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CIGRE US National Committee
2022 Grid of the Future Symposium

Real-Time Simulation Model of Network Protectors for Performance Evaluation of Secondary Distribution Networks

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SUMMARY

Due to advent of customer-owned Distributed Energy Resources (DERs), such as solar photovoltaic and energy storage systems, installed at residential and commercial facilities in networked systems, the reliability of secondary distribution networks can be significantly impacted. In particular, the operation philosophy of Network Protectors (NP) is challenged due to the presence of DERs, and the protection system may misoperate due to reverse power flow and elevated voltage levels caused by DERs. Therefore, it is important to analyze the impact of newly added DERs on the operation of NPs. This requires developing and verifying proper models of NPs for various time-domain studies and real-time closed-loop testing. Currently, such models have not been developed due to limited penetration of DERs on secondary networks. However, it is very critical to use an accurate representation of NPs for protection system assessment in secondary distribution networks as NPs are widely utilized in networked distribution systems of many utilities. In this paper, a model is developed for NPs for time-domain simulation analysis. The developed model is verified by Hardware-in-the-Loop (HIL) testing of a commercial product and comparing the test results with the simulation results from the developed model. In addition, the developed model is used in a sample secondary distribution network to further examine the effectiveness of the proposed model for secondary distribution protection analysis.

KEYWORDS

Network Protector Relays, Secondary Power Networks, Real Time Simulation, Hardware-in-the-Loop Testing

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I. INTRODUCTION

Networked distribution systems are usually deployed in densely populated areas where high reliability and service continuity are important. The design of these systems ensures that customer supply is maintained for one or more contingencies on the primary distribution grid [1]. Figure 1 shows a typical secondary distribution network which is a common type of networked distribution grids. As can be seen in this figure, each secondary network is supplied by multiple step-down network transformers connected to one or more radial Medium-Voltage (MV) feeders. Therefore, even with the loss of one or more primary (MV) feeders, the secondary network will remain energized [2].

