

Modeling and Simulation of Protection Logic for In-Feeder Fault Detection in a Microgrid System

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Abstract

The issue of ensuring selective and reliable earth faults in modern microgrids still persists due to sympathetic zero sequence currents and multi-source coupling complexities. In this paper, the customized Earth Fault Protection (EFP) logic has been formulated and tested to successfully discriminate between true in-feeder Earth faults and other non-fault sympathetic currents within the AC microgrid environment modeled in MATLAB/Simulink. The customized logic utilizes the dual-threshold strategy with residual current (I_0) and the minimum phase current (I_{\min}), further bolstered by time-blocking action to prevent unwarranted operations. The simulation results indicate that the customized protection logic provides complete immunity to false operations during sympathetic I_0 currents. Yet, it also manifests sensitivity to low-intensity internal faults if the stationary I_{\min} threshold is unexceeded. The customized solution compares favorably with the state-of-the-art in terms of simplicity, understandability, and direct realizability without requiring heavy computations through artificial intelligence frameworks such as ANFIS topology-independent models and AI-powered microgrid fault detection techniques.

Keywords

AC Microgrids, Protection Method, In-Feeder Fault Detection, Minimum Phase Current, Residual Current

1. Introduction

During recent years, microgrids have been found to be one of the emerging concepts that have been prominently influencing power system engineering [1] [2]. Recent demands for sustainable and resilient energy infrastructure have made mi-

crogrids one of the prominent enablers for improving reliability, resiliency, and sustainable designs for the power system. Microgrids can be generally defined as a mini power system with multiple DERs such as synchronous generators, solar panels (PV), wind turbines, and battery energy storage systems providing service to local loads enclosed by a microgrid boundary [3].

Contrary to traditional central power grids, microgrids have the advantage of dynamically switching between operating modes, which can be both grid-connected and islanded, as depicted in [4]. During grid-connected mode, microgrids can, with optimum utilization, transfer power to and from the central utility grid. During islanded modes, microgrids can effectively stand-alone without any connection to the utility grids. This makes microgrids especially interesting for hospitals, universities, and even military installations and remote regions, which require an uninterrupted power supply [5] [6].

However, with increasing penetration by renewables and distributed generation, the operation and protection systems face substantial challenges. The intermittency inherent in renewable energy sources, with power fluctuations during their operations, causes variation in voltage and frequency. Additionally, because of distributed generation, bidirectional power flow can hinder fault detection, coordination, and selectivity. Conventional protection concepts, originally developed for radial distribution networks with one-way current flow, might not effectively ensure fault selectivity in microgrids [7]. Consider, for example, when there is a fault in one feeder, current contribution can come both from the utility grid and DER units; thus, it will be hard to identify the actual fault and classify it as internal versus external [8] [9].

This can be made even more evident, which shows a simplified protection coordination scheme for a microgrid. Based on [10] [11], it can be noted how all these devices have to work in sync with each other for efficient fault isolation with minimal disruption to the supply for the non-affected feeders. Uncoordinated performance between these devices can cause problems such as nuisance tripping, instability, or even a cascading disconnection.

Therefore, there is a growing requirement for intelligent and adaptable protection logic, which is able to dynamically adjust itself based on system characteristics and fault types. These protection logics must be capable of combining real-time values, signal processing, and decision algorithms to distinguish between actual in-feeder faults and sympathetic/external fault types. Notably, by including variables such as residual current and minimum phase current in advanced fault detection algorithms, improved sensitivity and selectivity can be attained [10] [12] [13].

This work is concerned with simulating a protection logic process for in-feeder fault detection. The model developed includes actual system components like synchronous generators, transformers, RL loads, lines, and a point of grid connection (PCC). The proposed protection scheme employs current detection logic, which includes the residual current value I_0 and the minimal phase current. Using sim-

ulation, it is demonstrated how this protection logic can be used for avoiding false operations and for improving selectivity.

The current research work will help in providing an applied framework for understanding and verifying micro-grid protection strategies by using simulation environments. The research will help in improving fault discrimination accuracy by analyzing actual and false fault circumstances.

Although the suggested dual-threshold protection logic is aimed at improving selectivity and reliability in microgrid earth fault protection, the paper also strongly analyzes its trade-offs, including the loss of sensitivity to low-intensity internal faults. This paper does not just make a presentation of a protection scheme, but rather offers a systematic characterization of the scheme performance during different fault scenario, the limitation of the scheme and the way forward to improve the scheme. This would make sure that the findings are placed not as the ultimate answer, but as a moderate evaluation of a workable, computationally light approach to protection, fit to be used in a microgrid applications in real-time.

The following section is dedicated to a literature review and related studies on micro-grid protection, pointing out critical developments and current research gaps.

2. Literature Review

With regards to modern power systems, there has been extensive research work conducted on micro-grid protection and fault detection, in addition to integration with distributed energy, due to the increasing trend towards a decentralized and renewable energy-powered grid. Recent literature has emphasized improved micro-grid stability, intelligence, and robustness with regard to control and security strategies for both grid-connected and islanded micro-grids. This article will provide a brief summary on recent literature work to outline the research gaps that this work attempts to bridge.

Recent literature has focused on addressing vulnerabilities of distributed generation systems. Maghami *et al.* (2025) discussed in considerable detail vulnerability assessment for grid-connected distributed generation systems subject to coordinated cyber-attacks. Their work showed that sensitivity to 10% communication delay resulted in 6% variation in voltage levels for DER-based networks, which can have adverse effects on overall system robustness. The current subject matter highlights the need for implementing protection levels for smart grids and micro-grids against cyber-physical threats [14].

