protectors for low and high-DER cases.
- Protection that does not permit back-feeding of fault current onto a de-energized primary feeder.

B. Adaptive protection design overview

The secondary network adaptive protection logic was designed to enable limited reverse flow of power from the secondary network to the primary feeder, while still providing fast and coordinated protection tripping for primary-side feeder faults. This logic design can be used to supplement existing logic and can be customized based on site or grid-specific requirements. The proposed logic implements the following:

Close Logic

The following are the close settings that could be implemented for network protector relays subject to DER load variations:

- Standard Close Settings - In this mode, the relay looks for forward-closing conditions and a 1.4V differential voltage across the open switch. In case of DER being present, and potentially elevated levels of secondary voltage, a relaxed close setting that can be enabled remotely by SCADA to initiate closure at 0.5V differential can be used.
- Permissive Close - The permissive close mode could be applied in areas with high penetration of DER. In this mode, if the forward feed conditions have not been met, the relay allows for the switch to be closed into reverse flow if the differential voltage on any phase does not exceed 5V. This option can also be implemented via SCADA. This closing method could be used with a two-stage closing logic such that it periodically attempts close operations if the network protector remains open for a defined period.

Trip Logic

As a convention, forward direction represents positive flow of power from the primary feeder through the network protector towards the secondary network. A negative power flow represents reverse power flow, that is, power flowing from the secondary network through the network protector towards the primary feeder. The adaptive protection scheme calculates power flow from voltage and current phasors.

When the calculated rate of change of real power (RoCoP) is higher than a user programmable forward threshold and the measured forward real power is greater than the forward power threshold, a timer is started. This timer serves the function of blocking the reverse rate of change of real power element for through faults (as highlighted in the red box in Figure 1).

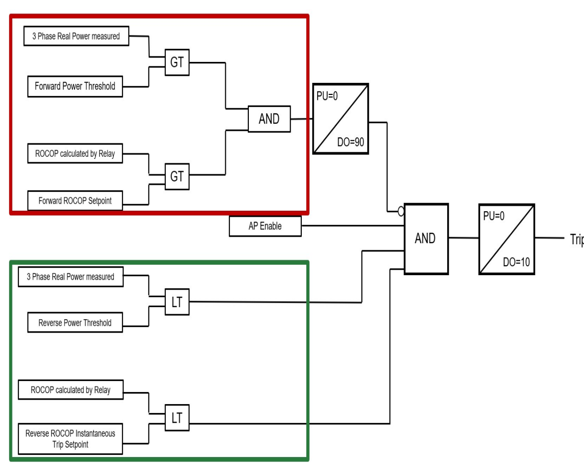

Figure 1. Proposed adaptive protection scheme logic diagram.

If the calculated rate of change of real power is less than the reverse RoCoP setting and the reverse real power flow is lower than the reverse power pickup setting (as highlighted in the green box in Figure 1), with the adaptive protection scheme enabled, a trip command is generated as long as the blocking timer is not active. Figure 1 shows the logic diagram of the proposed AP scheme.

For the sake of testing for this project, an easily available off-the-shelf commercial microprocessor-based digital relay was used by EPRI to perform the laboratory testing. The previously discussed RoCoP logic was converted to relay-specific logic and uploaded to the relay along with site-specific configuration settings.

The relay does not calculate the rate of change of power internally. Therefore, this had to be calculated using custom logic programmed into the relay. To store consecutive three-phase power measurements for calculating RoCoP, conditioning timers, binary and math variables were used. The time interval for RoCoP was set at 100ms (6 cycles). For RoCoP calculation, the following calculation is implemented.

$$RoC\ of\ Power = \frac{Power\ Flow_i\ -\ Power\ Flow_{i-1}}{Time\ Interval} \quad (1)$$

where,

Power Flow$_i$ = Most recent real power flow measurement

Power Flow$_{i-1}$ = Power flow measurement at previous calculation interval

Time Interval = Defined to be 100ms

Appendix 1 documents the logic from Figure 1 as it was programmed in the microprocessor relay for use in the laboratory testing of the RoCoP protection scheme.