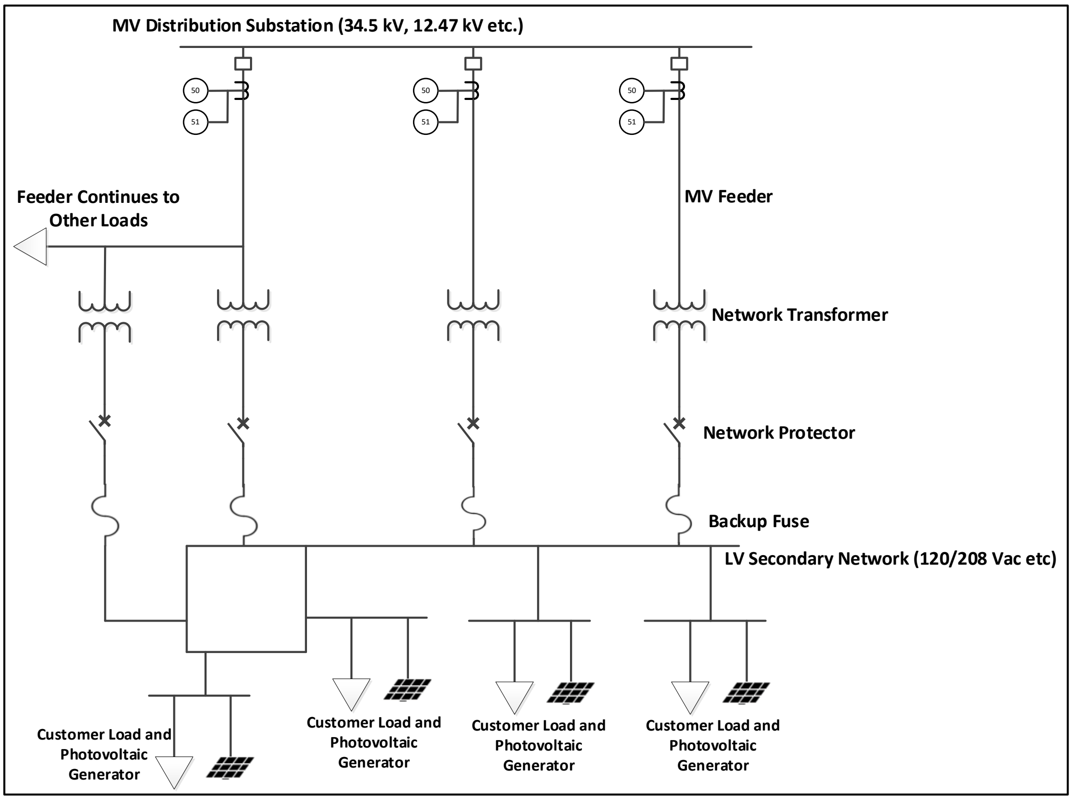

Figure 1. An example secondary distribution system

Network transformers are connected to the secondary network through Network Protectors (NP). A NP is an electrically operated low-voltage air circuit breaker with self-contained relays (and a backup fuse) for controlling its operation [3]. NPs are also used to trip in response to reverse flow of power from the secondary network up to the MV feeder; this disconnects the secondary network from faulted MV feeders and prevents unintentional loop flows between the radial feeders. In addition, upon restoration of the upstream feeder, the NPs should automatically close. The close command is issued when the network voltage is adequately close to the upstream grid voltage (i.e., the network voltage is lower by a certain magnitude and within certain degrees of the upstream grid as described in Section II).

As the penetration of Distributed Energy Resources (DERs) increases, several factors can impact the proper operation of NPs. Two main issues associated with NP performance in a DER-dominated network are described in the following paragraphs:

(i) The first issue is that the NP trips when a DER results in reverse power flow. NP reverse power protection settings are typically configured very sensitively to ensure that the network protector can detect upstream network outages where the only reverse flow will be due to transformer magnetizing current[1]. In such cases, the NP should operate to de-energize the upstream grid.

[1] A typical setting would be a pickup current of 0.15% of current transformer rating [2].

DERs can cause false trip of DERs if the pickup settings are not raised. While increasing pickup settings could prevent tripping during load conditions, it would prevent the relay from detecting upstream open circuits.

(ii) The second issue is related to network protectors failing to automatically close when DERs cause elevated voltages on the network. High penetrations of DERs can result in an increase in network voltage which, in turn, can lead to NPs failure to automatically close. This is because the voltage difference requirement may not be met. As a result, the number of sources feeding the networked grid will be reduced, leading to reduced reliability of secondary network systems.

There are several potential mitigation solutions proposed to address these challenges, including centralized and decentralized solutions. However, for a cost-effective protection solution, it is important to study the secondary distribution network to identify the issues and their severity. To that end, this paper focuses on developing a standard model for NPs that can be used for both time-domain studies as well as real-time closed-loop testing. The developed model is verified through type testing against two types of NPs from different vendors. Finally, the results of a Hardware-in-the-Loop (HIL) testing that was performed for secondary distribution network are presented. The tests were executed using both physical and simulated NPs to demonstrate the accuracy of the proposed NP model.

II. NETWORK PROTECTOR RELAYS

A. NP Relay Operation Philosophy and Settings

The main operational objectives of the Network Protector relay include the following [4]:

- To prevent power flow from secondary network to primary circuit by opening the circuit breaker using its directional power trip function.
- To enable automatic reconnection of the circuit when forward power flow condition is restored; this is achieved by closing the circuit breaker using its close characteristics that operates based on sensing system voltage.

Figure 2 and Figure 3 show the typical NP relay characteristics. Figure 2 shows the typical close characteristic curves of network protector relays where the curves from two vendors are compared. The close region is determined based on whether the three-phase power could flow into the network when the breaker is closed. This region can be adjusted using programmable settings on the relay. For Vendor 1, these settings include Master Line and Phasing Line. For Vendor 2, these settings include Relay Close Line, Tilt Angle, and Phase Detection Angle.

Figure 3 shows the typical reverse trip characteristic curves of network protector relays where the curves from the two vendors are compared. The reverse trip region is determined based on whether reverse power could flow into the network when the breaker is closed. This region can be adjusted using programmable settings on the relay. For Vendor 1, these settings include reverse trip setting and time delay. For Vendor 2, these settings include sensitive trip line and tilt angle. Typical network protector relay settings and their functions are described in Table 1.

A. Comparison of Setting Parameters between two NP Relay Vendors

In this section, main protection functions and characteristics of network protectors of two main vendors namely Vendor 1 and Vendor 2 are compared to list out all the settings. This information is utilized to develop a real time simulation model that can represent the available setting in the main NP products.

