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HIL simulation and testing of the distribution network's automatic reconfiguration

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***Abstract*— Distribution system network reconfiguration involves the optimization of the configuration of electrical distribution networks to enhance their performance, reliability, and efficiency. In this research work, distribution networks can be designed to automatically reconfigure themselves in response to faults, load changes, or other disturbances. This automatic reconfiguration can help minimize outage durations and improve system reliability. The hardware-in-the-loop (HIL) simulation results can significantly improve distribution networks' flexibility, reliability, and efficiency.**

Keywords—Network reconfiguration, distribution system, overcurrent protection.

I. Introduction

Reconfiguring the distribution network is a crucial method frequently applied to raise the reliability of distribution systems. Generally, it involves figuring out the ideal arrangement of switches needed to solve a fault condition. Overcurrent protection relays are essential components used to control switches or circuit breakers in the distribution system. These relays are positioned strategically within a feeder of a distribution system. The relay trip isolates the faulty power line segment. To reduce power outages, relays are frequently employed as field devices in conjunction with sectionalizers, fuses, and reclosers [1].

Feeder automation (FA) is one of the crucial components of the smart grid. FA is utilized to shorten outage and restoration times, increase power quality, and lower maintenance costs. As a result of this, several scholars have discussed the development of FA to enhance the flexibility, reliability, and efficiency of the distribution system feeders. In [2] several approaches have been proposed to address the problem of service restoration. These techniques include expert systems, knowledge-based systems, heuristic approaches, artificial intelligence methods combined with search algorithms, and hybrid approaches such as fuzzy logic methods. The study in [3] proposed and validated a supply restoration technique for the IEEE 33-node distribution system that involves coordinating numerous Soft open point (SOP) devices. The technique uses SOPs placed at different locations in the distribution network to support voltage and effectively increase the range of supply restoration. The authors [4] proposed a two-stage technique to tackle centralized self-healing in power distribution networks. Self-healing abilities include distribution grid reconfiguration and, if necessary, certain nodes and/or load-shedding zones. Thus, the suggested technique determines the condition of the switching devices to efficiently isolate a problematic zone and reduce the number of disconnected nodes and zones while confirming that the system's operational and electrical limitations are not breached. The work in [5] used Power Swarm Optimization methods to optimize micro-grid construction, operation, and self-healing control, resulting in flexible energy management and improved system performance.

In [1], The authors proposed and demonstrated how to back-feed a segment of the network that gets isolated as a result of an upstream fault and how to discriminate between upstream and downstream protective devices. In [6] the authors proposed an approach for identifying a faulty node in an active distribution network. The method is based on Tellegen's technique, which states that distinct network zones, each with a two-port network and PMUs to measure the current and voltage phasors at its extreme ends, should be processed in parallel. The method was validated using a Real-Time platform. [7] developed a method for detecting faulty feeders that uses image identification of superimposed zero-sequence currents. This method was also validated on RTDS. In [8], with the use of the RTDS, a real-time status estimate for distribution grids observed by Phasor Measurement Units was proposed.

This paper describes a hardware-in-the-loop (HIL) real-time simulation for network reconfiguring of the distribution system during fault conditions. Following the introduction, Section II presents the modeling and simulation of the distribution system. Section III contains studies on short circuits. The test bench implementation is provided in Section IV, and the simulation results are addressed in Section V. Section VI depicts the conclusion.

II. Modeling and Simulation of a Distribution Network Used for the Study

A 22 kV distribution network with feeders 1 and 2 safe gauded by four overcurrent relays is examined in this section—namely, SEL-351A relays. The simulations examine the overcurrent protection relay's functionality and coordination. The protection relays are positioned on the outgoing and downstream of each feeder. Fig. 1 depicts the modeled distribution network. In this section, the load flow simulation is also analyzed.

The load flow studies for the three case configurations listed below are carried out using the load flow network design shown in Figure 1.

- Case 1: The Normally Open Point (NOP) circuit breaker is open, and Feeders 1 and 2 supply their own loads.

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- Case 2: The Normally Open Point is closed, Feeder 2 outgoing circuit breaker is in the open position, and the entire load of the distribution network is supplied by Feeder 1.
- Case 3: The Normally Open Point is closed, Feeder 1 outgoing circuit breaker is in the open position, and the entire load of the distribution network is supplied by Feeder 2.