III. Pre-deployment Testing and Preparation

The utility model under consideration was built in OpenDSS software. The secondary network model under analysis consists of primary radial feeders and multiple 480V or 208V secondary networks supplied through delta/wye connected network transformers. Network protectors (NWPs) are situated on the LV side of these network transformers. The network protectors would typically trip in response to reverse power flow from the secondary network to the primary feeder. Various studies were preformed to simulate the voltage and current flow through the network protector for a variety of system conditions. Simulated scenarios include:

1. Planned outage of the primary feeder requiring all connected network protectors to automatically trip, while network protectors connected to in-service feeders remain operational.
2. Short-circuit faults on the primary feeder requiring all connected network protectors to automatically trip, while network protectors connected to un-faulted in-service feeders remain operational.
3. Other disturbances on the high voltage grid including short circuit faults, auto-reclosing, requiring all network protectors to remain stable (not trip).

Key network protector locations were identified, and various simulations were performed. Each scenario was studied using stepped-event analysis in OpenDSS with a subset studied using time-domain EMT simulations. The following analyses were performed on the grid model:

1) Primary feeder outage:

a. Run power flow simulations and log steady state power flow through each network protector (pre-event).
b. Open the feeder circuit breaker of each feeder in turn and log power flow through each network protector (event).
c. Open all network protectors connected to the outaged primary feeder and log power flow through remaining in-service network protectors (post-event).

2) Primary feeder faults:

a. Run a power flow simulation and log steady state power flow through each network protector (pre-event).
b. Apply fault to the primary feeder and log power flow through each network protector (event).
c. Open the primary feeder circuit breaker of the faulted feeder and log power flow through each network protector (event).
d. Open all network protectors connected to faulted feeder and log power flow through remaining in-service network protectors (post-event).

3) Secondary network faults:

a. Run a power flow simulation and log steady state power flow through each network protector (pre-event).
b. Apply fault to secondary network and log power flow through each network protector (event).

Each study was used to assess the effectiveness of reverse power and reverse rate of change of power (RoCoP) elements for each network protector in each scenario. In every case, the simulation results were stored and converted to a COMTRADE file for playback to the relay for testing. To capture the effect of fault contributions from DER integration, all the simulations were then repeated for varying percentages of DER penetration (0%, 100% and 200%). It should be noted that the percentages are w.r.t the total load fed within each secondary network. The DER was placed at the load side bus of the various network protectors.

Based on the criteria listed above, network protectors were selected to evaluate the RoCoP logic. Numerous tests were generated, which were specific to each network protector under test.

The following fault locations were used for the hardware in the loop testing:

- Load bushings of the primary feeder breaker (hereafter denoted as **Far end faults**)
- High side bushings of the network transformer (hereafter denoted as **Near end faults**)
- Secondary network faults on the load side bus of the network protector (hereafter denoted as **Forward faults**)

The third fault location is part of the negative testing to verify that the network protectors did not trip for faults in the secondary network. Apart from these faults, primary feeder outage cases were also simulated (hereby referred to as **switching cases**). Figure 2 illustrates an example for the various fault locations pertaining to the numerous types of scenarios constructed for a 2 NWP secondary network.

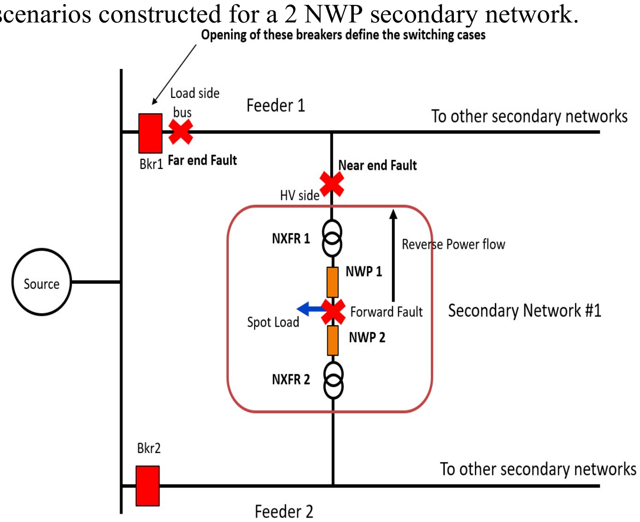

Figure 2. Example SLD view for various categories of fault locations.

Test plan documents were generated for functional conformance testing, technological conformance testing, and functional application testing of each adaptive protection scheme. COMTRADE files from the simulations were collected in these test plan documents for playback to the protection relay with the programmed logic under test and the relay behavior was evaluated against set criteria in terms of trip time. An example of the test plan along with the results for a secondary network with 3 NWPs is illustrated in Figure 3.