Discussing the implication of energy storage systems (ESS) for supporting grid stability, Mushid and Khan (2025) conducted a thorough literature review on battery energy storage systems (BESS) for supporting ancillary service functions in the distribution networks. The findings revealed that with the implementation of BESS, it is possible to alleviate up to 18% of the overall peak load demands and enhance system frequency by 25% during transient disturbances. Nonetheless, it

was highlighted by these authors that technological issues such as aging effects and compatibility with traditional protection relays have not been properly addressed [15].

Another research stream involved the introduction of a Proximal Policy Optimization (PPO)-based controller by Hasheminasab *et al.* (2025) for improving the accuracy and transient response in microgrids. The simulation outcome revealed a 45% improvement in steady-state error and 32% improvement in dynamic response time with the proposed PPO controller compared to conventional control approaches based on traditional droop control strategies. This research work highlights the increasing use of reinforcement learning algorithms for improving microgrid flexibility [16].

Momesso *et al.* (2024) investigated the effects caused by transportable battery energy storage systems (BESS) on protection systems used in conventional distribution networks. According to this research, it has been found that with mobile BESS, fault current levels can vary by 20%, which causes issues with the coordination timing of overcurrent protection relays if traditional coordination is adopted [17].

Similarly, Dai *et al.* (2025) proposed a fault section location scheme for active distribution networks by designing a new subtraction-average-based optimizer (SABO). The experimental result showed that the proposed scheme can locate fault sections with an accuracy of 96.8%, which is about 9% better than other heuristic approaches. This improvement proves that hybrid optimizers are useful in fault detection and isolation for active micro-grids [18].

Despite these developments, there is a gap in literature with regards to a systematic approach that incorporates adaptive protection logic with real-time coordination between feeders and microgrid interfaces. Most approaches have been geared towards ensuring fault detection accuracy or control stability without considering issues related to dynamic interactions between protection relays, fault current, and coordination delay for multi-feeder micro-grids.

Hence, this current research work intends to design and verify an intelligent protection logic for micro-grid feeders, which should have the ability to identify actual in-feeder fault occurrences and external sympathetic disturbances. The current research work is going to bridge this significant research gap by combining both time delay blocking concepts and logical fault identification.

3. Materials and Methods

The research paper uses a digital simulation research approach to design and experiment with a customized Earth fault Protection (EFP) logic on an AC microgrid.

MATLAB/Simulink software was developed to create the simulation environment because it has sophisticated software to model an electrical system and analyze its behavior across different operating conditions.

The methodology incorporates a new logic algorithm into the network model

to assess its capability to discriminate between true Earth Faults and sympathetic zero sequence currents, which may result into the failure of the traditional protection systems.

The implementation of the methodology was carried out in two major stages:

- The initial step consisted in creating an interactive MATLAB interface (GUI) that would create experimental signals of line and neutral currents and test the logic of proposed protection.
- The second step was concerned with the implementation of this logic into a realistic Simulink model of a microgrid to verify the behavior of protection in a variety of operating conditions (true fault, sympathetic state, and normal operation).

The approach will offer an empirical insight into how the system will react to the different variables that include current thresholds and time barrier (T1), which can make the accuracy and reliability of the protection system to be enhanced in advance before the actual deployment of the system on the ground.

3.1. Microgrid System Components and Modeling

The microgrid employed in this paper is a three-phase AC microgrid at low/medium voltage with the input of the public grid through a point common coupling (PCC).

This system strives to portray a real-world operating environment in which the proposed protection algorithms may be experimented safely and realistically.

A description of the system components will be detailed as follows (See **Figure 1**):

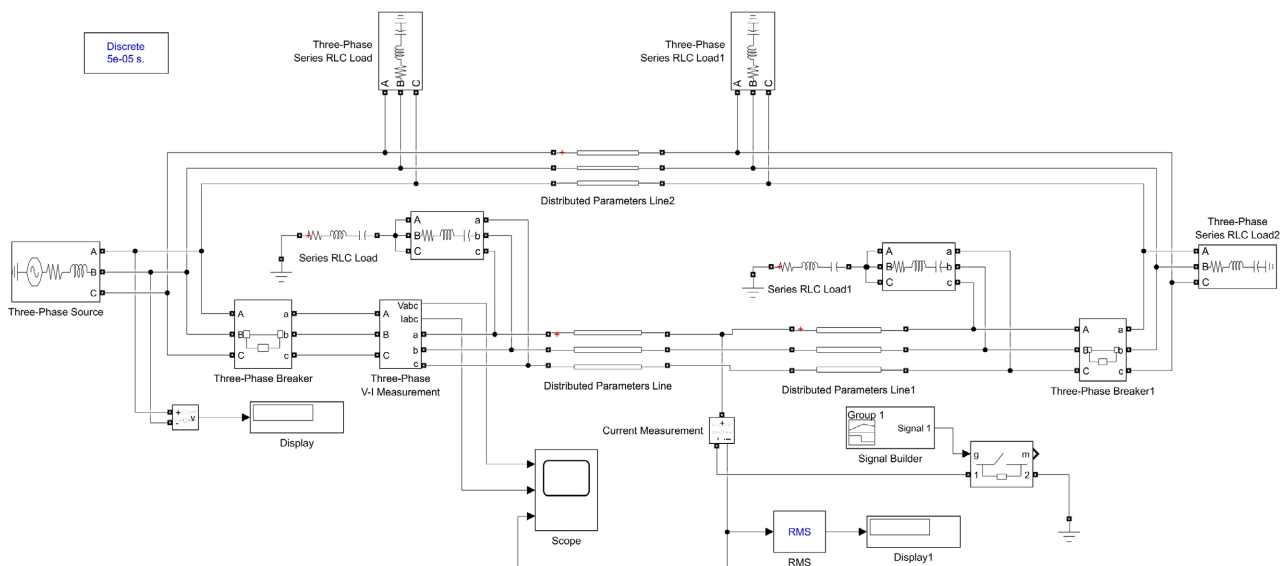


Figure 1. Research modelling.