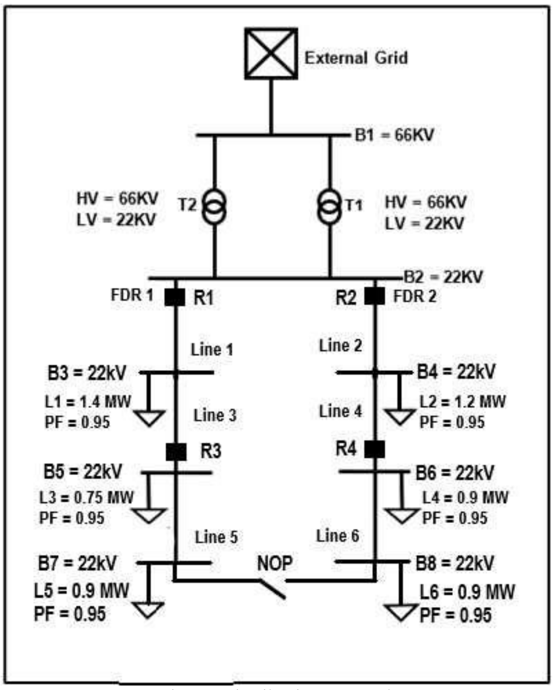

Fig. 1. Distribution network

As depicted in Fig. 1, the examined distribution system functions normally with transformers 1 and 2 in service and the normally open point in an open position. Two transformers are in place if one fails or needs maintenance, preventing blackouts [9], [10]. Case 1 was performed to ensure each feeder could supply its load. Cases 2 and 3 were simulated to ensure that if there is a fault condition or maintenance upstream of either feeder, the NOP will be closed to back-feed the downstream customers.

The cases discussed were all done to confirm that each configuration's voltage profile is within the satisfactory range. The three load flow configurations were executed as outlined in IEEE Standard 141-1993 requirements [11]. This ensures that standards and regulations of the power system are followed and that not any of these configurations burdens the transformers or overhead wires. The load flow simulations determine the rate at which real, reactive, and current power flow through the distribution system is being studied.

Three Cases serve as the foundation for the load flow analyses in Table I to Table III:

TABLE I. SUMMARY OF SIMULATION RESULTS: BUSBAR VOLTAGES

Components	Voltage (PU)		
	Case 1	***Case 2***	***Case 3***
Bus 1 (Slack)	1.0000	1.0000	1.0000
Bus 2 (PV)	0.9647	0.9625	0.9625
Bus 3 (PQ)	0.9638	0.9552	0.9599
Bus 4 (PQ)	0.9640	0.9599	0.9558
Bus 5 (PQ)	0.9637	0.9557	0.9579
Bus 6 (PQ)	0.9636	0.9578	0.9562
Bus 7 (PQ)	0.9635	0.9562	0.9572
Bus 8 (PQ)	0.9634	0.9570	0.9566

TABLE II. SUMMARY OF SIMULATION RESULTS: TRANSFORMER CURRENTS

Components	Primary/Secondary Currents (kA)		
	Case 1	***Case 2***	***Case 3***
Transformer 1	0.0579/0.1655	0.05810/0.664	0.0581/0.1664
Transformer 2	0.0579/0.1655	0.05810/0.664	0.0581/0.1664

TABLE III. SUMMARY OF SIMULATION RESULTS: LOAD ACTIVE POWER, REACTIVE POWER, AND CURRENTS

Components	Active Power (MW), Reactive Power (MVAr), Currents (kA)		
	Case 1	***Case 2***	***Case 3***
Load 1	1.4 MW, 0.46 MVAr 0.07 kA	1.4 MW 0.46 MVAr 0.07 kA	1.4 MW 0.46 MVAr 0.07 kA
Load 2	1.2 MW 0.39 MVAr, 0.06 kA	1.2 MW 0.39 MVAr 0.06 kA	1.2 MW 0.39 MVAr 0.06 kA
Load 3	1.5 MW 0.49 MVAr 0.07 kA	1.5 MW 0.49 MVAr 0.07 kA	1.5 MW 0.49 MVAr 0.07 kA
Load 4	0.9 MW 0.3 MVAr 0.05 kA	0.9 MW 0.3 MVAr 0.05 kA	0.9 MW 0.3 MVAr 0.05 kA
Load 5	0.75 MW 0.24 MVAr 0.04 kA	0.75 MW 0.24 MVAr 0.04 kA	0.75 MW 0.24 MVAr 0.04 kA
Load 6	0.9 MW 0.29 MVAr 0.05 kA	0.9 MW 0.29 MVAr 0.05 kA	0.9 MW 0.29 MVAr 0.05 kA