As can be seen on the left side of the figure, the various tests to be performed are included under sections such as % of DER penetration followed by a subcategory of a switching or fault case (LG, LL or 3-ph). For example, the case highlighted in red in the figure refers to a far end TPH fault at 0% DER penetration in the network. Similarly, cases pertaining to various levels of DER penetration as well as various fault types were created. The three objects highlighted inside the red box correspond to the 3 NWP measurements taken at their respective locations.

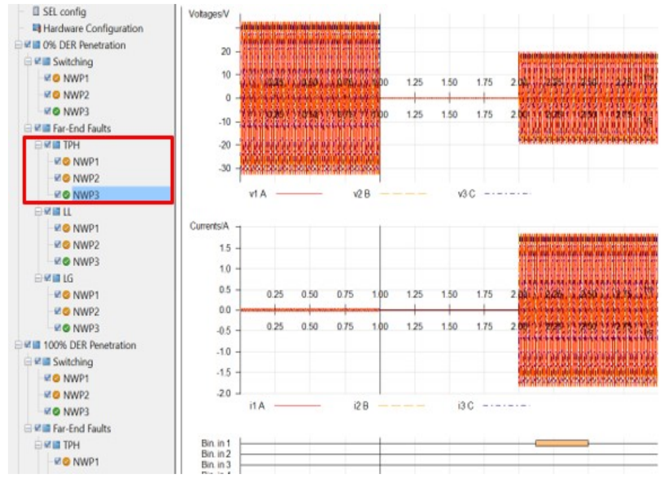

Figure 3. Example of a test plan document.

IV. Experimental Test results

A. Test Bench Setup

Once the appropriate scenarios (over 100 in number) as discussed in the previous section along with their associated test plan documents were created, the final hardware test bench was setup using a three-phase test set to provide the three-phase secondary voltage and current signals to be eventually fed to the relay.

Figure 4 illustrates the information flow diagram of the test bench HIL setup used for testing the adaptive protection logic schemes. Connections for a trip and block contacts from the relay to binary inputs of the test set enabled precise relay trip or block times to be included in the relay test report.

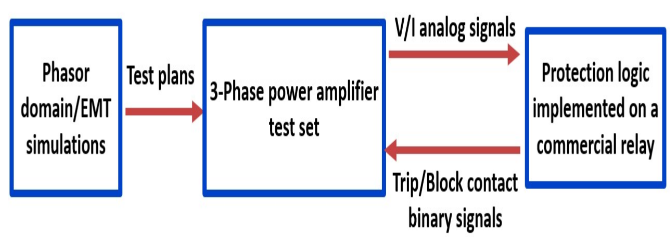

Figure 4. Information flow diagram of the HIL setup.

B. OpenDSS Test Results

After the protection logic was programmed in the relay and the necessary test plans were created, testing was conducted to observe the performance of the scheme. For preliminary testing based on phasor domain simulations, two secondary networks were considered – one fed by two network protectors and another fed by three network protectors. The former (hereby referred to as *Network A*) is fed by two 1000kVA network transformers while the latter (hereby referred to as *Network B*) is fed by three 500kVA network transformers. A few scenarios (among the numerous cases that were assessed) are illustrated below for the sake of brevity and convenience of the reader.

Case 1 (Successful Blocking operation): Near end SLG fault for Network A

In this case a single line to ground fault was applied at the near end (refer to *Section IV* for explanation) of the NWP1 location as illustrated in Figure 2 under 200% DER penetration. In this case, although NWP1 sees reverse power and should trip, NWP2 would see forward power and should block its tripping function. Figure 5 illustrates the COMTRADE event file as observed by the protection relay under test (emulating as NWP 2 in this case). This event file was exported from the relay. This served to sanity check the operation and to verify if the measurements fed to the relay (as shown in Figure 6) matched the relay's analog inputs.

