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Analysis of 20 kV Underground Cable Network Implementation on SM3 Feeder, Tomohon Main Substation

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Abstract

The continuous growth of electricity demand requires a reliable and efficient distribution system. The SM3 Feeder at the Tomohon Main Substation (GI Tomohon), managed by PT PLN (Persero) UP3 Manado, is a critical medium-voltage distribution network serving the Tomohon city centre area. The feeder currently employs overhead aerial conductors that are vulnerable to environmental disturbances such as extreme weather, strong winds, lightning, and vegetation contact, which leads to frequent outages and reduced supply quality. This study investigates the implementation of a 20 kV underground cable network on the SM3 Feeder as a strategy to improve system reliability. The methodology encompasses field surveys, technical data collection, and comparative performance analysis of the distribution system before and after underground cable implementation. Quantitative analysis was applied to evaluate technical parameters including fault frequency, and the reliability indices SAIDI and SAIFI, while qualitative analysis is used to assess the practical advantages and constraints observed during field implementation. Results demonstrate that underground cable implementation significantly reduces environmentally induced faults, providing improvements in safety, system reliability, and urban aesthetics. Although capital investment and installation costs are considerably higher than those of overhead networks, the long-term operational benefits including substantial reduction in fault frequency, improved supply continuity, and longer service life justify the investment. Underground cable networks are thus confirmed as an effective solution for enhancing power distribution quality and reliability, particularly in urban areas with high fault incidence.

INTRODUCTION

The continuous growth of electricity demand, driven by population growth, urbanisation, and industrial expansion, requires distribution networks that are reliable, efficient, and safe. Medium-voltage (MV) distribution networks operating at 20 kV form the primary link between transmission substations and end-users, and their reliability directly determines the quality of power supply experienced by consumers (Bindi et al., 2023; Buhari, 2016; Guillén-López et al., 2024; Osunde, 2022; Salanga et al., 2025).

In Indonesia, medium-voltage distribution infrastructure predominantly consists of Overhead Medium-Voltage Lines *SUTM (Saluran Udara Tegangan Menengah*) mounted on poles along public roads. While SUTM requires lower initial capital investment, it is inherently susceptible to environmental disturbances, including strong winds, heavy rainfall, lightning strikes, and vegetation contact (Akbar et al., 2024; Ilango, 2025; Ismail, 2017). These events result in both temporary and permanent faults that cause outages, reduce service quality, and impose economic costs on both the utility and consumers (Ghodeswar et al., 2025; Sanstad et al., 2020).

The SM3 Feeder at the Tomohon Main Substation (GI Tomohon), operated by PT PLN (Persero) UP3 Manado, serves the central commercial and civic district of Tomohon City in North Sulawesi Province. The feeder's route traverses areas of dense vegetation and is exposed to the high lightning intensity characteristic of the region, resulting in a fault rate above the national average (Dube & Letsatsi, n.d.; Panteli & Mancarella, 2015). Given the critical nature of the loads supplied including commercial establishments, government offices, and public service facilities improving feeder reliability is a priority (Adesina et al., 2024; Afzali et al., 2019; Moradi-Sarvestani et al., 2024).

Underground cable networks, known as *SKTM (Saluran Kabel Tegangan Menengah)*, offer a technically superior alternative to overhead lines for urban environments. By routing conductors beneath the ground surface, *SKTM* eliminates exposure to aerial environmental hazards, improves public safety, and enhances the aesthetic quality of urban streetscapes (Agustan et al., 2025; Bawono, 2020). The principal barrier to widespread adoption is the significantly higher capital cost of underground installation compared to overhead construction (Dadzie et al., 2018; Maruvanchery et al., 2020; Sadeghi et al., 2022).

The urgency of this research is driven by three factors. First, PT PLN is under regulatory pressure to continuously improve SAIDI and SAIFI indices as part of its public service obligation. Second, the financial impact of frequent outages on commercial customers in Tomohon city centre is substantial, creating demand-side pressure for improved reliability. Third, the recent availability of N2XSY cable specifications aligned with international standards (IEC 60502) enables a technically robust implementation that was not feasible a decade ago. Therefore, documenting and analyzing this implementation provides timely guidance for similar projects across eastern Indonesia.

The novelty of this research lies in three specific contributions. First, it provides a detailed, segment-by-segment documentation of *SKTM* construction methods applied to a live 20 kV feeder in an active urban environment, categorized by terrain type (open ground, pedestrian pathways, and highway crossings using horizontal boring). Second, it presents a comparative analysis of pre- and post-implementation reliability indices (SAIDI, SAIFI, ENS) using actual field data from a 12-month period. Third, it provides a practical technical and economic feasibility assessment that incorporates local constraints including subsurface infrastructure conflicts, workforce skill gaps for fault location, and thermal management in volcanic soil conditions. This differs from previous studies that focused on simulation or theoretical calculations rather than real implementation data.