III. SHORT CIRCUIT STUDIES, CURRENT TRANSFORMER SELECTION, AND OVERCURRENT PROTECTION SYSTEM CONFIGURATION

A. Short Circuit Studies

This section summarizes the conclusions from the short circuit simulations. Short circuits are used on both feeders 1 and 2 in the simulated distribution network.

F1 and F3 in the table represents Fault 1 and Fault 3, and FDR1 is feeder 1.

The locations of the faults are shown in Fig. 1. Specifically, feeder lines 1 and 3 are used to simulate fault F1, and feeder line 5 is used to model fault F3.

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TABLE IV. SIMULATION RESULTS FOR SHORT CIRCUIT STUDIES

Fault Type	Fault Location	Current (kA)
Three-phase fault	F1 at FDR 1 at Line 1	6.246
	F3 at FDR 1 at Line 3	5.886

B. *Current Transformer Selection*

When employing current transformers for protection relaying, as stated in [12]. The highest value of the load current of a designed power system shouldn't be greater than the rated primary current of the CT. The maximum CT ratio that is allowed would be selected to lower wiring size and offer the optimum capabilities and performance.

The secondary current of the CT should not be more than twenty times the rated current during the maximum symmetrical fault current on the primary. [12]. 400:1 is the chosen CT ratio. When Feeder 1 supplies the entire distribution system, the highest value of the load current of the network is attained, which is 0.3323kA. This current satisfies IEEE C37.230-2007 requirements since it is smaller than the primary current of the CT. Equation 1 can be used to calculate the relay operating time, which can then be obtained by following IEC 60255 and IEEE C37.112 standards.

$$T = TMS \times \frac{0.14}{\left(\frac{I}{I_s}\right)^{\alpha} - 1} \qquad (1)$$

Where:
T is a relay's operational time
TMS is the time multiplier setting
I is the secondary current detected by the relay
I_s is current setting
α and β are slope constants

C. *Overcurrent Protection System Configuration*

The current of the pick-up setting (51P) was calculated by multiplication of load current by a factor of 1.5. The phase pick-up current was then multiplied by 25% to determine the residual time overcurrent pick-up (51G). Table V displays the relay R1 and R3 configurations.

TABLE V. RELAY 1 (R1) AND RELAY 3 (R3) SETTINGS

Protection relay	Line section	Overcurrent pick-up elements	Overcurrent Characteristic curve	Primary pick-up current	Secondary (I) at 400:1 CT ratio	Time dial	Direction
Relay 1 (R1)	Line 1	51P	IEC Normal inverse	(332.3×1.5) = 498.45A	1.25A	0.2	Non-directional
		51G		(498.45×0.25) = 124.61A	0.31A	0.22	
Relay 3 (R3)	Line 3	51P	IEC Normal inverse	(273×1.5) = 409.5A	1.02A	0.05	
		51G		(409.5×0.25) = 102.38A	0.26A		

IV. NETWORK RECONFIGURATION SCHEME IMPLEMENTATION

The CSAEMS lab at DEECE CPUT was used to conduct the simulation test for a real-time network reconfiguration scheme.

This section displays the HIL simulations using the Real Time Digitals Simulator (RTDS) and relays R1, R3, and NOP as shown in Figure 2. This is done to reconfigure the network when there is an upstream fault in either FDR's 1 or 2.