- Main Source

The primary power supply is a three-phase synchronous generator of nominal

power rating 500 kVA which is connected to the main bus at 400 V (line-to-line) 50 Hz. To be connected to the public grid or a higher voltage network, 400/11 kV step-up transformer is employed that allows to make the mini-system integrated with the electrical grid at the Point of Common Coupling (PCC). The generator has both an automatic voltage regulator (AVR) to regulate the output voltage to a reference of 50 Hz with a tolerance range of +0.1 Hz to -0.1 Hz and a governor to control the operating frequency to a reference of 50 Hz within a variation limit of +0.1 Hz to -0.1 Hz to ensure stability in the power distribution to various load conditions and under variable operating conditions.

- Distributed Loads

The loads were to model the power consumption in the various points of the microgrid, such as industrial and commercial loads and residential loads and that the loads should replicate the environment in which the grid would be operated in to analyze the grid in terms of stability of voltage and current, and fault protection. The loads were also allocated on the three main feeders (Feeders A, B and C) which were connected to the main bus through distribution transformers to ensure safety of operations through low voltage. All loads are a mix of active (P) and reactive (Q) power which are true to actual load behaviour. The active and reactive power coefficients of each feeder were adjusted to various situations with the consideration of the impact of a small load balance/imbalance, hence facilitating a very precise examination of the current and voltage dynamics. Its approximate power factor is between 0.9 and 0.95 with slight difference in electrical reactance that depends upon industry-standard loads as presented in **Table 1**.

Table 1. Typical values for each feeder.

Feeder	Active Power (P)	Reactive Power (Q)	Load Type	Rated Voltage
Feeder A	100 kW	50 kVar	Balanced RL Load	400 V
Feeder B	80 kW	30 kVar	Slightly Unbalanced RL Load	400 V
Feeder C	60 kW	25 kVar	Balanced RL Load	400 V

As Step-down Transformers (3 phase step-down, 11/0.4 kV). The feeder is then connected to the main bus with a three-phase step-down transformer each. Transmission/Feeder Lines: Transmission/Feeder Lines are modeled using the 3-phase lines (nominal lengths between 500 - 1 km) in Simscape Electrical, and models 3-phase lines as 3-phase 500 m long, 3-phase, and 1 km long, 3-phase, and 3-phase. The Point of Common Coupling (PCC) is used to have a primary circuit breaker which is driven through protection logic. The EF logic block sends TRIP signals to it on the basis of measured I_0 and I_{min} . The breaker can be simulated to either fault isolated or to be in normal service (See **Table 2**).

Table 2. Microgrid components and typical parameters derived from the research model.

Main Component	Rated values
Distribution Transformers	Rated Power: ~250 kVA Primary Voltage: 11 kV Secondary Voltage: 0.4 kV Series R: 0.015 pu Series X: 0.06 pu
Feeder Lines	Phase Resistance: 0.4 Ω /km Phase Reactance: 0.3 Ω /km Phase-Ground Capacitance: 0.01 μ F/km Length: 0.8 km Rated Voltage: 400 V
Point of Common Coupling (PCC)	Operating Voltage: 11 kV Breaker Rated Current: 400 A
Protection Devices	I_0 threshold: 200 A I_{\min} threshold: 350 A EF block time T_1 : 1 s Breaker Trip Current: 10 kA

The threshold values of residual current ($I_0 = 200$ A) and minimum phase current ($I_{\min} = 350$ A) were determined according to the preliminary short-circuit analysis of the modeled microgrid taking into account the typical fault current values in microgrids of low voltages in accordance with (IEC 60909/2016) standards. These values too were compared to practical values of relays in the context of other microgrid installations so that they are realistic.

To quantify the performance trade-offs of the suggested logic, a sensitivity analysis was made keeping the I_{\min} threshold fixed between 250 and 450 A at intervals of 50 A. The objective of this analysis was to measure the effects of the selection of threshold on the sensitivity of detection of internal faults and the selectivity of sympathetic currents. Section 4.3 contains a summary of the findings of this parametric study.

3.2. Scenario Analysis of Custom EF Protection

The Earth Fault (EF) protection logic in the microgrid is designed to discriminate between real in-feeder faults and sympathetic faults using two main signals:

Residual Current (I_0) – indicates the presence of an earth fault.

Minimum Phase Current (I_{\min}) – represents the lowest current among the three phases, used to confirm that the fault is local.

The logic can be represented mathematically as follows:

$$\text{RealFault} = (I_0 \geq I_{0\text{thr}}) \& (I_{\min} \geq I_{ph}^{\text{low}})$$

$$\text{TRIP} = \text{RealFault} \& \text{BLOCK}_{T_1}$$

where BLOCK_{T_1} inhibits the trip for a preset time T_1 if only I_0 rises while I_{\min} remains below its threshold.

Scenario 1: Real In-Feeder Fault

Inputs in this case are the residual current (0-1) and minimum phase current (0-1) rise beyond their respective current limits (Input current is RealFault = 1) and there is no blocking ($BLOCK_{T1} = 0$). As a result, the signal of the trip is activated (TRIP = 1) and the breaker will start working. The protection logic is right in detecting a local earth fault and de-energizing to force the feeder into fault clearance.