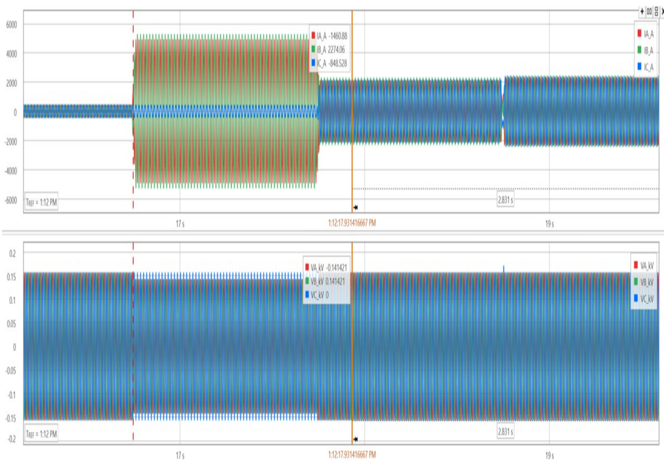

Figure 5. Three-phase currents and voltages as observed by the relay.

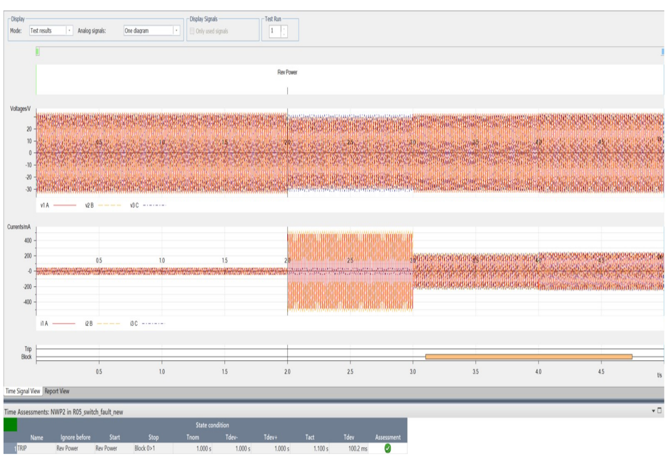

Figure 6. Three-phase voltages and currents as supplied by the test set.

Figure 7 depicts the three-phase real power (top) and RoCoP values (middle) calculated by the relay as a part of the AP scheme. The Trip (OUT101) and block (OUT102) signal timing diagram (bottom) is also illustrated in the figure. As it can be seen, the scheme was able to correctly perform the block operation of NWP2 and only assert the block signal.

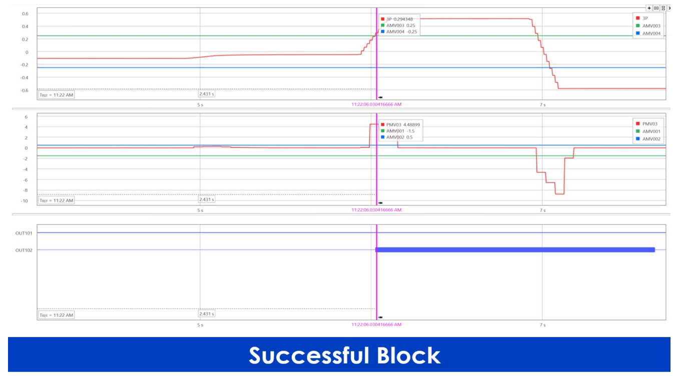

Figure 7. Measured 3ph real power and cacluated RoCoP values.

Case 2 (Successful Tripping operation): Far end 3-ph fault for Network B

In this case, three network transformers (and their associated NWPs: NWP3, NWP4 and NWP5) make up the secondary network. A 3-ph fault was applied at the far end location (refer to *Section IV* for explanation) of NWP4 under 100% DER penetration. Hence, in this case, NWP4 would observe high reverse power flow during faulted conditions and the scheme should be able to properly trip the device and should not issue any blocking signal.

Figure 8 illustrates the relay COMTRADE event file as observed by the relay (emulating as NWP 4 in this case).

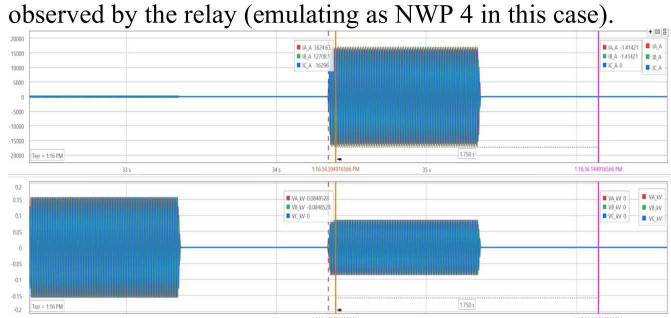

Figure 8. Three-phase currents and voltages as observed by the relay.