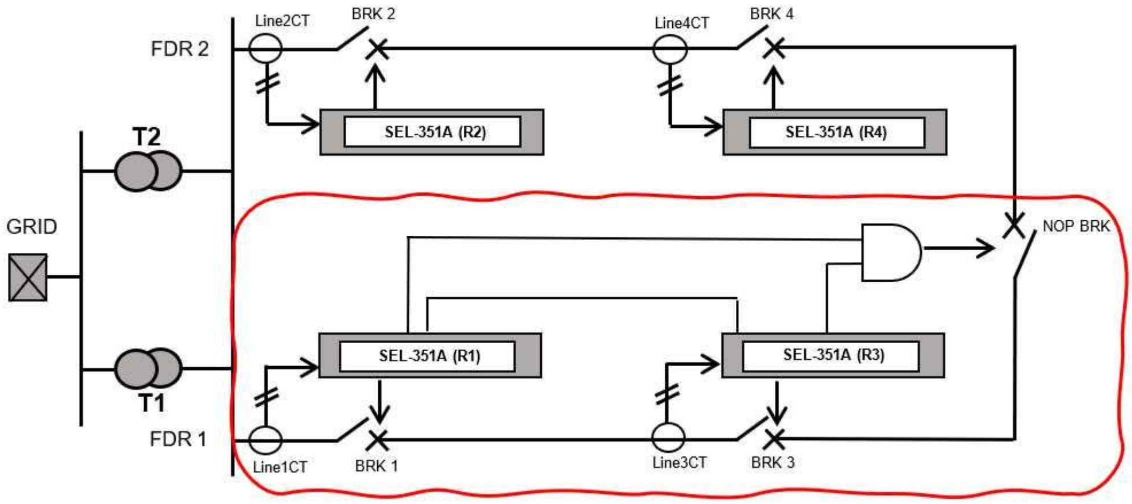

Fig. 2. Scheme for network reconfiguration

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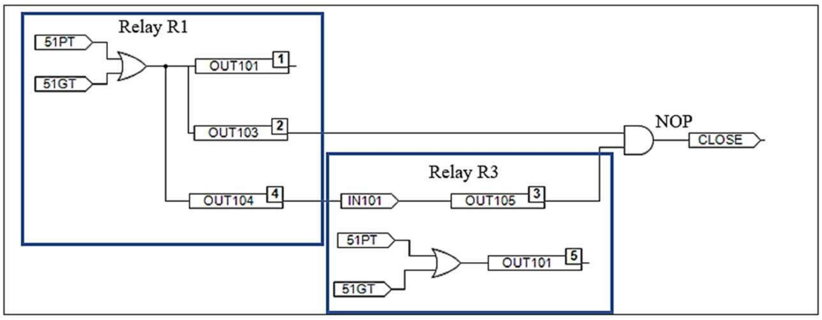

Fig. 3. R1, R3, and NOP logic

Fig. 3 depicts the implemented logic for relays R1, R3, and NOP, respectively. When a fault occurs between relays R1 and R3, R1 will trip, sending an open (logic 1) signal to R3 and a close command to the NOP.

R3 and NOP receive signals with high status from either of the configured overrent elements (51GT OR 51PT), which are routed through R1's outputs 103 and 104. Via R1 outputs 103 and 104, either of the over-current elements (51GT or 51PT) can send high-status (logical 1) signals to R3 and NOP. R3 uses input 101 to obtain the high status before sending a close signal via OUT105 to the NOP. The NOP relay closes the normally open point circuit breaker positioned to the digital inputs of RTDS when both close commands from R1 and R3 trigger it.

V. Results and Discussion

The studied scenario was performed to test the functionality of the network reconfiguration technique. The overcurrent relay performance was assessed through hardware in the loop simulations in the distribution system.

A Three-phase fault condition was simulated on Line 2 to test the functionality of R1. Fig. 4 displays the fault current seen by R1. Fig. 5 presents the elements triggered when R1 picked up the fault. 51P is the pick-up overcurrent element triggered when the fault occurred, 51PT is the trip element for 51P to clear the fault condition, and outputs 103 and 104 are the signals sent to R3 and NOP, respectively. The purpose of these signals is to open R1 and close the NOP. As seen in Fig. 4, the relay took 495 ms to clear the fault.

Fig. 6 presents the R3 operation due to the R1 trip signal. Input 101 was triggered due to OUT104 of R1 and sent a close command via OUT105 to close the NOP. The NOP closes to supply the load between R3 and NOP when it gets both high signals from R1 and R3.