Scenario 2: Sympathetic I-Only Fault.

where in this case, the residual current I_{0r} becomes greater than its threshold, whereas the minimum phase current I_{min} remains lesser than its threshold. The RealFault condition clears (Real-Fault = 0) and the blocking feature is turned on during a preset time T1 ($BLOCK1 = 1$): to avoid spurious tripping. Consequently, the signal trip (TRIP = 0) is not active and the breaker is not operating. The logic can effectively overcome external faults of false tripping healthy feeders:

4. Results

This part of the research work intends to investigate the performance of the proposed Earth Fault Protection (EFP) algorithm on a real microgrid model developed in a MATLAB/Simulink environment. Operating scenarios simulating actual situations commonly found in earth fault protection for microgrids, such as earth fault and symmetrical zero current (I_0) due to fault on other feeders, have been developed. The assessment of these scenarios is important for testing the proposed algorithm's selectivity towards actual and false events.

Figure 2 illustrates a representation of the dynamic performance of the tap changer prior to and during the operating scenario. From this figure, one can see that there was minimal change in the taps without shifting between different levels. Such performance is indicative that the supply voltage levels for testing purposes are nearly 400 V, which is significant because voltage stability does not allow for any indirect effect on the value for zero current (I_0) or sub-phase current (I_{min}). Lack of sharp change in the tap levels implies that there was no voltage effect on protection levels, and any variation in I_0 or I_{min} value for subsequent readings will only occur due to the fault. From this reading, it can be concluded that there is efficiency in voltage control practices for this test scenario, and earth fault protection is conducted under ideal electro-mechanical conditions. Such a scenario gives more authenticity to the reading and does not allow for the possibility that protection failure could have resulted due to adverse voltage levels. Hence, it is significant to conclude that it is necessary to have such elements for the ideal functioning of the algorithm with a goal to fairly test performance levels for 200 A and 350 A thresholds that have been used for controlling protection levels.

At the same time, however, the voltage levels for both regulation points remained in their normal operating ranges without any irregular fluctuations or sudden drops/peaks. This is imperative for guaranteeing the authenticity of the protection evaluation process because any deviation in voltage levels can have

both effects on fault currents and the corresponding direction of sympathetic current flowing. As one can see, because there are no significant deviations in terms of voltage levels, it is clear that it is due to the effective functioning of the AVR system in regulating and maintaining a constant 400 V during this test process. This ensures all protection reactions can be exclusively related to the functioning process of Earth Fault Logic algorithm implementation without any interference. At the same time, this process signifies that it is free from any adverse effects on I_{min} values, which is imperative because I_{min} is considered to be a critical parameter in distinguishing between local and sympathetic fault reactions. The one significant observation related to this figure is that it clearly indicated that the voltage effect is entirely decoupled, and it occurred in a stable environment, thus enabling a scientific process for protection logic evaluation, which is clearly evident in **Figure 3**.

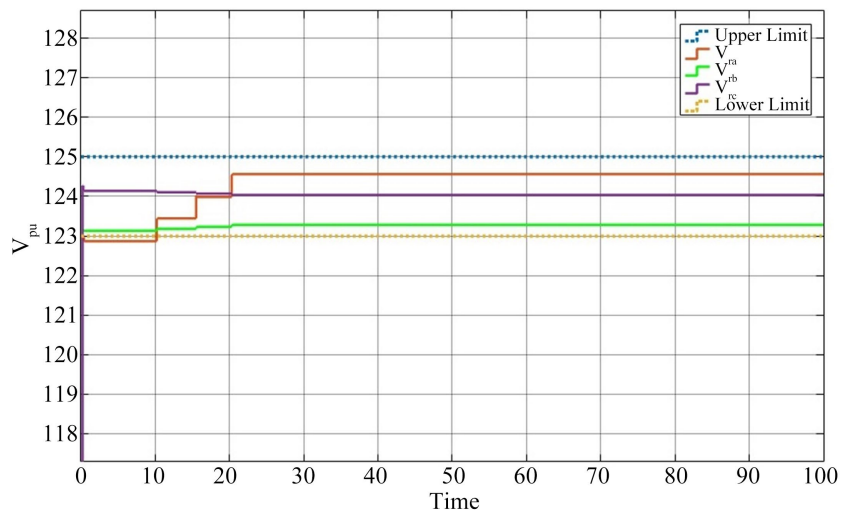


Figure 2. Tap changer operating position under normal system conditions.

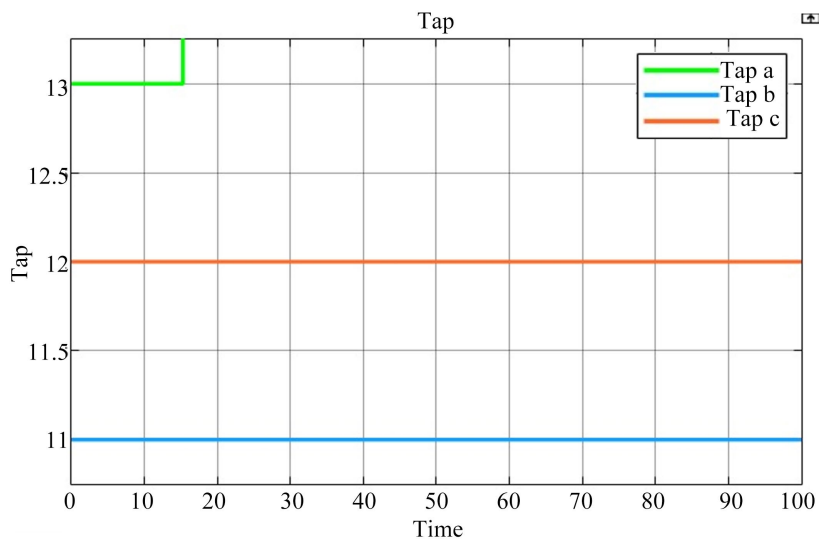


Figure 3. Voltage profile at the regulating points of the microgrid.