This study aims to: (1) analyse the existing fault characteristics and reliability performance of the SM3 Feeder; (2) document the technical implementation of the underground cable network on the feeder; (3) document the *SKTM* construction methods applied to each type of terrain in the SM3 Feeder line, including the selection of cables based on KHA calculations; and (4) assess the technical and economic feasibility of underground cable deployment as a reliability improvement strategy.

RESEARCH METHODOLOGY

A. Research Design

This study employed a descriptive research design with a combined quantitative and qualitative approach. The quantitative component involves collection and analysis of technical data including fault records, conductor and cable specifications, and measured reliability indices to evaluate the performance impact of underground cable implementation. The qualitative component involves field observation and structured interviews with PT PLN (Persero) UP3 Manado protection and network engineers to characterise implementation constraints, operational challenges, and maintenance requirements.

B. Problem Identification

The reliability problem on the SM3 Feeder was identified through analysis of 12-month historical fault records provided by PT PLN (Persero) UP3 Manado. The records document each fault event by date, time, duration, fault type, affected section, number of customers interrupted, and cause. The analysis confirmed that the majority of faults originated from overhead line exposure to the environment, with tree contact and lightning constituting the dominant causes.

In addition to fault frequency, the feeder's physical condition was assessed through field surveys, including visual inspection of poles, conductors, insulators, and pole-mounted equipment. Areas with the highest fault density were mapped as priority candidates for underground cable replacement.

C. Installation and Maintenance Constraints

The installation of underground cable on the SM3 Feeder presented several technical and logistical challenges. The trenching route traversed the urban core of Tomohon City, where underground infrastructure including water mains, drainage channels, and telecommunications ducts created coordination requirements with multiple stakeholders. Minimum trench depth for 20 kV cable per PLN construction standards is 600 mm, with a sand bedding layer and a warning tape installed above the cable.

Fault location on underground cables requires specialised instruments, principally the Time Domain Reflectometer (TDR) and the Murray Loop Test set, which send a signal or current pulse along the cable and measure the time or impedance of the reflection to calculate the distance to the fault. This is fundamentally different from overhead line fault location, which is often accomplished by visual inspection, and necessitates a higher level of technical skill and equipment availability.

D. Data Collection

Data collected for this study includes: (1) feeder network data conductor type, cross-section, total length, number and capacity of distribution transformers; (2) network component inventory number of poles, substations, switching points, and line section switches; (3) fault history event date and time, fault type, restoration duration, cause, and number of customers affected, covering a 12-month pre-implementation period; and (4) post-implementation fault records covering the first 12 months of underground cable operation, used to compute post-implementation reliability indices.

RESULTS AND DISCUSSION

A. SM3 Feeder Technical Data

The SM3 Feeder supplies eleven distribution substations distributed across the Tomohon City centre. Table 1 presents the complete list of substations together with the installed transformer capacity at each point.

Table 1. Distribution Substations on the SM3 Feeder, Tomohon Main Substation

No.	Feeder Name	Substation Name	Transformer Capacity (kVA)
1	SM3	Wuling / Suzuki Kakaskasen	50
2	SM3	Kakaskasen 2 – Tax Office Front	50
3	SM3	Ukit	200
4	SM3	Beside PLN Office	100
5	SM3	Thales	200
6	SM3	KFC	100
7	SM3	Bank BNI	200
8	SM3	Grand Central	160
9	SM3	Modern Fashion	200
10	SM3	Pizza Hut	100
11	SM3	Matani	400

The total installed transformer capacity on the SM3 Feeder is 1,560 kVA, served by 11 distribution substations. The highest single-unit capacity is the Matani substation at 400 kVA, supplying industrial and commercial loads in that district. The conductor characteristics of the network are summarised in Table 2.

Table 2. SM3 Feeder Conductor Data

Network Type	Total Length (m)	Conductor Used
Medium Voltage Network	2,758	A3CS
Low Voltage Network	2,758	NFAAX

Both the medium-voltage and low-voltage sections of the feeder have a total length of 2,758 m. The MV network uses A3CS conductor and the LV network uses NFAAX, both of which are XLPE-insulated aluminium conductors appropriate for underground service. The full network component inventory is presented in Table 3.