The main protection functions and their descriptions are shown in Table 2. The protection functions compared include sensitive mode/reverse trip, overcurrent protection and close characteristics. These functions are compared for two vendors namely Vendor 1 and Vendor 2. By comparing the protection functions between these two functions, Vendor 2 offers the relay with more settings than Vendor 1. For Sensitive Mode/Reverse Trip, Vendor 2 offers an additional setting called ‘Trip Tilt Angle’ when compared with Vendor 1. For Close Characteristics, Vendor 2 offers additional close modes such as automatic close, normal close etc. when compared to Vendor 1.

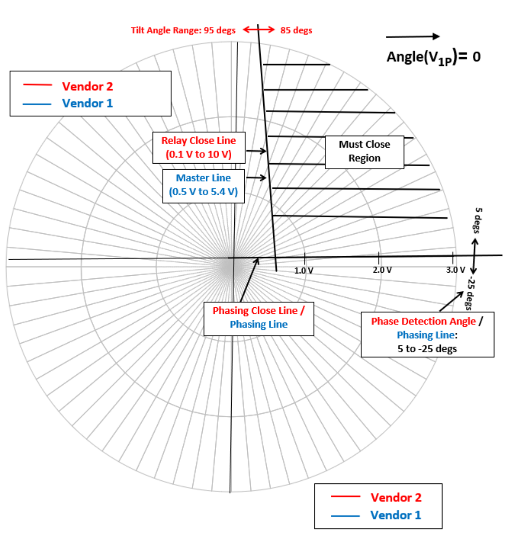

Figure 2. Comparing typical close characteristics of network protector relays between two vendors

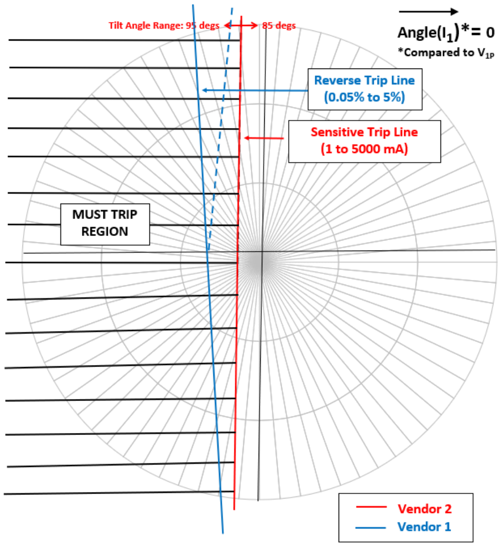

Figure 3. Comparing typical reverse trip characteristics of network protector relays between two vendors

Table 1. NP relay protection settings

Protection Category	Protection Setting/Function	Setting/Function Description
Reverse Current Protection	Sensitive Mode / Reverse Trip	These settings determine the reverse trip characteristics of the relay. This function measures positive sequence voltage (V_1) and current (I_1) and calculates the quantity ($I_1COSØ$ (positive sequence current multiplied by cosine of angle between V_1 and I_1)). If this quantity is greater than pickup setting and if the angle between the V_1 and I_1 falls in the trip region, trip is initiated.
	Overcurrent Protection	The functioning of this setting is similar to reverse trip where it is set to provide protection under high overcurrent scenarios. The functioning of this element can be either independent or linked to sensitive trip settings (as per information provided in manual).
Voltage-Based Protection	Close Characteristics	This characteristic is used to determine the close region of the relay which is based on grid voltage and reverse power flow conditions.

Table 2. Comparative review of two NP vendors

Protection Setting/Function	NP Relay (Vendor 1)	NP Relay (Vendor 2)
Sensitive Mode / Reverse Trip	- Reverse Trip (RT) - Time Delay (TD)	- Sensitive Trip Pickup current - Sensitive Trip Delay - Trip Tilt Angle
Overcurrent Protection	- Overcurrent Pickup (OC)	- Instantaneous Trip Pickup - Time Delay Setting and Extended Time Delay
Close Characteristics	- Straight Line Master Line Setting (ST ML) - Overvoltage Phasing Voltage (ML) - Phasing Line (PL) - Left Hand Master Line (LH ML)	- Close modes include Automatic Close, Normal Close, Relaxed Close Feature, Dead Network close, and Circle Close - The main parameters include: ○ Reclose Volts ○ Phase Detection Angle ○ Tilt Angle ○ Detection Offset ○ Close Time Delay.