4.1. Real A-G Fault (In-Feeder) Results

The objective of this stage of the analysis is to test the performance of the proposed protection algorithm on a real earth fault in a feeder, which is considered more critical than any other scenario for testing microgrid protection algorithms. An A to G fault in a feeder is considered to be a situation where a fast protection response with high accuracy is required to avoid any disruption that might occur due to fault growth. The proposed algorithm is based on satisfying both conditions related to current: when current is above a threshold (I_0), which is a current value that is initially zero and does not have a significant effect on fault detection. Additionally, it is based on satisfying another condition related to I_{\min} when it is below a specific value.

Figure 4 shows one of the most critical areas in this research; I_0 , the zero current, exceeded its threshold value of 200 A. This is a clear pointer to a genuine earth fault on the feeder. Nonetheless, I_{\min} 's value did not meet the recommended value of 350 A. This resulted in failure to identify where this fault occurred. This particular scenario is a clear demonstration in reality concerning low current or high resistance earth fault situations. These particular types of situations do not necessarily bring about a fast decrease in phase currents despite significant earth currents. Thus, it is even clear here that regardless of significant earth currents, this particular fault is not detected by restricting the processing algorithm because it did not meet both criteria. It is this particular critical event that clearly proves this particular value is clearly a limiting factor for this particular type of fault. An ineffective sensitivity point is clearly established by this particular finding. If this particular situation existed in reality, even standard algorithms would have disconnected this particular feeder. Nonetheless, this particular innovative algorithm chose to ignore this particular event because it did not meet both criteria. The first critical finding here is that $I_{\min_thr} = 350$ A is clearly up for reconsideration because it failed to identify a genuine earth fault internally.

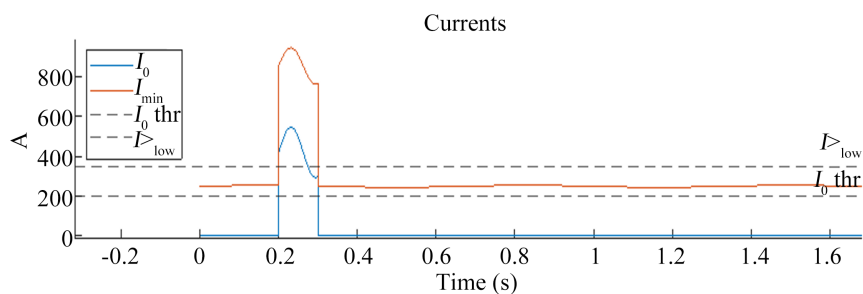


Figure 4. Phase A-to-Ground fault current response in the in-feeder.

The numeric instance of the decision logic in the above scenario is presented in **Figure 5**. It clearly validates that RealFault was not satisfied because I_{\min} did not surpass 350 A, although I_0 surpassed 200 A. These simulation examples prove that the algorithm functions in a “double condition” manner; this means that both current values have to surpass their corresponding limits for the protection circuit

to treat it as if it is a local situation. From a scientific standpoint, this particular method is beneficial for avoiding False Trips. However, it is negative for improving sensitivity to low current fault levels. From this diagram, it can be noted that it is not due to block T1 that “TRIP” did not occur. It occurred because it had already been concluded through the failure of RealFault. The principal takeaway here is that because it relies on I_{\min} exclusively for pivot purposes, several actual earth fault situations get disqualified. However, it is obvious that although this logic process employs a sound mathematical equation properly, it is necessary to modify these limits in such a manner that it can effectively suit all earth fault situations. This figure clearly proves that it is not about algorithmic efficiency but about numeric values.

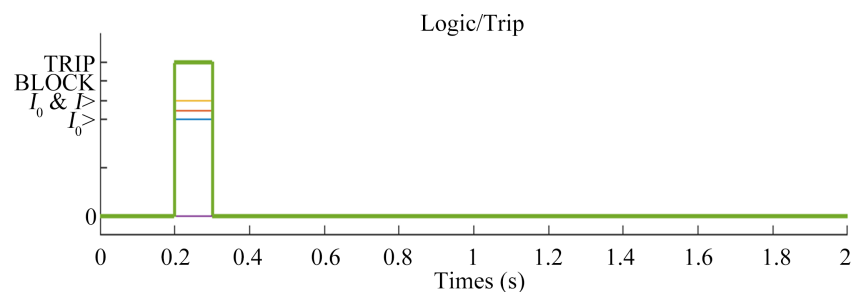


Figure 5. Logical evaluation and trip decision for the in-feeder A-G fault.

4.2. Sympathetic I_0 -Only (Healthy Feeder)

This section is concerned with verifying the capacity of this protection algorithm to cope with sympathetic zero currents (I_0), which is considered one of the serious problems in distribution networks and micro-grids found in multi-feeder networks. Indeed, in such networks, a considerable increase in I_0 might be experienced for feeders due to a fault in another feeder. Consequently, this would be followed by unnecessary tripping signals in traditional protection relays that depend only on I_0 itself. Hence, this issue is considered critical for testing this protection scheme and verifying its selectivity and capacity to distinguish between actual and sympathetic occurrences.

