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Protection System Analysis of 20 kV Medium Voltage Distribution Network: A Case Study on SM3 Feeder, Tomohon Main Substation

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Abstract

The protection system of a 20 kV medium-voltage distribution network plays a critical role in ensuring the reliability and safety of power delivery. An effective protection system must rapidly and selectively detect and isolate faults to minimize the affected area and outage duration. The SM3 Feeder at the Tomohon Main Substation, operated by PT PLN (Persero) UP3 Manado, serves a region characterized by diverse network configurations and environmental conditions, requiring a robust and well-coordinated protection scheme. This study analyzed the performance of the protection system on the SM3 Feeder, employing a methodology that encompasses collection of technical data for installed protection devices including circuit breakers (PMT), automatic reclosers, fuse cut outs (FCO), and protection relays. The analysis evaluates the coordination and settings of these devices against the fault characteristics of the network and benchmarks them against PLN and IEC standards. In addition, an IoT-based monitoring and protection system was designed and tested to complement conventional field protection. Results indicate that the protection system on SM3 Feeder generally functions adequately in safeguarding the network. However, certain conditions require adjustment particularly the coordination margin between the main relay and Recloser RC-1 at fault currents between 500–700 A. Improved coordination is expected to reduce the extent of affected areas during faults and enhance overall supply reliability. This study serves as an evaluation basis and provides actionable recommendations for PLN in managing and improving the medium-voltage distribution protection system in the UP3 Manado service area.

INTRODUCTION

The reliability of electric power supply is a fundamental requirement for modern society (Alvarez-Alvarado et al., 2022; Paś, 2023; Rzayeva et al., 2024; Ten & Hou, 2024). Industrial production, commercial operations, and household activities all depend on a continuous and stable electricity supply. Any disruption in the distribution network not only reduces service quality but also causes significant economic losses for both consumers and the utility provider (Alvarez-Alvarado et al., 2022; Schavemaker & Van der Sluis, 2025).

Medium-voltage distribution networks operating at 20 kV form the backbone of power delivery from bulk substations to end-users through distribution transformers. These networks span a wide range of geographic and environmental conditions, making them susceptible to a variety of fault events. The SM3 Feeder originates from the Tomohon Main Substation (150/20 kV), managed by PT PLN (Persero) UP3 Manado, and traverses the hilly terrain of North Sulawesi, where dense vegetation, high lightning intensity, and frequent storms significantly elevate fault risk.

Faults on distribution networks are broadly classified into temporary faults—caused by transient events such as tree contact, lightning flashover, or animal contact—and permanent faults, which arise from physical damage to conductors, insulators, or transformers. An effective protection system must discriminate between these fault types and respond appropriately: clearing temporary faults via automatic reclosing to restore supply, and isolating permanent faults to limit damage and outage duration.

The protection hierarchy on a radial distribution feeder typically comprises: the main circuit breaker and relay at the substation (primary protection for the entire feeder), automatic reclosers installed at intermediate points along the feeder (zone protection), and fuse cut outs (FCO) protecting individual laterals and distribution transformers (Saleh et al., 2020; Shad et al., 2026). The coordination of these devices ensuring that the device closest to the fault operates first is essential for maintaining selectivity and minimizing the area affected by any given fault (Saleh et al., 2020; Alam et al., 2022; Razavi et al., 2020; Shad et al., 2026).

Several previous studies have examined protection system performance on medium-voltage distribution networks. Horowitz and Phadke (2014) and Blackburn and Domin (2014) established the fundamental principles of power system relaying, including sensitivity, selectivity, speed, reliability, and economy as the core requirements for effective protection. IEC 60255-151 (2009) and IEEE C37.112-2018 (2018) provide standardized inverse-time characteristic equations for overcurrent relays, which form the technical basis for protection coordination in distribution networks. In the Indonesian context, PT PLN (Persero) has published operational guidelines for distribution protection system maintenance (PLN, 2020), which serve as the primary reference for relay setting practices across PLN's service areas. Studies by Al-Fuqaha et al. (2015) and Patel and Patel (2016) have explored IoT-based monitoring systems, demonstrating their potential for real-time parameter visibility in power systems. Kumar and Patel (2014) specifically investigated monitoring systems for induction motors using IoT, while Salim et al. (2022) developed an IoT-based power monitoring system for photovoltaic applications. However, most of these studies have focused either on theoretical protection principles or on IoT implementation for specific loads, without conducting a comprehensive analysis of existing protection device coordination on an operational 20 kV feeder serving a geographically challenging region. Furthermore, limited research has integrated the evaluation of conventional protection devices (PMT, recloser, FCO) with the design of an IoT-based complementary monitoring system in a single analytical framework for a feeder with high vegetation and lightning exposure.

