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Analysis of Voltage Drop and Power Loss Calculations in the Edelweiss Feeder of PT PLN (Persero) Abepura Customer Service Unit

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Abstract: This study evaluates the performance of the 20 kV Edelweiss feeder by analysing transformer loading, voltage drop, and technical power losses in a radial distribution network. The analysis is based on a bus-by-bus electrical model derived from feeder topology, conductor impedance, load current, power factor, and segment length data. Voltage profiles and technical losses are quantified using established three-phase power flow relationships based on Ohm's law and Kirchhoff's current law, enabling the assessment of cumulative voltage drop and loss propagation along the feeder. The results show that the feeder maintains a highly stable voltage profile, with a total voltage drop of 41.422 V, equivalent to approximately 0.207% of the nominal 20 kV voltage. Total active and reactive power losses are 7.3103 kW and 4.7821 kVAR, respectively, with more than 96% of these losses concentrated in Bus 2 and Bus 3. The findings demonstrate that technical losses are governed primarily by current accumulation, electrical distance, and topological position within the radial network rather than by conductor length alone. This study contributes a feeder-level understanding of how upstream current aggregation shapes voltage-drop and loss distribution, providing empirical evidence for identifying critical segments in medium-voltage radial distribution systems.

Keywords: voltage; power; distribution; distance; performance



SDGs Problem Solving

This research contributes to SDG Chapter #7 by examining voltage drop and power loss in a medium voltage feeder. This allows to identify critical network points for targeted efficiency improvements, loss reduction and reliable energy delivery, thus contributing to affordable, sustainable and modern energy systems for all as promoted by the United Nations' Sustainable Development Goals.

Conflict of Interest Statement: The author(s) declares that the research was conducted in the absence of any commercial or financial relationship that could be construed as a potential conflict of interest.

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1. INTRODUCTION

The existence of an electric power distribution system constitutes a fundamental pillar in supporting national development dynamics, where the reliability of energy delivery is a critical performance indicator for PT PLN (Persero). Within the operational area of the Abepura Customer Service Unit (ULP), the Edelweiss feeder plays a central role in distributing electrical energy from the substation to load centers, including residential, commercial, and increasingly expanding public facilities. However, during energy transmission, inherent technical phenomena emerge, notably voltage drops and power losses along the distribution lines.

The voltage drop in 20 kV distribution networks is primarily governed by the inherent resistance and reactance of the conductors, as well as the electrical distance between the energy source and the far-end load (Sadiq and Antar, 2024). When the voltage deviation exceeds the permissible limits, such as those defined in the SPLN standards (+5% and −10% of the nominal voltage), equipment performance degradation and an increased risk of system instability may arise. In parallel, technical losses caused by conductor heating (I^2R losses) reflect inefficiencies in energy transfer and contribute directly to operational and economic losses in power distribution systems (Boghdady, Nasser and Zahab, 2022; Saleh and Alalouch, 2025).

Empirical studies on medium-voltage distribution systems have consistently shown that voltage drop and technical losses are strongly affected by feeder topology, load distribution, conductor impedance, and phase imbalance. Previous investigations have focused on the impacts of load imbalance, network reconfiguration, and reactive power management in improving feeder performance (Albuquerque, 2021; Babu and Dhal, 2024; Zolfaghari and Jalilian, 2026). While these studies provide valuable insights into the general behavior of radial distribution networks, their findings cannot be directly generalized to all feeders because electrical performance is highly dependent on feeder-specific characteristics, including network configuration, load concentration, conductor length, and operational conditions.

In the Abepura distribution area, the Edelweiss feeder serves a strategic role in supplying electricity to residential communities, university facilities, commercial buildings, and public infrastructure. The feeder consists of multiple branching nodes and distribution transformers with non-uniform load distribution, creating conditions that may influence voltage regulation and technical losses differently from those reported in other distribution systems. Despite its operational importance, no comprehensive study has been conducted to quantify the cumulative voltage drop, identify the dominant sources of technical losses, and evaluate the relationship between feeder topology and loss concentration along the Edelweiss feeder. Existing assessments in the Abepura network have largely focused on feeder reconfiguration or transformer loading issues, leaving a limited understanding of the electrical performance of this particular feeder under its current operating conditions.

This study addresses this gap by performing a detailed technical evaluation of the 20 kV Edelweiss feeder using actual operational data from PT PLN (Persero) ULP Abepura. The analysis focuses on transformer loading, voltage drop behavior, and active and reactive power losses across individual feeder segments. Unlike conventional evaluations that emphasize total feeder losses only, this work identifies the spatial distribution of losses and voltage deviations along the feeder and examines how

current accumulation, electrical distance, and network topology influence these phenomena. The findings provide feeder-specific evidence that can support operational decision-making, loss-reduction strategies, and future distribution network planning within the Abepura service area.