Table 3. SM3 Feeder Network Component Inventory

No.	Network Component	Quantity
1	Low-Voltage Support Poles (excluding poles at substations)	73
2	Total Distribution Substations	11
3	Cantol Substations (pole-mounted)	2
4	Portal Substations	7
5	Concrete (kiosk) Substations	2
6	Branching Points	23
7	Load Break Switch (LBS)	1

The feeder network incorporates 73 low-voltage support poles, 11 distribution substations of three construction types (cantol, portal, and concrete kiosk), 23 branching points, and one Load Break Switch (LBS). The LBS provides a means to sectionalize the feeder for fault isolation and load transfer operations.

B. Comparative Analysis: Overhead vs. Underground Networks

The selection between overhead distribution (SUTM) and underground cable (*SKTM*) involves a multi-criteria technical and economic assessment. Table 4 presents a systematic comparison of the two network types across the key evaluation dimensions applicable to the SM3 Feeder context.

Table 4. Comparative Analysis of Overhead (SUTM) and Underground Cable (*SKTM*) Networks

Aspect	Overhead Line (SUTM)	Underground Cable (*SKTM*)
Fault Resistance	Vulnerable to weather, wind, and tree contact	Highly resistant to environmental disturbances
Safety	Higher risk of accidents	Lower risk of accidents for public and workers
Urban Aesthetics	Cables visible, less aesthetic	Underground, clean appearance
Installation Cost	Lower initial investment	3–5× higher initial investment
Maintenance Access	Easy, direct access	Requires excavation, more complex
Service Life	±20 years	±30–40 years
Power Losses	Higher (corona losses)	Lower overall losses
Fault Location	Visual inspection possible	Requires TDR or Murray Loop Test equipment

As shown in Table 4, underground cable networks are technically superior to overhead lines in all reliability- and safety-related dimensions: they are inherently immune to environmental faults (tree contact, lightning-induced flashover, wind-driven conductor clashing, and animal contact), eliminate the risk of live conductor exposure to the public, and remove the visual intrusion of overhead infrastructure from the urban environment. Their principal disadvantages higher installation cost and more complex fault location procedures are manageable through appropriate capital planning and workforce training.

C. Implementation of *SKTM* Construction on SM3 Feeder

The physical implementation of the ground cable network at the SM3 Feeder was carried out following the standard construction method of PT PLN (Persero) which was adjusted to the type of terrain on each segment of the feeder line along 2,758 m. Each segment of the path requires a different construction approach according to the surface conditions and land allocation travelled, including park/open land areas, sidewalks and environmental roads, and highway crossings.

1. Implementation of Excavation and Cable Installation

On segments that pass through open ground and gardens, excavation is carried out with a minimum depth of 80 cm to 100 cm depending on the number of cables installed. Before the cable is laid, the excavation base is coated with sand 10 cm thick. After the cable is installed, it is covered with a concrete slab marked PLN 20 kV 6 cm thick as mechanical protection. In the segments under sidewalks and neighbourhood roads, the depth of excavation was increased to 150 cm for 1–4 cables and 170 cm for 5 or more cables, in anticipation of the pressure of traffic loads on the surface. All excavations on the environmental road were resurfaced with sand to prevent cable deformation due to dynamic loads, and the road surface was returned to its original condition. At highway crossing points, excavation is carried out by the horizontal boring method using a drilling machine to avoid cutting asphalt. As soon as the drilling work is completed, iron pipes with a diameter of at least 6 inches are installed as a cable protection sheath on the crossing path.

2. Selection of TM Ground Cable Conveyor – Type N2XSY

The stage of determining the type and size of the conductor is carried out based on the calculation of cable size and cable length according to the results of distance measurement and customer growth calculation for the next 5 years. For the planning of this SM3 Feeder, the type of Ground Cable Channel used is type N2XSY with a working voltage of 3.6/6 (7.2) kV, which meets IEC 60502 and SPLN 43-5 standards. N2XSY type cables consist of copper conductors, XLPE (Cross-Linked Polyethylene) insulation, semi-conductive coating, copper wire/tape shielding, polyester tape, and PVC outer sheath. This combination of materials provides good mechanical protection, adequate electrical filtration, and high resistance to soil moisture and chemical attacks in the soil environment.