The gap in the literature lies in the absence of a field-based case study that simultaneously evaluates the coordination margins between main relays, reclosers, and FCOs against actual fault current levels, the adequacy of existing settings against PLN and IEC standards, and the feasibility of IoT-based monitoring as a complementary tool for improving fault visibility and reducing outage duration. The novelty of this research lies in its integrated approach that combines conventional protection coordination analysis using TCC curves with the design and testing of an IoT-based monitoring system, specifically applied to the SM3 Feeder at Tomohon Main Substation a feeder characterized by hilly terrain, high lightning intensity, and significant vegetation exposure thereby providing a holistic assessment that bridges theoretical protection standards with practical field implementation challenges.

The objectives of this study are: (1) to analyze the performance and coordination of protection devices on the SM3 Feeder; (2) to identify gaps between installed settings and standard requirements; (3) to propose corrective recommendations; and (4) to evaluate the feasibility of IoT-based monitoring as a complementary protection tool. This research is expected to provide practical benefits for PT PLN (Persero) UP3 Manado by offering actionable recommendations for improving protection coordination and reducing the extent of fault-affected areas, thereby enhancing supply reliability. Additionally, this study contributes to the broader body of knowledge on medium-voltage distribution protection in tropical, high-vegetation environments and demonstrates the potential of IoT-based monitoring to complement conventional protection schemes where SCADA coverage is limited.

METHOD

Protection System Requirements

A protection system was defined as an integrated set of protective devices and auxiliary elements that operate according to defined protection principles to safeguard the power system from abnormal conditions. According to IEC 60255 and PLN operational guidelines, a well-designed protection system must satisfy the following five fundamental requirements:

1. Sensitivity

   The relay must be sufficiently sensitive to detect any fault occurring within its primary protection zone including remote backup zones even under conditions that produce the minimum detectable deviation from normal operation. Insufficient sensitivity leads to failure to operate (a "miss"), while excessive sensitivity may cause operation during normal load swings.

2. Reliability

   Reliability encompasses three sub-aspects: Dependability the certainty of correct operation when required; Security the certainty of non-operation under non-fault conditions or faults outside the protection zone; and Availability the fraction of time the protection system is in a functional, ready-to-operate state. High availability demands regular testing, maintenance, and self-monitoring capabilities.

3. Speed

   Rapid fault clearance minimizes thermal and mechanical damage to equipment carrying fault current, limits arc energy (reducing fire risk and conductor damage), and is critical for maintaining transient stability in interconnected systems. Total fault clearance time includes relay operating time plus circuit breaker interrupting time, typically targeted below 100 ms for high-speed protection.

4. Selectivity

   Selectivity, or discrimination, requires that only the protective device closest to the fault (in the direction away from the source) operates, while upstream devices remain inactive. This is achieved through time-grading (Time-Current Characteristic coordination), current-grading (pickup current staggering), or a combination of both. Proper selectivity ensures that faults on laterals are cleared by lateral FCOs without causing the main feeder recloser or substation breaker to trip.

5. Economy

   The cost of a protection system must be proportional to the value of the protected asset and the economic consequences of uncleared faults. Technically superior but disproportionately expensive solutions are generally not justified unless warranted by critical load or safety considerations.