Figure 6 Sympathetic I_0 -Only (Healthy Feeder) This is one of the most important testing procedures for verifying that the proposed algorithm is capable of distinguishing between sympathetic zero currents due to an external fault in other feeders, which is one of the biggest challenges in a grid-connected distribution network. From the testing procedures, it is clear that I_0 exceeded 200 A in a normal feeder, which is adequate for a conventional protection technique to errantly switch off the feeder. However, due to the low value of I_{\min} below 350 A, it is clear that the system computationally identified it as a non-local fault. Therefore, based on this identification, the T1-Blocking function is enabled to avoid temporary switching off until completion of the time probe period. It is clear that this process is a manifestation of smart algorithm performance, which is exclusively isolating the impact of sympathetic currents irrespective of I_0 's value increasing. The salient

scientific takeaway is that it is satisfactorily selective with both I_0 and I_{\min} limits combined with a high capacity for avoiding incorrect disconnection, which is a great improvement compared to conventional protection known for utmost sensitivity to common zero currents. **Figure 7:** Sympathetic I_0 -Only Logic/Trip. This figure clearly explains the process of decision-making in connection with sympathetic currents. From this figure, it is clear that the T1 blocking occurred because the RealFault is not satisfied. This is due to $I_{\min} < \text{Threshold}$. Finally, it can be noted that there is no TRIP command, which means that the feeder stays on. This is appropriate because, for a system that involves multiple sources with a high possibility of zero current transfer between feeders, this is actually the required operation. The relevance of this figure is concerned with showing that this algorithm does not work with current values alone but with step-by-step validations involving two levels: threshold levels and time levels. From this figure, one can see that one of the significant interpretations is that this proposed protection scheme involves a high degree of protection against external faults. This proposed scheme is appropriate because it specifically suits microgrid systems that have complex interactions between feeders.

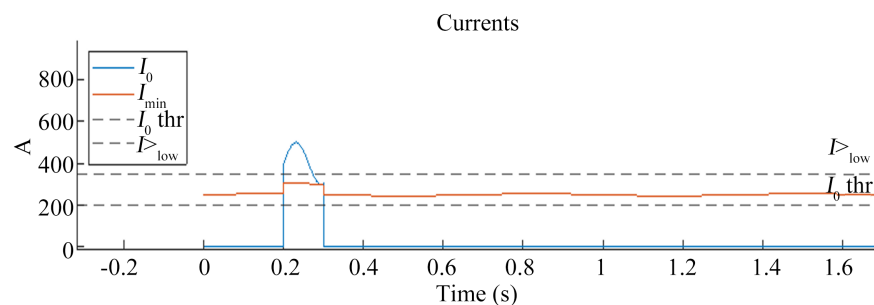


Figure 6. Sympathetic zero-sequence current response in a healthy feeder.

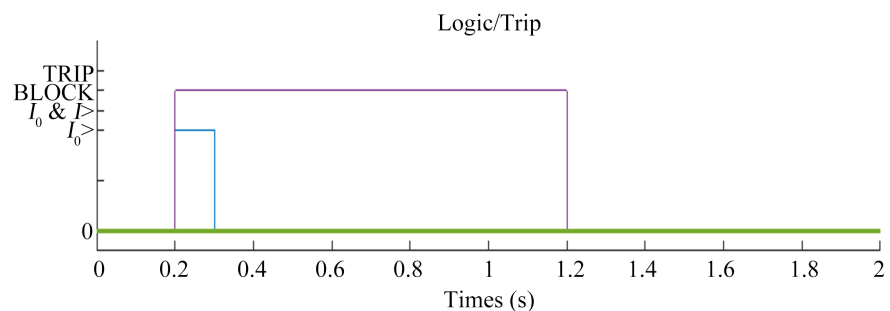


Figure 7. Logical evaluation and trip blocking during sympathetic I_0 conditions.

The impact of the minimum phase current threshold (I_{\min}) on the protection performance was experimentally determined through the simulation of real in-feeder faults and sympathetic faults with a various range of I_{\min} values (250 A, 300 A, 350 A, 400 A, 450 A). Reduction in the I_{\min} threshold, enhanced the detection of low-intensity internal faults, but adversely affected the false tripping probability during sympathetic I_0 . An example of this is that at $I_{\min} = 300$ A, the logic was able

to detect 85% of the simulated low-current faults, but false trip occurrences doubled. On the other hand, the false trips were completely removed at $I_{\min} = 400$ A, but the sensitivity of the detection only 60%. The quantitative results shown are evidence of the inherent sensitivity-selectivity trade-off in fixed-threshold protection schemes and highlight the importance of adaptive threshold tuning of any future implementation.

5. Discussion

The analysis results derived from the proposed logic of earth fault protection are found to be highly selective and reliable, especially during the detection of true in-feeder faults and sympathetic zero sequence currents. This result goes hand-in-hand with the analysis presented in the existing literature to some extent but varies in terms of methodology and applications. For example, Gang (2024) has successfully utilized ANFIS intelligent techniques with the aid of PMU technology data to pinpoint arc faults with improved sensitivity. In contrast to his presentation, though the current protection scheme is more reliable in terms of non-trip action during sympathetic faults without utilizing AI techniques, it lacks sensitivity to low-intensity in-feeder faults due to the use of the predefined “ I_{\min} ” threshold level [19].