III. Network Protector Model for Real Time Simulation

This section describes the model that is developed for real time simulation of NP relays for evaluation of protection schemes in secondary networks. Figure 4 shows the NP relay's logic diagram developed based on the NP relay operation philosophy and protection settings as described in Section II. This logic is used to develop the real time model for the NP relay in RTDS.

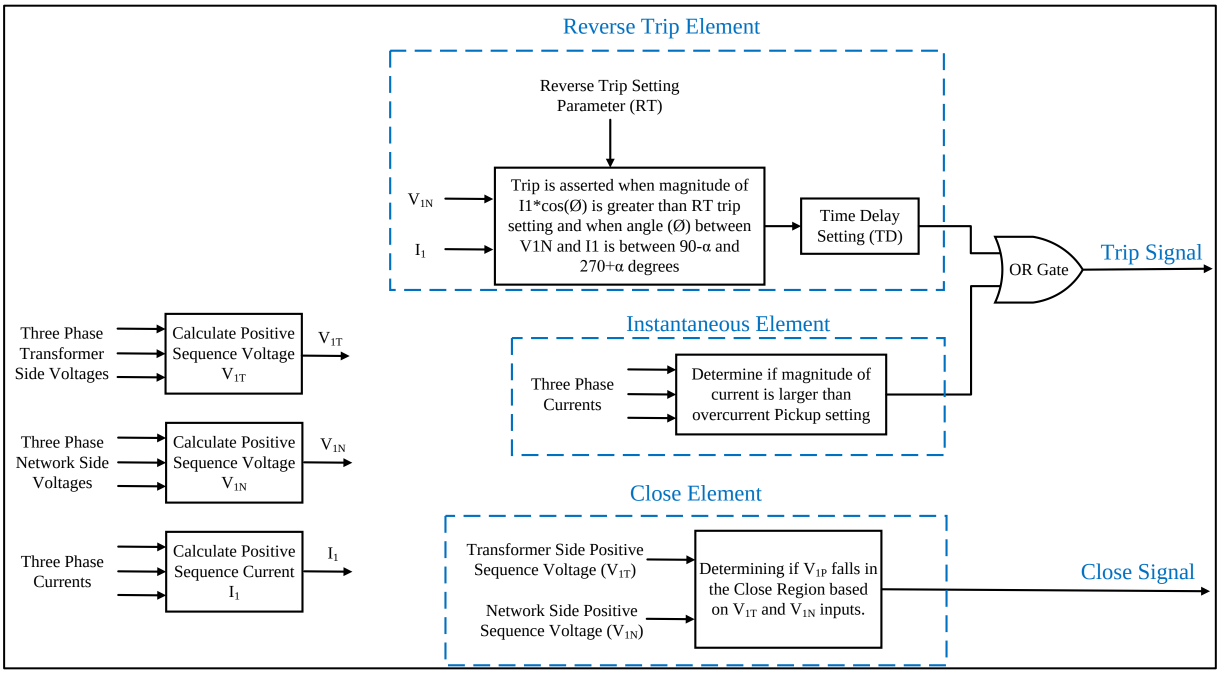

Figure 4. Network protector logic diagram

IV. Network Protector Relay Type Test

A hardware-in-the-loop (HIL) real-time simulation test setup was developed to conduct type tests on the network protector (NP) relay and evaluate its performance under different fault scenarios. The objective of the HIL type test include:

- Analyzing the settings of the network protector relay under test to:
  - Verify the directional logic
  - Verify reverse trip characteristics and settings
  - Verify close characteristics and settings
- Use type test results to verify a simulated model of the NP relay characteristics developed in RTDS

A. Type Test Setup

Figure 5 and Figure 6 show the HIL testbed diagram and the lab setup. The test setup consists of:

- A network protector relay as the device under test. There are three LED indicators on the NP relay showing its status, including: The green LED indicates close status, the yellow LED indicates float status (meaning the network protector will maintain its previous status while in float condition), and the red LED indicates trip status.
- Real-Time Digital Simulator (RTDS) [5] to simulate the power circuit (voltage and current sources).
- Amplifiers to convert RTDS low-level analog signals to proper voltage and current levels for feeding to the NP relay.
- Digital inputs/outputs to exchange digital signals between RTDS and the NP relay (including the NP breaker status and NP relay trip and close signals).