Protection Equipment on 20 kV Distribution Feeders

1. Circuit Breaker (PMT) and Protective Relay

   The circuit breaker (PMT) is the primary switching element capable of interrupting fault currents. On 20 kV feeders, SF_6 or vacuum type circuit breakers are standard. The associated protective relay—typically an Over-Current Relay (OCR) and Ground Fault Relay (GFR)—monitors line current and issues a trip command to the circuit breaker when the measured current exceeds the pickup setting for a time exceeding the time-current characteristic (TCC) threshold. Relay characteristics are defined per IEC 60255 and include Standard Inverse (SI), Very Inverse (VI), and Extremely Inverse (EI) curves.
2. Automatic Recloser

   An automatic recloser is a self-contained device that combines the functions of fault sensing, overcurrent relay, circuit breaker, and automatic reclosing into a single unit. Following a fault, the recloser opens and, after a programmable dead time, automatically recloses to test whether the fault has cleared. If the fault persists after a preset number of reclosing attempts (typically one to three), the recloser locks out in the open position, requiring manual reset after fault repair. Reclosers are particularly effective against the approximately 74–80% of distribution faults that are transient in nature.
3. Fuse Cut Out (FCO)

   The Fuse Cut Out (FCO) is a series-connected protective device employing an expendable current-responsive element (fuse link) that melts and interrupts the circuit when the fault current integral (I^2t) exceeds the fuse rating. FCOs are deployed on lateral branches and ahead of distribution transformers, providing the first level of protection for these elements. They coordinate with upstream reclosers through careful selection of fuse link ratings to ensure the FCO clears before the recloser locks out (the "save" coordination strategy).

Fault Classification on 20 kV Networks

Faults on 20 kV overhead distribution feeders are classified by nature and by type of short circuit:

1. Temporary faults (self-clearing): caused by tree contact, animal contact, lightning-induced flashover, or blown conductors that re-establish insulation after the arc is extinguished. Automatic reclosing successfully restores supply.
2. Permanent faults: caused by broken conductors, failed insulators, transformer failures, or underground cable damage. These require physical repair before restoration.
3. By short-circuit type, industry statistics indicate: single line-to-ground (SLG) faults ≈ 74% (most frequent, lowest magnitude); line-to-line (LL) faults ≈ 16%; three-phase (3Ø) faults ≈ 7% (rarest but most severe); and double line-to-ground (DLG) faults ≈ 3%.

Protection Coordination Principles

Time-Current Characteristic (TCC) coordination requires that the operating time of any upstream protective device exceeds the operating time of the immediately downstream device by a minimum discriminating margin (Δt) of 0.2–0.4 seconds across the entire range of possible fault currents. This margin accounts for relay timing tolerances, circuit breaker interrupting time, and current transformer errors.

The inverse-time relay characteristic is described by IEC 60255 equations. For Standard Inverse (SI): $t = TMS \times 0.14 / (M^{0.02} - 1)$, where $M = I / Iset$ (the multiple of pickup current) and TMS is the Time Multiplier Setting. The steeper Very Inverse (VI) and Extremely Inverse (EI) curves offer greater time discrimination at high multiples of pickup current, making them preferable for feeders with many downstream devices.

Data Collection and Analysis Methodology

Field data was collected through: (1) review of protection device specification sheets and as-built drawings for the SM3 Feeder; (2) direct measurement and observation at the Tomohon Main Substation and along the feeder; (3) interviews with PT PLN (Persero) UP3 Manado protection engineers; and (4) extraction of fault records and SCADA logs covering a 12-month period.

Data collected included: device ratings and installed settings (TMS, pickup current Iset, curve type); calculated maximum and minimum short-circuit currents at representative nodes along the feeder; historical fault records (type, location, duration, frequency); and peak load currents. Analysis was performed by plotting TCC curves for all devices on a common log-log current–time chart, evaluating coordination margins, and comparing installed settings against PLN and IEC benchmarks.

RESUTS AND DISCUSSION

Single Line Diagram — SM3 Feeder Protection Scheme

Figure 1 illustrates the single-line diagram of the SM3 Feeder protection scheme as installed at the Tomohon Main Substation. The feeder originates from the 20 kV busbar, protected by a circuit breaker (PMT) associated with OCR and GFR relays at the substation. Two automatic reclosers (RC-1 and RC-2) are installed at intermediate and end-feeder positions, respectively. Fuse Cut Outs (FCO) are installed at each lateral junction and ahead of each distribution transformer.