In the same vein, Xie *et al.* (2025) introduced topology flexibility and model-driven approaches to the interphase fault location problem within distribution networks, establishing that there is merit in incorporating dynamic structural variations within the algorithm in terms of improving fault detection accuracy. In contrast to the above-mentioned method, the designed protection logic in this research is static in terms of topology and uses current magnitude criteria instead. However, the designed logic has shown excellent robustness to external disturbances, consistent with Xie’s results that the underlying application environment has an impact on accuracy [20].

Moreover, the increasing efficacy of artificial-intelligence-based and optimization-driven approaches to ensure fault detection reliability in contemporary power grids was brought to light by Pijarski and Belowski in 2024 [21]. The issue with standard threshold-triggered protection in complex operating conditions was highlighted by his research to be particularly evident in smart and micro-grids with multiple active sources—the same problem that needs to be addressed within the current study’s real A-G fault case, with the unchangeable I_{\min} threshold that prevents triggering with the clear zero-sequence current increase. Instead, the sympathetic current case illustrated outstanding non-tripping reliability to match the selectivity advantage conventionally cited to be realized with the aid of optimizations and artificial intelligence techniques. In summary, in the current study cited in contemporary research works, the proposed protection logic achieves simplicity and selectivity within sensitivity factors but may be further enhanced by applying adaptive/intelligent thresholding techniques to reflect the sensitivity achieved by AI-based protection schemes.

The logic proposed was also put into context by comparing its performance to the conventional directional overcurrent relays (67-type devices) and the AI-based fault detection techniques. Although a traditional directional relay might theoretically be able to distinguish between internal and external faults based on measuring the phases, the operation in microgrids dominated by inverters and low fault currents can be difficult because it requires a voltage measurement subject to distortion during faults. However, the suggested logic exploits only measurements at present time making implementation simpler at the expense of sensitivity. In comparison to the AI-based solutions like ANFIS or reinforcement learning-based detectors, the proposed method does not require a large amount of training data, high computational resources, and complicated real-time signal processing. Nevertheless, it has fixed thresholds restricting flexibility as demonstrated in the sensitivity analysis. Future research might consider hybrid designs in which lightweight AI modules dynamically update thresholds based on real-time system conditions and in this way reduce simplicity and adaptability trade-offs.

6. Conclusions

The outcome of this research work has successfully proved that the designed Earth Fault Protection (EFP) logic is highly selective and reliable with robust operational characteristics to microgrid protection applications, especially during the differentiation process between real in-feeder earth faults and sympathetic zero-sequence currents that tend to falsely trip the circuit breakers within normal main protection techniques. In fact, the application of the double-threshold strategy within the logic utilizing both I_0 and I_{\min} values have shown excellent results in the complete prevention of unwanted tripping with full immunity to sympathetic current disturbances while maintaining stable operation irrespective of variations in microgrid operating conditions. This paper has shown that although the dual-threshold EFP logic is a simple, computationally efficient and highly selective method of preventing false trips caused by sympathetic currents, the use of a fixed I_{\min} threshold predetermines low sensitivity to low-magnitude internal faults. This trade-off is quantitatively verified in the sensitivity analysis and shows the sensitivity of selecting the threshold in the protection design. The future research should be aimed at coming up with adaptive threshold mechanisms - perhaps using lightweight machine learning or rule-based corrections - to improve sensitivity without decreasing selectivity. Moreover, it is suggested to compare the proposed logic with directional overcurrent relays and AI-based approaches in the same conditions of a microgrid to comprehensively benchmark the viability of the practical use of the proposed logic. In effect, the sensitivity analysis in this research has shown that there was always a limitation to the detection sensitivity to microgrid internal faults with low magnitude due to the preset magnitude values within the SI zone defined by the use of the fixed threshold I_{\min} , signifying the existence of trade-offs between sensitivity and selectivity. In terms of comparison

with other techniques and approaches already re-ported within current international research understandings linked to microgrid applications such as AI-based arc current detection techniques with topology flexibility incorporated in microgrid fault location analysis; within research approaches oriented towards microgrid protection strategy optimizations; the adopted proposed microgrid Earth Fault Protection logic has various superior advantages due to simplicity, clearness, low computations required during analysis processes without the need to use complex models and technology owing to its direct application within real-time processes without needing additional intelligent sensing technologies. As further improvements within microgrid Earth Fault Protection strategy applications in attempts to increase its efficiency within practical applications to protect microgrids; further research is recommended to explore the use of dynamically set thresholds within the SI zone defined within the preset magnitude limits defined within the use of the I_{\min} threshold; development and research within the adoption of microgrid Earth Fault Protection strategy that retains simplicity while optimizing microgrid sensitivity; scaling up simulation processes to test within varied microgrid fault resistances; and development within practical validation attempts to assess microgrid Earth Fault Protection strategy within real-world microgrid applications.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