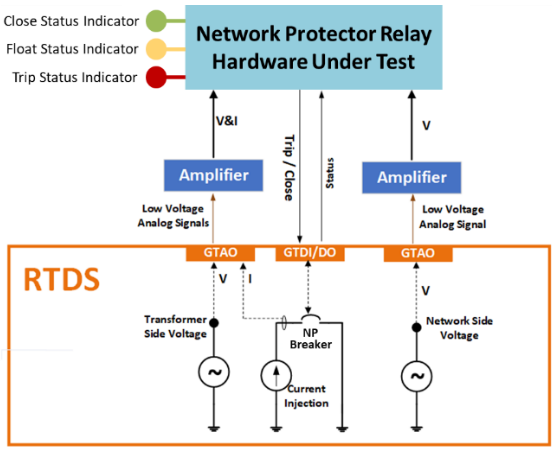

Figure 5. RTDS HIL Type Test Setup for NP Relay

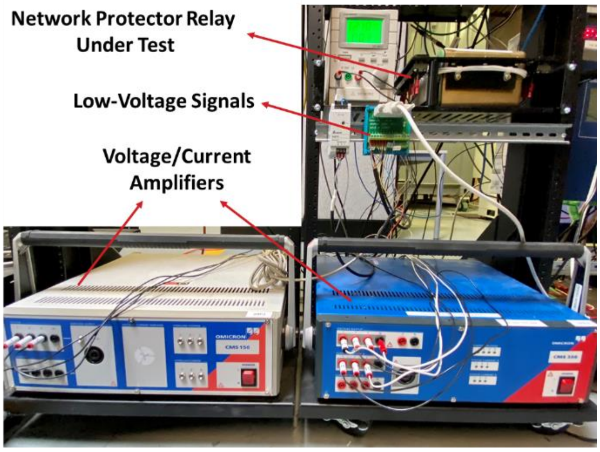

Figure 6. HIL Laboratory Test Setup

B. *Test Approach*

For the type tests, the simplified test circuit shown in Figure 5 was built in RTDS to perform HIL type tests with the NP relay hardware. The tests were performed by varying the transformer and network side voltages, and the currents using separate voltage/current sources in RTDS simulation environment to create the desired operating condition experienced by the NP relay. For testing the closing characteristic, the magnitude and phase angle of the transformer and network side voltages were varied in steps and the response of the NP relay's close characteristic was recorded. For testing the reverse trip characteristic, the magnitude and phase angle of current is varied in steps and response of the NP relay's reverse trip characteristic was recorded.

C. *Test Results and NP Relay Model Validation*

Figure 7 and Figure 8 show the test results by applying various voltages and currents to the NP relay as explained in Section IV.A and observing the status of the three indicators on the relay. The characteristic curves of the NP relay are also overlayed in these diagrams. It is observed that the performance of the relay has a good match with the expected results form the characteristic curves based on the set parameters.

Figure 9 shows the Comtrade plots from the test results for measuring the time delay between a disturbance initiation and trip signal generation by the NP relay. The disturbance was created by applying a sudden 180 degrees phase shift in the current at the time indicated be an orange vertical line in the figure. It was observed from test results that the NP relay generated a trip signal due to reverse current about 113.2 msec after the disturbance initiation. This response time includes a delay of 100 msec due to the TD setting of the NP relay as well as the additional detection time.

The output of the simulation model developed for the NP relay was also verified against the HIL test results shown in Figure 7 and their comparison showed a very good match.

V. PROTECTION SYSTEM EVALUATION IN A SAMPLE SECONDARY NETWORK

A sample secondary network as part of a larger system was modeled in RTDS and the developed NP relay model was used to evaluate the protection system performance and coordination between feeder relays and network protectors in response to different fault scenarios. The SLD of the sample secondary network is shown in Figure 10.