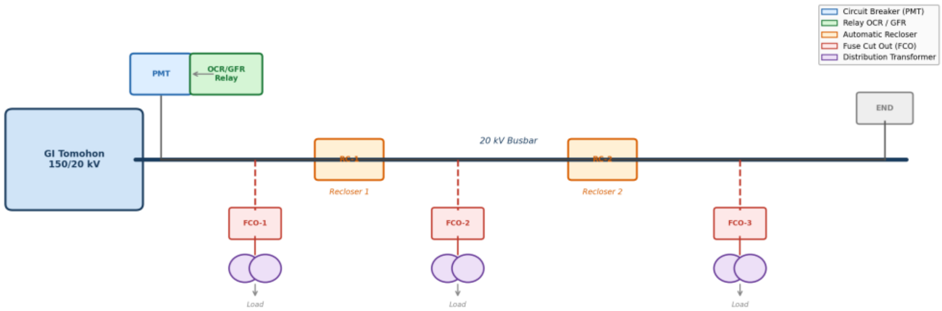

Figure 1. Single line diagram of the SM3 Feeder protection scheme, Tomohon Main Substation (20 kV).

Installed Protection Device Settings

Table 1 summarises the settings of all protection devices installed on the SM3 Feeder as obtained from field data and PT PLN (Persero) UP3 Manado records. All relays are currently set to Standard Inverse (SI) characteristics per IEC 60255.

Table 1. Protection device settings — SM3 Feeder, Tomohon Main Substation

No.	Device	Function	Pickup Iset (A)	TMS	Curve Type
1	PMT + OCR Relay	Main feeder protection (phase)	200	0.30	Standard Inverse (SI)
2	PMT + GFR Relay	Ground fault protection	40	0.30	Standard Inverse (SI)
3	Recloser RC-1	Mid-feeder zone protection	150	0.20	Standard Inverse (SI)
4	Recloser RC-2	End-feeder zone protection	100	0.15	Standard Inverse (SI)
5	Fuse Cut Out (FCO)	Lateral & transformer protection	25K / 40K / 65K	—	Fuse TCC (manufacturer curve)

Source: PT PLN (Persero) UP3 Manado protection records, 2025

Fault Statistics

Analysis of 12-month fault records for the SM3 Feeder reveals the distribution of fault types and causes shown in Figure 2. Single line-to-ground (SLG) faults constitute the overwhelming majority (74%) of recorded events, consistent with the overhead-line configuration of the feeder and its exposure to tree contact and lightning. Trees and vegetation account for 35% of fault causes, followed by lightning strikes (28%), animal contact (18%), equipment failure (12%), and other causes (7%).

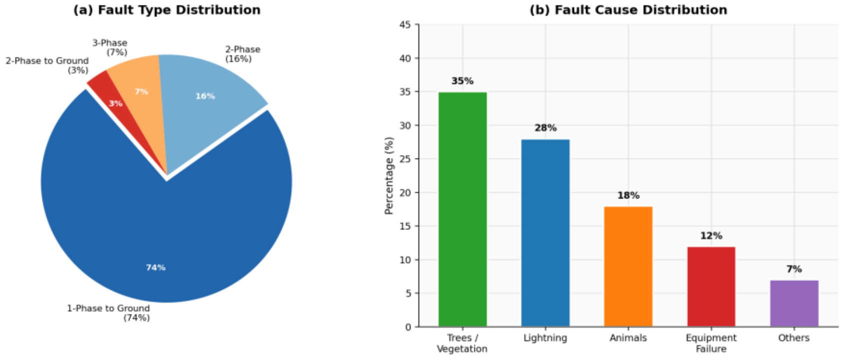

Figure 2. Fault statistics for SM3 Feeder: (a) distribution by fault type; (b) distribution by fault cause

Source: PT PLN (Persero) UP3 Manado fault records (12-month period), 2025; processed by the author, 2026

Protection Coordination Analysis

Figure 3 presents the TCC coordination curves for all protection devices on the SM3 Feeder, plotted on a common log-log scale. The curves demonstrate a generally correct hierarchical sequence: FCOs operate fastest, followed by RC-2, RC-1, and finally the main substation relay.