Figure 9 depicts the three-phase real power (top) and RoCoP values (middle) calculated by the relay as part of the scheme. The trip (OUT101) and block (OUT102) signal timing diagram (bottom) is also illustrated in the figure. As can be seen, the scheme was able to correctly perform the Trip operation of NWP4 and only assert the trip signal.

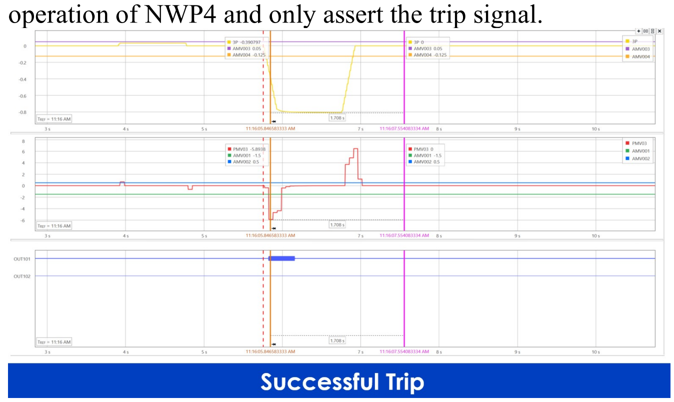

Figure 9. Measured 3ph real power and cacluated RoCoP values.

C. *EMT Simulation Test Results*

In addition to the testing using OpenDSS simulations, EMT simulations were also conducted. EMT modeling and analyses were performed to assess the DER and system transient behavior and relay performance during sudden changes such as faults and switching operations. These assessments aimed to capture any unusual transient behavior that could deteriorate the reliable functioning of the protection scheme. The time domain current and voltage waveforms were extracted as COMTRADE files and used for relay testing. A part of the OpenDSS model of the meshed secondary network was first modeled in EMTP. Apart from the cases of switching scenarios and far end/near end/forward faults, simulation results generated from faults on the incoming lines feeding the distribution station with feeders supplying the secondary networks were also studied as a part of the testing in order to ensure that the NWPs do not mis-operate spuriously for these cases. One such case is described in this section.

Case 3 (Non-Tripping operation): Incoming line 3-ph fault

A three-phase fault on an incoming line (not the primary feeder) - with 100% DER contribution (in secondary networks) was applied and the fault study results were generated. For such line faults, the NWPs of the secondary networks should not trip even though they might see reverse power. This was ensured by the proposed scheme as illustrated below.

The current, voltage, and power recordings from the simulations (as shown below in Figures 10-12) are taken at the secondary side of a particular network transformer, where the network protectors are connected. The sequence of fault occurrence and breaker operations are as follows:

- Normal Operation
- 3-Ph fault on an incomer line bus at time 3s
- Operation of the incomer line breakers to isolate the fault at time 3.5s

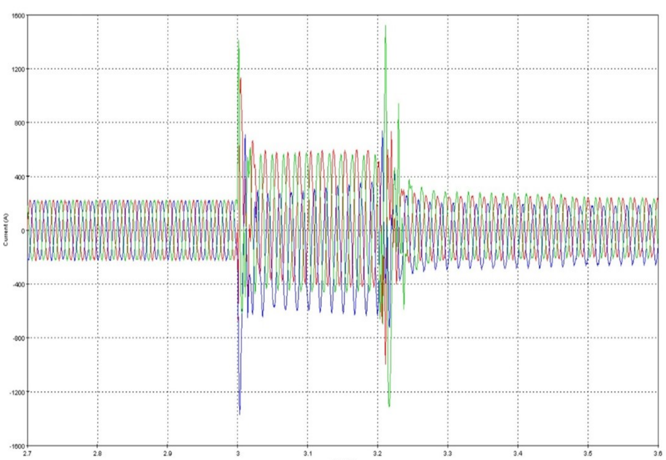

Figure 10. 3ph Current waveforms of the NWP for an incomer line fault.