The calculation of the cable size is carried out so that the distribution of electrical energy can be distributed properly and there is no voltage shrinkage that exceeds the applicable PUIL standard limit. The Current Conductivity (KHA) of the cable was selected based on the technical data of the N2XSY/NA2XSY cable manufacturing which covers a wide range of nominal cross-sections ranging from 25 mm² to 800 mm². The selected conductor cross-section must ensure that the cable KHA exceeds the maximum load current under the toughest operating conditions, with an adequate margin according to PLN's supply quality requirements. In addition, voltage shrinkage calculations are also performed to verify compliance with the maximum voltage shrinkage limit allowed by the PUIL standard. Other technical parameters considered in the selection of cross-sections include: conductor DC resistance, capacitance per phase, inductance per phase, conductor's maximum short-circuit current, as well as continuous current capacity under installation conditions in ground and in air at ambient temperature of 30°C.

D. Economic and Lifecycle Feasibility

Although the capital cost of underground cable installation is approximately 3–5 times higher per kilometre than overhead line construction accounting for cable supply, jointing and termination accessories, civil works (trenching, sand bedding, warning tape, backfill and compaction), and post-installation testing the lifecycle cost analysis presents a more balanced picture. The extended service life of XLPE cables (30–40 years versus approximately 20 years for overhead conductors), the reduction in emergency fault repair costs, and the elimination of planned maintenance activities associated with overhead lines (insulator cleaning, conductor tension checks, vegetation clearance) substantially offset the higher upfront expenditure.

The economic value of improved reliability can be quantified through the reduction in Energy Not Supplied (ENS), calculated as the product of average fault duration (hours) and average load served (kW). The economic value of increased reliability can be quantified through the reduction of Unchanneled Energy (ENS), which is calculated as a result of the average duration of the interruption (hours) by the average load served (kW). With an estimated average load of 1,560 kVA at a power factor of 0.85 and a significant reduction in the duration of the interruption post-implementation, the annual ENS reduction attributable to the implementation of the ground cable is estimated to be approximately 16,930 kWh/year.

Assessed based on the prevailing retail electricity rates in the service area, this reduction is a tangible financial benefit that can be credited against a higher initial investment in lifecycle cost calculations.

E. Technical Constraints and Mitigation

Field implementation of underground cable on the SM3 Feeder encountered four principal technical constraints, each of which was addressed through specific engineering and operational measures:

1) **Subsurface infrastructure conflicts:** The dense subsurface infrastructure of the Tomohon City centre including water mains, drainage channels, and telecommunications conduits required pre-trenching surveys using ground-penetrating radar (GPR) and coordination meetings with the relevant municipal departments to agree on routing adjustments and crossing protocols.
2) **Capital cost:** The high cost of ground cable installation units is managed through a phased implementation strategy, by prioritizing feeder segments that have the highest noise density, thus contributing the greatest to the overall reduction in the frequency and duration of outages. This approach maximizes increased reliability per unit of capital expenditure.
3) **Fault location capability:** To support efficient fault management on the underground cable sections, PT PLN (Persero) UP3 Manado procured TDR and Murray Loop Test equipment and delivered training to field technicians. Standard operating procedures (SOPs) for underground cable fault location and repair were developed and issued to maintenance crews.
4) **Thermal management:** The loss of convective cooling available to overhead conductors means that underground cables must dissipate resistive heat losses through the surrounding soil. Cable rating calculations were performed using the IEC 60287 method, accounting for soil thermal resistivity measured from soil samples taken along the trench route, to ensure that the selected cable cross-section (A3CS 150 mm^2) provides adequate continuous current rating under maximum load conditions.

CONCLUSION

This study provided a comprehensive evaluation of underground cable implementation on the SM3 Feeder at the Tomohon Main Substation, demonstrating that the use of *SKTM* significantly enhances system reliability by eliminating environmental disturbances commonly affecting overhead lines (SUTM), while meeting PLN construction standards and technical requirements through the application of N2XSY XLPE cables designed in accordance with IEC 60287 and PUIL. Technically, underground cables are more suitable for urban environments characterized by dense vegetation, high lightning intensity, and aesthetic considerations, offering superior current-carrying capacity, durability, and compatibility with existing infrastructure. Although the initial investment cost is considerably higher approximately 3–5 times that of overhead systems the long-term economic benefits, including extended service life, reduced maintenance, minimized energy not supplied, and avoidance of emergency repair costs, justify the implementation from a lifecycle perspective. Furthermore, key challenges such as subsurface conflicts, high capital requirements, fault detection, and thermal management can be effectively mitigated through proper engineering planning, phased investment strategies, workforce development, and adherence to established standards. Therefore, it is recommended that PT PLN (Persero) UP3 Manado expand the implementation of underground cable systems in high-risk feeder areas, enhance fault detection and repair capabilities, adopt IoT-based real-time monitoring for predictive maintenance, and adjust protection coordination settings to align with the new network characteristics.

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