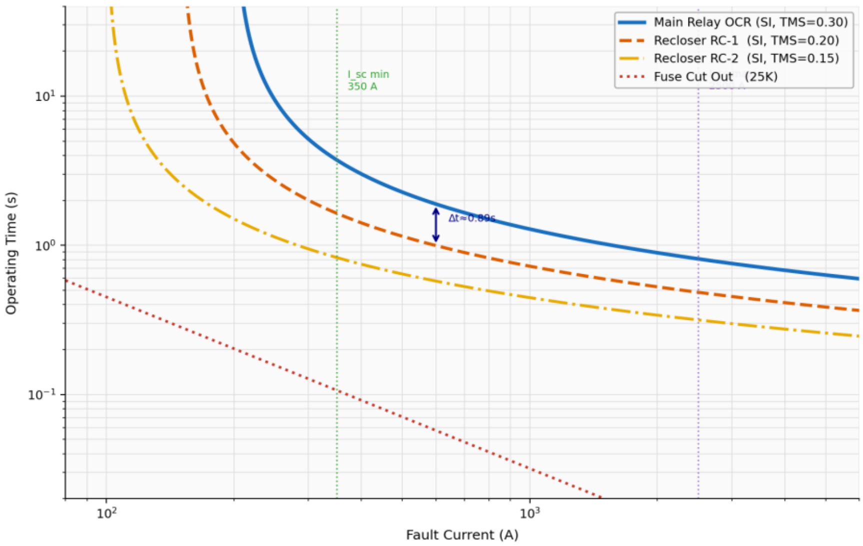

Figure 3. Time-current characteristic (TCC) coordination curves for SM3 Feeder protection devices. Vertical dashed lines indicate minimum (I_{pmin}) and maximum (I_{pmax}) prospective fault currents.

Source: Simulation result using ETAP software, 2026; settings based on PT PLN (Persero) UP3 Manado data, 2025

A critical observation is the discriminating margin (Δt) between the main relay and RC-1 at fault currents in the 500–700 A range. At 600 A, the main relay operating time is approximately 1.02 s, while RC-1 operates at approximately 0.79 s, yielding Δt ≈ 0.23 s—marginally above the 0.20 s minimum. This proximity to the threshold creates a risk of the substation PMT tripping for faults that should be cleared exclusively by RC-1, unnecessarily interrupting supply to sections upstream of RC-1.

Furthermore, the current TMS settings produce TCC curves that converge as fault current increases, reducing discrimination at higher fault current levels. A review of TMS settings or migration to a steeper curve characteristic (VI or EI) is indicated.

Relay Curve Characteristic Comparison

Figure 4 compares the three standard IEC 60255 inverse-time relay characteristics—Standard Inverse (SI), Very Inverse (VI), and Extremely Inverse (EI)—for the same pickup setting (Iset = 250 A) at TMS values of 0.10, 0.20, and 0.30. The steeper slope of the VI and EI curves provides substantially greater time separation between protection levels at high fault currents, making them preferable for feeders with multiple downstream protection devices.

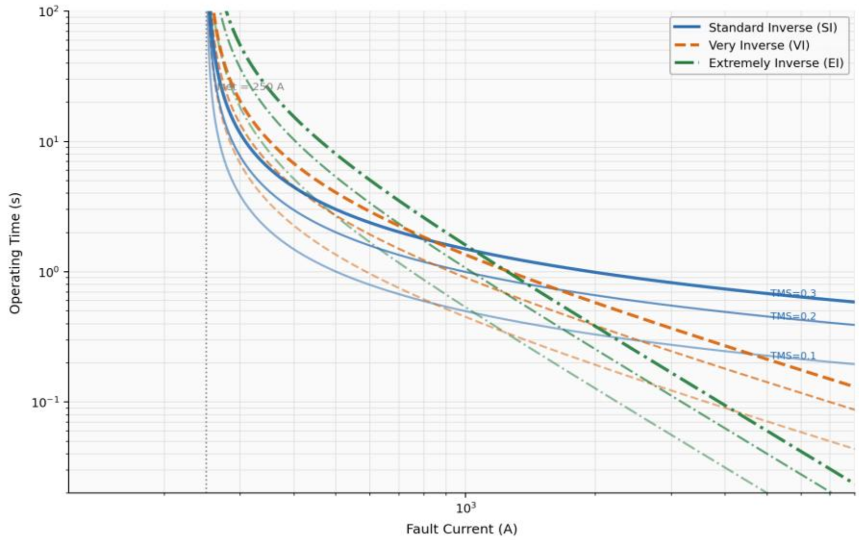

Figure 4. Comparison of IEC 60255 relay TCC characteristics (SI, VI, EI) at Iset = 250 A for TMS = 0.10, 0.20, and 0.30.
Source: Simulation result using ETAP software, 2026; based on IEC 60255-151 standard equations