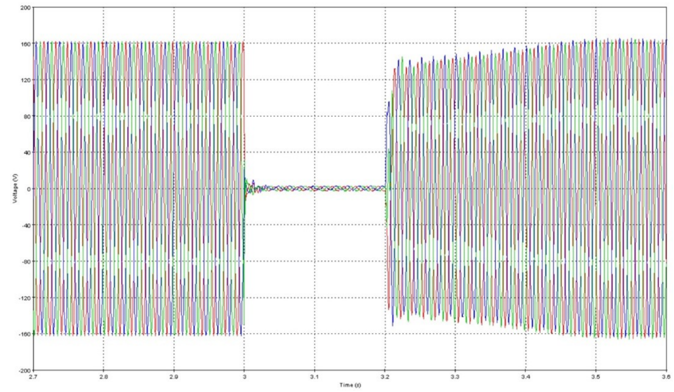

Figure 11. 3ph Voltage waveforms of the NWP for an incomer line fault.

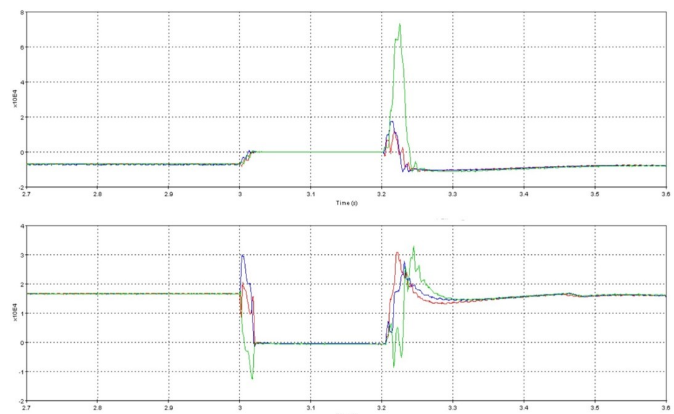

Figure 12. Active (Top) and Reactive (Bottom) power waveforms of the NWP for an incomer line fault.

Figure 13 illustrates the test plan for this particular case that was executed using the test set. It can be seen that the relay emulating the corresponding NWP did not issue any trip signal (*Bin in 1* at the bottom) in this case as expected and the scheme worked desirably.

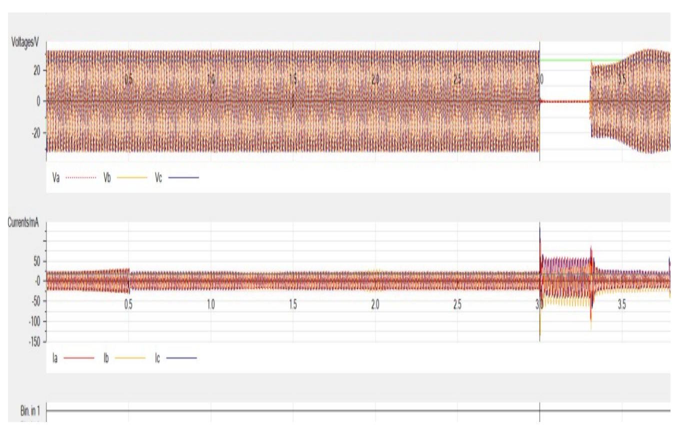

Figure 13. Three-phase voltages and currents as supplied by the test set

The complete details of the extensive logic testing that was carried out for this project can be found in [5].

V. CONCLUSIONS AND FUTURE WORK

The simulations and testing results show that the rate of change of power based adaptive protection scheme for network protectors can reliably detect primary feeder faults and outages and correspondingly trip the network protector. Though cookbook settings may become apparent over time, currently it is recommended that studies be performed to determine the appropriate settings for the rate of change of power thresholds based on the level of expected penetration.

It should be noted that all logic development and testing was performed using a protection relay and not a network protector due to ease of availability. Network protectors do not have the capability to support custom logic unlike modern microprocessor-based protection relays; therefore, the adaptive protection logic needs to be included in the firmware of the network protector whereby it can be turned ON or OFF and the corresponding protection settings can be programmed for appropriate operation.

To that end, it is necessary to include the network protector manufacturer when planning to adopt this scheme so that the equipment manufacturer can help set this up for success. Presently the authors of this paper worked with one manufacturer to trial this logic out in their commercial network protectors. Future testing should reveal if any tweaks are needed to the logic to account for network protector behavior that may have been overlooked during initial testing using a microprocessor relay.