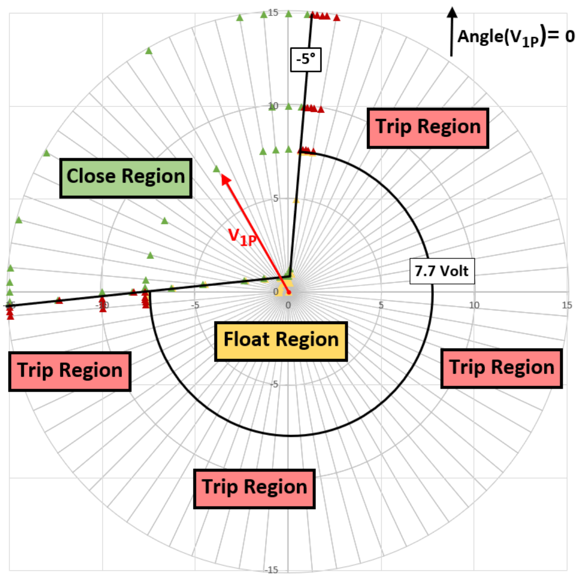

Figure 7. Test results for close characteristics

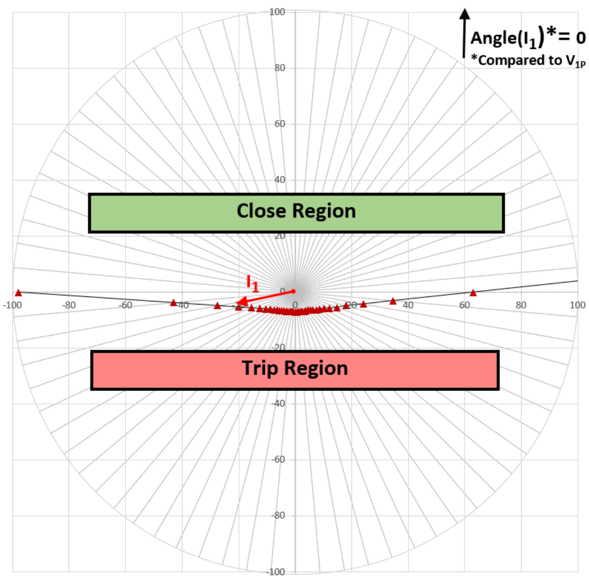

Figure 8. Test results for reverse trip characteristics

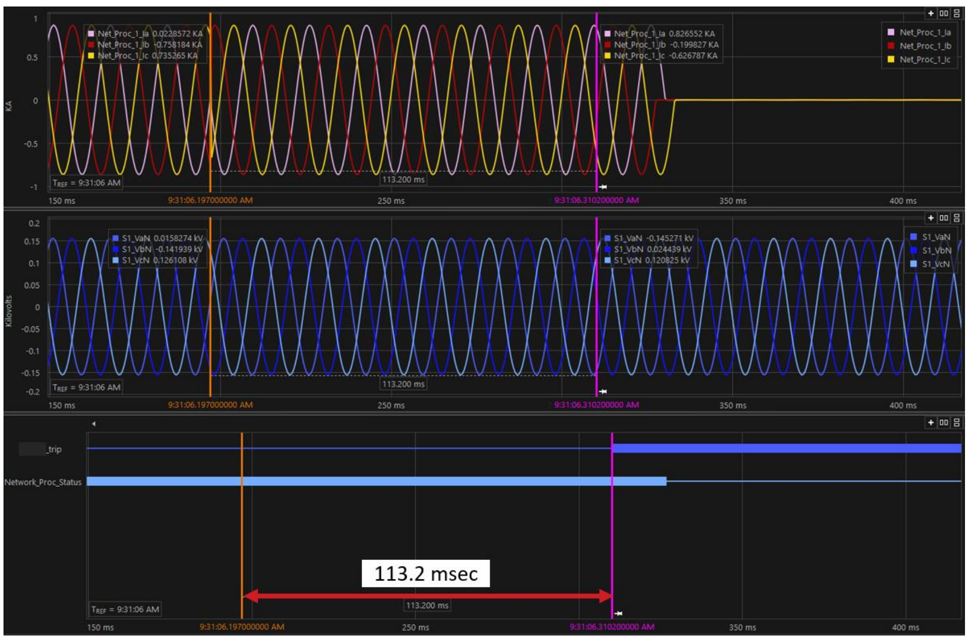

Figure 9. Comtrade plots of NP relay current, transformer side voltage, NP relay's trip signal and breaker status (from top to bottom).