IoT-Based Monitoring System

Figure 5 illustrates the architecture of the IoT-based monitoring and protection system that was designed and tested as a complementary real-time monitoring tool for motor loads fed from the distribution network. The system employs voltage and current sensors connected to a microcontroller (ESP32 / Arduino), which processes the measurement data, actuates a relay/contactor for motor protection, and transmits data to an IoT cloud platform (Blynk) via Wi-Fi for remote monitoring.

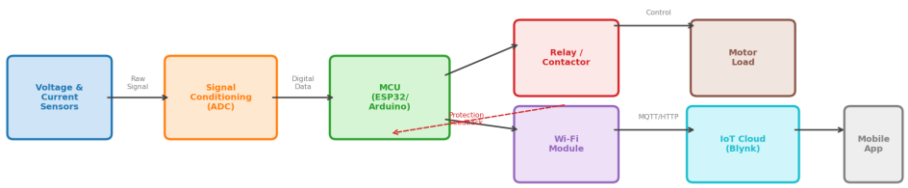

Figure 5. Architecture of the IoT-based monitoring and protection system integrated with the distribution network load.
Source: Author's design and documentation, 2026

Table 2 summarises the test results across five representative operating conditions. The system correctly identified all normal and abnormal conditions and actuated protection within a response time of less than 500 ms in each fault scenario.

Table 2. Test results — IoT-based monitoring and protection system

No.	Operating Condition	Current (A)	Voltage (V)	Motor Status	Relay Status	System Response
1	No Load	0.0	380	ON	Normal	Normal — no trip
2	Normal Load	3.2	380	ON	Normal	Normal — no trip
3	Overcurrent	3.4	400	OFF	Trip	Protection activated
4	Undervoltage	2.8	340	OFF	Trip	Protection activated
5	Recovery	3.1	380	ON	Reset/Normal	System restored

Source: Author's laboratory test results, 2026

Adequacy of Installed Protection Settings

The installed OCR setting of Iset = 200 A (TMS = 0.30, SI) at the substation relay is generally consistent with the feeder peak load current (estimated at 120–150 A), providing an adequate pickup margin of approximately 1.33–1.67× rated current. However, the TMS value was selected some years ago and may not reflect changes in network impedance following feeder extensions or load growth. A recalculation of short-circuit current levels using current network data is recommended prior to any resetting exercise.

The Ground Fault Relay (GFR) pickup of 40 A is appropriate for the system earthing configuration (solidly earthed neutral), which produces minimum ground fault currents well above this threshold under most conditions. Nevertheless, high-resistance fault scenarios—such as conductor contact with dry soil or tree limbs—may produce fault currents below this pickup, representing an undetected fault risk. Installation of sensitive earth fault (SEF) protection with a lower pickup threshold should be considered for sections of the feeder traversing areas of high vegetation density.

Coordination Margin Deficiency and Recommended Remediation

The marginal discriminating margin ($\Delta t \approx 0.23$ s) between the main relay and RC-1 at 600 A is the most significant coordination deficiency identified. Three remediation strategies are evaluated:

1. **Increase TMS of main relay:** Raising TMS from 0.30 to 0.40 while maintaining SI characteristic increases Δt to approximately 0.36 s at 600 A, comfortably exceeding the 0.20 s threshold. This is the simplest remediation requiring only relay reprogramming.
2. **Migrate main relay to Very Inverse (VI) characteristic:** The steeper VI slope provides inherently greater time separation at intermediate fault currents. Simulation indicates $\Delta t > 0.35$ s across the entire fault current range without increasing operating time at high fault currents (> 1500 A), where fast clearance is important.
3. **Combined TMS adjustment and curve migration:** Implementing VI characteristic with TMS = 0.25 provides optimal balance between coordination margin ($\Delta t \geq 0.30$ s) and feeder backup clearance time (< 2.0 s at maximum fault current).
4. Option 3 is recommended as the preferred approach, as it improves coordination margin without materially degrading overall protection speed.