ACKNOWLEDGMENT

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APPENDIX 1 – RELAY SPECIFIC IMPLEMENTATION OF TRIPPING LOGIC

A SEL-451 relay was used for laboratory testing of the adaptive protection tripping logic. The specific logic that was programmed in the relay is documented in Table 1. An explanation of how the logic operates is included under the table.

TABLE I. RELAY SPECIFIC IMPLEMENTATION

Line	Adaptive Protection Logic
1	# AP ENABLE (PLT01)
2	PLT01S := NOT PLT01 AND PB1_PUL
3	PLT01R := PLT01 AND PB1_PUL
4	#
5	#SAMPLE 3-PHASE POWER ONCE PER 100 MILLISECONDS
6	PCT01PU := 3.000000
7	PCT01DO := 3.000000
8	PCT01IN := PLT01 AND NOT PCT01Q
9	PSV01 := R_TRIG PCT01Q
10	#
11	#THREE PHASE REAL POWER REGISTERS
12	PMV02 := PMV01 * PSV01 * PLT01 + PMV02 * NOT PSV01
13	PMV01 := 3P * PSV01 * PLT01 + PMV01 * NOT PSV01
14	#
15	#THREE PHASE ROCOP CALCULATION
16	#AMV001 = REVERSE ROCOP SETPOINT
17	#AMV002 = FORWARD ROCOP SETPOINT
18	PMV03 := (PMV01 - PMV02) / 0.100000
19	#
20	# REVERSE ROCOP COMPARISON AGAINST SETPOINT
21	PSV02 := 3P < AMV003
22	PSV03 := PMV03 < AMV001
23	#
24	# FORWARD ROCOP TIMER
25	PSV04 := 3P > AMV004
26	PCT04PU := 0.000000
27	PCT04DO := 90.000000 # FORWARD ROCOP BLOCK TIMER
28	PCT04IN := PSV04 AND PMV03 > AMV002
29	#
30	#ROCOP TRIP - PCT02Q
31	PCT02PU := 0.000000
32	PCT02DO := 10.000000
33	PCT02IN := PSV02 AND PSV03 AND NOT PCT04Q

As long as the adaptive protection scheme is enabled, the following process takes place every processing interval:

Lines 5-9: PCT01 is an oscillator setup with an interval of 100ms. It sets the PSV01 variable to logical 1 based on the trigger from the output of the PCT01 conditioning timer every 100ms (6 cycles).

Lines 10-12: Math variable PMV01 stores the value of measured three-phase power during this time interval while PMV02 stores the value from 100ms prior. Every 100ms, the value from PMV01 is transferred to PMV02 and a current three-phase power value measured by the relay gets stored in PMV01.

Lines 13-18: AMV001 is the user-defined trip setting for the reverse rate of change of power. AMV002 is the user-defined setting for the forward rate of change of power used by the through fault blocking timer. It should be noted that based on the number of network transformers feeding a spot load, the values of these user defined threshold values would change and are tailor- defined for individual networks. PMV03 calculates the Rate of Change of Power and uses formula defined earlier in Eq.1.

Lines 19-22: Variable PSV02 compares the measured power flow against the user-defined threshold AMV003 to ensure that power is flowing in the reverse direction. Variable PSV03 compares the calculated rate of change of power against the reverse rate of change of power threshold defined in AMV001.

Lines 23-28: Variable PSV04 compares the measured power flow against the user-defined threshold AMV004 to ensure that power is flowing in the forward direction. Timer PCT04 is the through fault blocking timer with a pickup delay of 0 cycles (PCT04PU) and a dropout delay of 90 cycles (PCT04DO). The timer starts when the calculated RoCoP is greater than AMV002.

Lines 29-33: Conditioning timer PCT02 is used to trip the network protector. The timer has a pickup delay of 0 cycles (PCT02PU). The dropout delay is set to 10 cycles (PCT02DO) to ensure the output contact of the relay stays asserted for enough time to allow the network protector tripping coil to energize and open the network protector. The input to the timer (PCT02IN) is asserted when the following conditions are satisfied:

- Measured power is flowing in the reverse direction (PSV02)
- The reverse rate of change of power is lower than the trip threshold (PSV03)
- The through fault blocking timer is not active (PCT04Q)

If all these conditions are satisfied the relay issues a trip command to the network protector.

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