The test cases are described in the following:

- **Preliminary test cases**: These tests are performed for initial validation of NP relay connections in the secondary network model. In this test, the primary feeder breaker for each feeder was opened and it was verified that the network protectors that are connected to the disconnected feeder on their transformer side would trip due to reverse current following opening the primary feeder breaker.
- **Fault studies**: The fault studies are intended to study the system conditions and protection system response during various fault scenarios. The study is performed for the faults on the primary circuit feeder (i.e. fault locations F1 to F5 in Figure 10) and the secondary circuit feeder (i.e. fault locations F6 to F8 in Figure 10).
- **Outage studies**: The outage (N-2 contingency) studies analyze the configuration where two of the incoming primary feeders supplying a Network Center are taken out of service. Therefore,

these studies are performed on the Network Centers that have more than two primary feeder supplies, i.e., NC3 in Figure 10.

- **Circulating currents**: The circulating current studies are performed to evaluate the scenario where the secondary network operates under a low load condition. In this scenario, the objective of the power flow study is to create back-feed conditions from the Network Centers and to evaluate the response of the protection system under these conditions.

From the test results, it was observed that the Time Delay (TD) parameter in the Reverse Trip setting of the NP relay has a significant impact on the coordination between the network protectors and the primary feeder relays. If the NP relays are set to trip immediately on reverse (fault) current, they may unnecessarily trip for faults on primary feeders. This is because the network protector will trip when experiencing reverse current before the primary feeder relay (main protection) operates (if TD is set at zero, i.e., TD=0.0 sec). Therefore, it is suggested to use a minimum of 100ms-200ms delay for reverse trip protection (e.g., TD=0.2 sec).

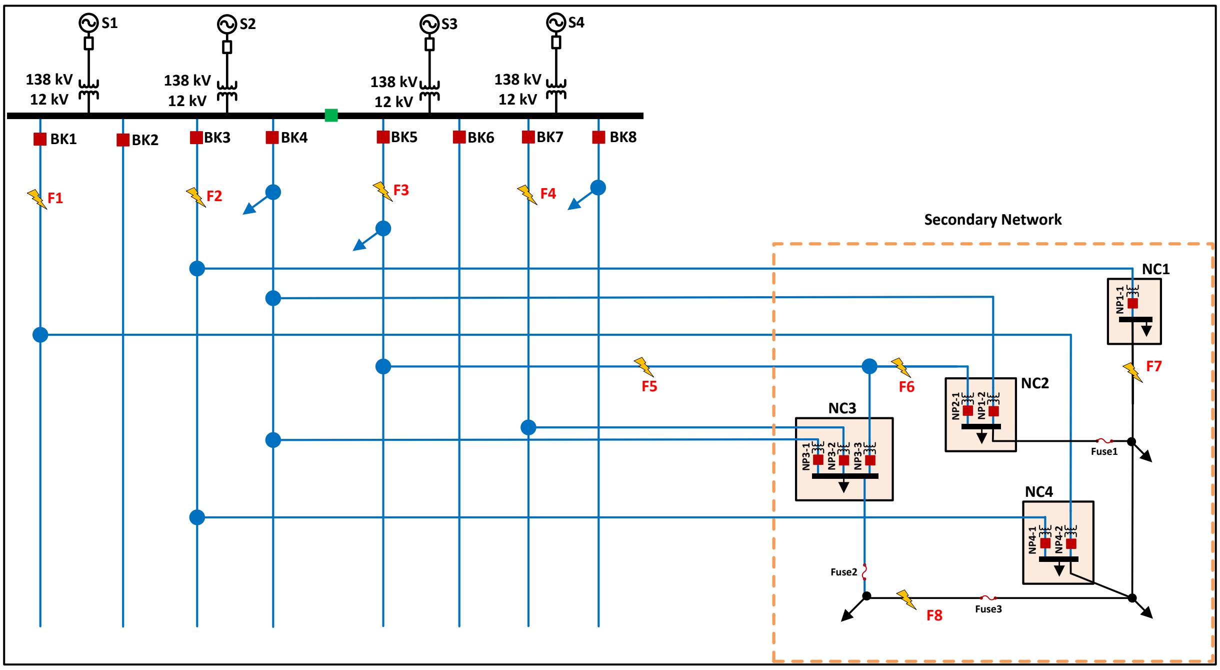

Figure 10. Single-Line Diagram of the Sample Secondary Network

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