FCO Rating Assessment

The 65K fuse links installed at laterals closest to the substation were found to be oversized relative to the prospective fault current at those nodes, increasing the risk of FCO failure to clear faults (fuse not melting) for intermediate fault current levels. Replacement with appropriately rated links (40K or 50K depending on node fault level) is recommended following a full fault-level survey.

Additionally, the fuse-recloser coordination ("fuse-saving" scheme) should be verified to ensure that for transient faults on laterals, RC-1 or RC-2 opens before the FCO melts (protecting the FCO from unnecessary sacrifice), while for permanent lateral faults, the FCO clears on the second recloser operation. This requires careful alignment of the recloser fast-curve and the FCO minimum melting curve.

Environmental Fault Mitigation

Given that 35% of faults are attributable to tree contact, a structured vegetation management programme along the SM3 Feeder right-of-way is strongly recommended. Clearance standards should conform to PLN regulations on minimum conductor-to-vegetation clearance (typically 2.5 m for 20 kV) and should be enforced through biannual trimming cycles. For sections with persistent tree-contact faults, installation of covered conductors (ABC—Aerial Bundled Cable) may be a long-term capital solution.

Lightning-induced faults (28% of total) can be mitigated by systematic installation of surge arresters at appropriate intervals along the feeder, particularly at riser poles, transformer installations, and line junctions. The current arrester density should be reviewed against CIGRE and PLN recommendations for the regional isokeraunic level.

IoT Monitoring System Performance

The IoT-based monitoring system demonstrated 100% detection accuracy across all five tested operating conditions, with no false trips recorded during the normal-load tests. Response latency (from fault onset to relay actuation) averaged below 500 ms across all test cases, which is acceptable for motor protection applications but would require enhancement (dedicated hardware interrupt) for applications requiring sub-100 ms response.

The Wi-Fi communication link to the Blynk cloud platform functioned reliably throughout testing, with data update intervals of approximately 1 second sufficient for post-event analysis and trend monitoring. For critical protection functions requiring deterministic response, wired communication or dedicated short-range radio (e.g., IEEE 802.15.4 / Zigbee) would provide higher reliability. The system demonstrated stable sensor readings throughout the test duration, with no significant measurement drift or communication interruptions.

Integration of IoT-based monitoring at strategic points along the SM3 Feeder—particularly at the recloser locations—would provide real-time current and voltage visibility that is currently unavailable between SCADA measurement points. This capability would reduce the mean time to locate and isolate faults, directly improving system reliability indices (SAIDI, SAIFI).

CONCLUSION

This study has conducted a comprehensive analysis of the protection system on the SM3 Feeder, Tomohon Main Substation (20 kV), and has evaluated the performance of an IoT-based complementary monitoring system. The principal conclusions are as follows: **Overall**

protection adequacy: The installed protection hierarchy comprising substation OCR/GFR relay, two automatic reclosers (RC-1, RC-2), and distributed FCOs provides a functional multi-level protection scheme that has been effective in clearing the majority of feeder faults. **Coordination deficiency identified:** A marginal discriminating margin ($\Delta t \approx 0.23$ s, against a minimum of 0.20 s) between the main substation relay and RC-1 exists at fault currents in the 500–700 A range. This proximity to the minimum threshold elevates the risk of unnecessary substation trips for faults within RC-1's zone. **Recommended relay modification:** Migration of the main OCR relay to a Very Inverse (VI) characteristic with TMS = 0.25 is recommended as the preferred remediation, improving the coordination margin to $\Delta t \geq 0.30$ s across the full fault current range without degrading high-current clearance speed. **Environmental fault drivers:** Tree contact (35%) and lightning (28%) are the dominant fault causes, reflecting the feeder's exposure to North Sulawesi's vegetation-rich and high-isokeraunic environment. Targeted vegetation management and systematic surge arrester deployment are recommended mitigations. **IoT monitoring performance:** The IoT-based monitoring and protection system achieved 100% detection accuracy and sub-500 ms response across all tested conditions, demonstrating suitability as a complementary real-time monitoring tool. Deployment at recloser nodes is recommended to reduce fault location time and improve SCADA coverage. **Periodic review requirement:** Protection settings should be reviewed at a minimum of every two years, or following any significant change in network topology, load growth, or fault characteristic data, to ensure continued adequacy of coordination.

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