VI. Conclusions

This paper presented an automatic network reconfiguration strategy for a distribution system. The chosen distribution network has been modeled on RTDS, and load flow studies have been simulated. The short circuit studies, CT selection, protection settings, and network reconfiguration logic have been specified. The proposed network reconfiguration technique reconfigured the distribution network when it encountered fault conditions. The downstream customers, who lost power due to an upstream fault, were back-fed by the alternative healthy feeder. The results were analysed in each scenario and indicated the effectiveness of the proposed method.

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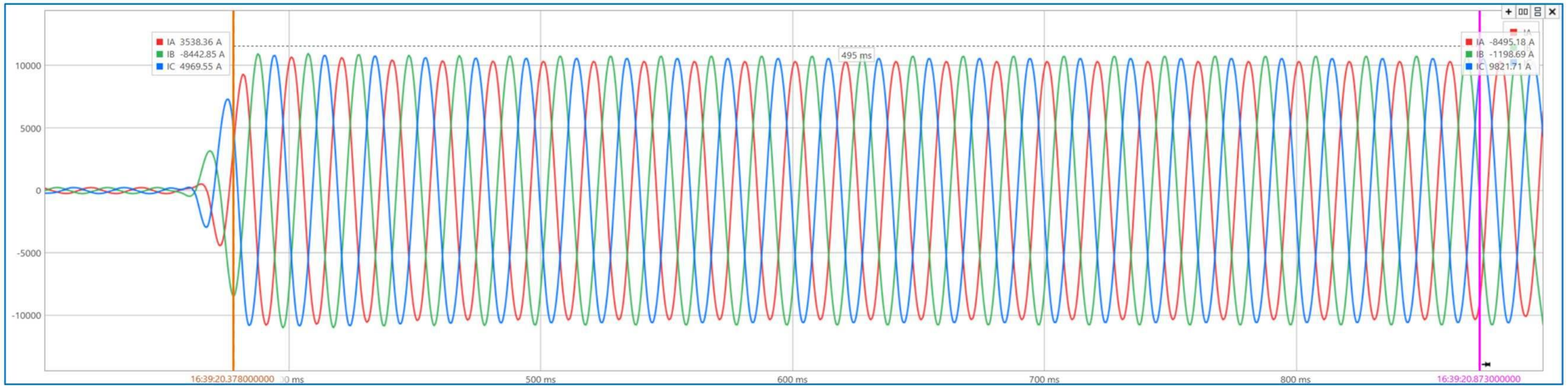

Fig. 4. R1 operation for a three-phase fault-current waveforms

Fig. 5. R1 operation for a three-phase fault - digital bits operation

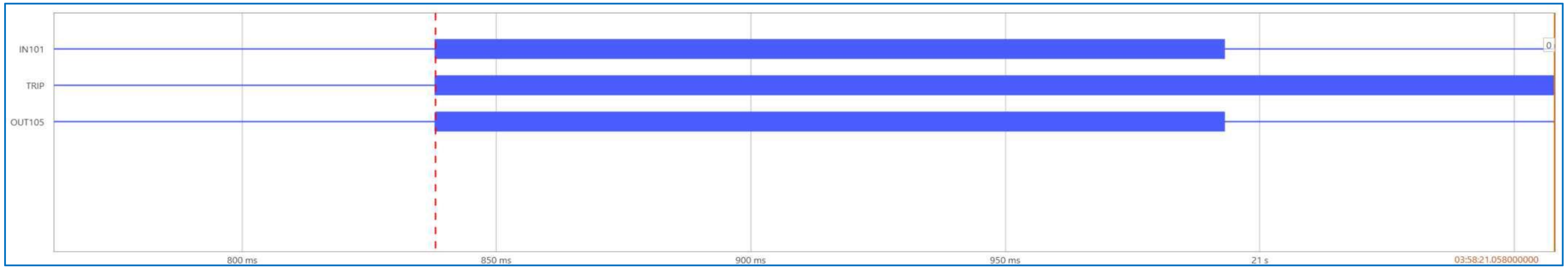

Fig. 6. R3 operation for three-phase fault