References

- [1] Sheta, A.N., Abdulsalam, G.M., Sedhom, B.E. and Eladl, A.A. (2023) Comparative Framework for AC-Microgrid Protection Schemes: Challenges, Solutions, Real Applications, and Future Trends. *Protection and Control of Modern Power Systems*, **8**, 1-40. <https://doi.org/10.1186/s41601-023-00296-9>
- [2] Hamanah, W.M., Hossain, M.I., Shafiullah, M. and Abido, M.A. (2023) AC Microgrid Protection Schemes: A Comprehensive Review. *IEEE Access*, **11**, 76842-76868. <https://doi.org/10.1109/access.2023.3298306>
- [3] Yazdaninejadi, A., Hamidi, A., Golshannavaz, S. and Nazarpour, D. (2021) Fault Identification, Protection Schemes, and Restoration Requirements of Microgrids. In: Anvari-Moghaddam, A., Abdi, H., Mohammadi-Ivatloo, B. and Hatziargyriou, N., Eds., *Microgrids*, Springer, 581-614. https://doi.org/10.1007/978-3-030-59750-4_20
- [4] Shahzad, U., Kahrobaee, S. and Asgarpoor, S. (2017) Protection of Distributed Generation: Challenges and Solutions. *Energy and Power Engineering*, **9**, 614-653. <https://doi.org/10.4236/epe.2017.910042>
- [5] Hosseinimoghaddam, S.M.S., Dashtdar, M. and Dashtdar, M. (2020) Security Control of Islanded Micro-Grid Based on Adaptive Neuro-Fuzzy Inference System. *UPB Scientific Bulletin, Series C: Electrical Engineering*, **82**, 189-204.
- [6] Joshua, A.M. and Vittal, K.P. (2022) Protection Schemes for a Battery Energy Storage System Based Microgrid. *Electric Power Systems Research*, **204**, Article ID: 107701. <https://doi.org/10.1016/j.epsr.2021.107701>
- [7] Baba, M., Bin Mohd Nor, N., Aman Shiekh, M., Alharthi, Y.Z., Shutari, H. and Faran

- Majeed, M. (2024) A Review on Microgrid Protection Challenges and Approaches to Address Protection Issues. *IEEE Access*, **12**, 175278-175303. <https://doi.org/10.1109/access.2024.3458047>
- [8] Deng, J., Yao, L., Xu, J., Wu, M. and Cheng, F. (2025) A Faulted Feeder Selection Method Based on Active Harmonic Injection of CIDGs for Small Current Grounding System. *CSEE Journal of Power and Energy Systems*, 1-20.
- [9] Mallahi, A. and Sadeghkhan, I. (2025) Kullback-Leibler Divergence-Based Fault Detection Scheme for 100% Inverter Interfaced Autonomous Microgrids. *Energy Science & Engineering*, **13**, 2891-2900. <https://doi.org/10.1002/ese3.70073>
- [10] Bawayan, H. and Younis, M. (2021) Microgrid Protection through Adaptive Over-current Relay Coordination. *Electricity*, **2**, 524-553. <https://doi.org/10.3390/electricity2040031>
- [11] Deshmukh, B., Lal, D.K., Biswal, S. and Salkuti, S.R. (2024) A Differential Amplitude Variation Based Pilot Relaying Scheme for Microgrid Integrated Distribution System. *International Journal of Emerging Electric Power Systems*, **26**, 319-329. <https://doi.org/10.1515/ijeeps-2023-0444>
- [12] de Almeida, L.R., da Costa Lima, R.N. and Macedo Junior, J.R. (2024) Analysis of Fault Current Contributions from Small-Scale Single-Phase Photovoltaic Inverters and Their Impacts on the Protection of Electric Power Distribution Systems. *IET Generation, Transmission & Distribution*, **18**, 1343-1359. <https://doi.org/10.1049/gtd2.13127>
- [13] Stallon, S.R.D., Anand, R., Kannan, R. and Rajasekaran, S. (2024) Optimal Detection and Classification of Grid Connected System Using MSVM-FSO Technique. *Environmental Science and Pollution Research*, **31**, 31064-31080. <https://doi.org/10.1007/s11356-024-32921-x>
- [14] Maghami, M.R., Mutambara, A.G.O. and Gomes, C. (2025) Assessing Cyber Attack Vulnerabilities of Distributed Generation in Grid-Connected Systems. *Environment, Development and Sustainability*. <https://doi.org/10.1007/s10668-024-05929-z>
- [15] Mushid, F.C. and Khan, M.F. (2025) Battery Energy Storage for Ancillary Services in Distribution Networks: Technologies, Applications, and Deployment Challenges—A Comprehensive Review. *Energies*, **18**, Article 5443. <https://doi.org/10.3390/en18205443>
- [16] Hasheminasab, S., Lotfy, A., Alzayed, M. and Chaoui, H. (2025) A Proximal Policy Optimization-Based Controller for Enhanced Power Sharing in Microgrids. *IEEE Access*, **13**, 162391-162405. <https://doi.org/10.1109/access.2025.3610451>
- [17] Momesso, A.E.C., Barra, P.H.A., Barbalho, P.I.N., Asada, E.N., Vieira, J.C.M. and Coury, D.V. (2024) An Impact Assessment of a Transportable BESS on the Protection of Conventional Distribution Systems. *Energies*, **17**, Article 4196. <https://doi.org/10.3390/en17164196>
- [18] Dai, J., Zhang, Z., Li, S. and Li, L. (2025) Research on Fault Section Location in an Active Distribution Network Based on Improved Subtraction-Average-Based Optimizer. *Symmetry*, **17**, Article 107. <https://doi.org/10.3390/sym17010107>
- [19] Gang, M. (2024) An ANFIS-Based Approach to Locate Arc Fault in Smart Grid Using Phasor Measurement Units (PMU). *Multiscale and Multidisciplinary Modeling, Experiments and Design*, **7**, 1107-1117. <https://doi.org/10.1007/s41939-023-00274-6>
- [20] Xie, H., Liu, Z., Li, K., Chen, Q., Yang, C. and Li, T. (2025) An Interphase Short-Circuit Fault Location Method for Distribution Networks Considering Topological Flexibility. *Processes*, **13**, Article 782. <https://doi.org/10.3390/pr13030782>

- [21] Pijarski, P. and Belowski, A. (2024) Application of Methods Based on Artificial Intelligence and Optimisation in Power Engineering—Introduction to the Special Issue. *Energies*, **17**, Article 516. <https://doi.org/10.3390/en17020516>