2. METHODOLOGY

The methodology adopted in this study follows a quantitative descriptive approach by integrating primary field data with established industry standards. The initial stage involves identifying the network topology based on the Single Line Diagram (SLD) of the Edelweiss feeder (Figure 1) to determine the sequence of substation connections, placement of protection devices, and length of each segment between nodes. The conductor impedance parameters are then determined with reference to the technical specifications of the AAAC conductors utilized by PLN, where the resistance and reactance values per kilometer are calculated in accordance with SPLN 41-10:1991 and SPLN 64:1985 standards (Norouzi, Firoozjaee and Rezaei, 2024; Parvizi *et al.*, 2025).

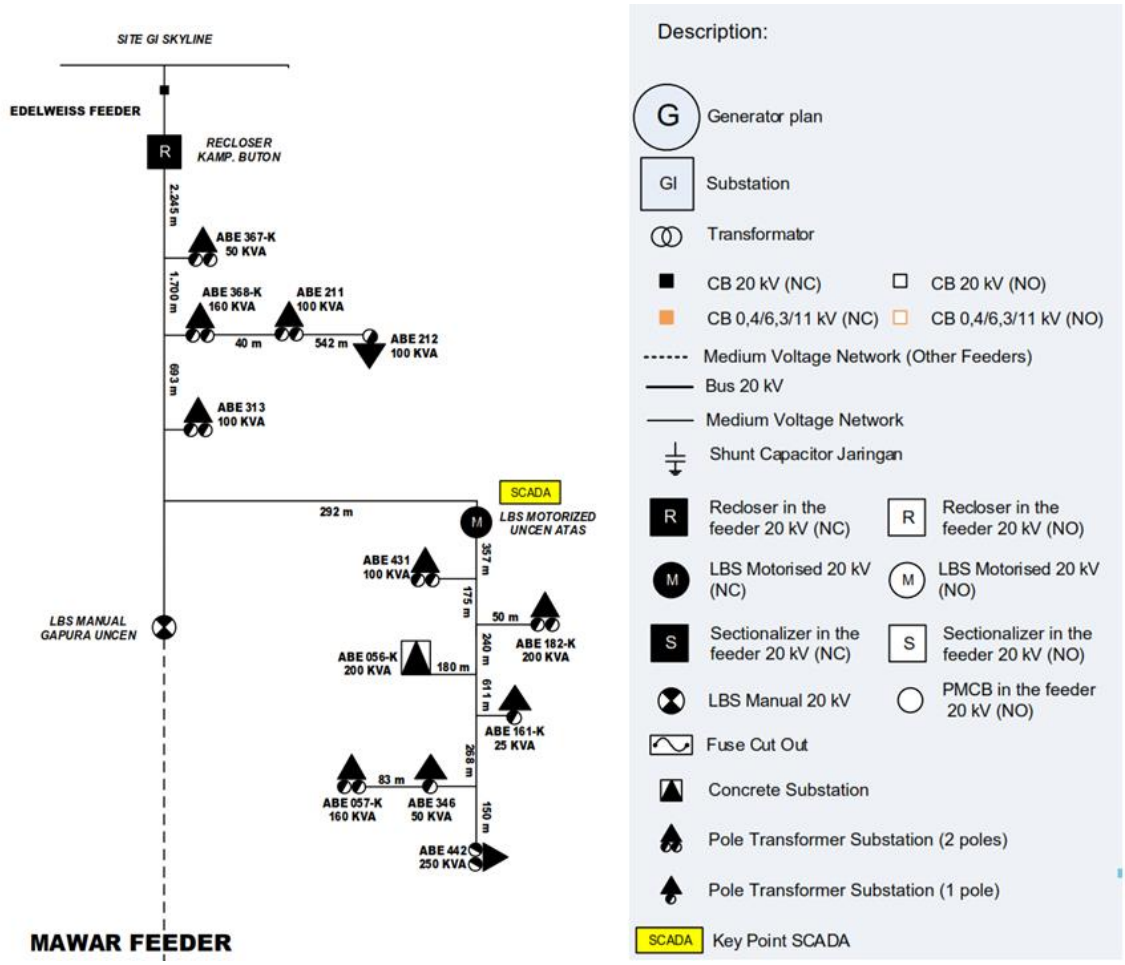


Figure 1. Single Line Diagram of the Edelweiss Feeder substation

2.1. Data Collection Procedure

The initial step in this analysis involved mapping the single line diagram (SLD) of the Edelweiss feeder. The SLD provides a structural representation of the network topology, extending from the 20 kV busbar at the substation to the location of each distribution transformer (Figure 2). The information extracted from the SLD includes: (1) the network configuration (radial, loop, or spindle), (2) the location of distribution substations along with the kVA rating of each transformer, (3) the type and size of conductors used in each segment between substations, and (4) the circuit length between successive nodes.

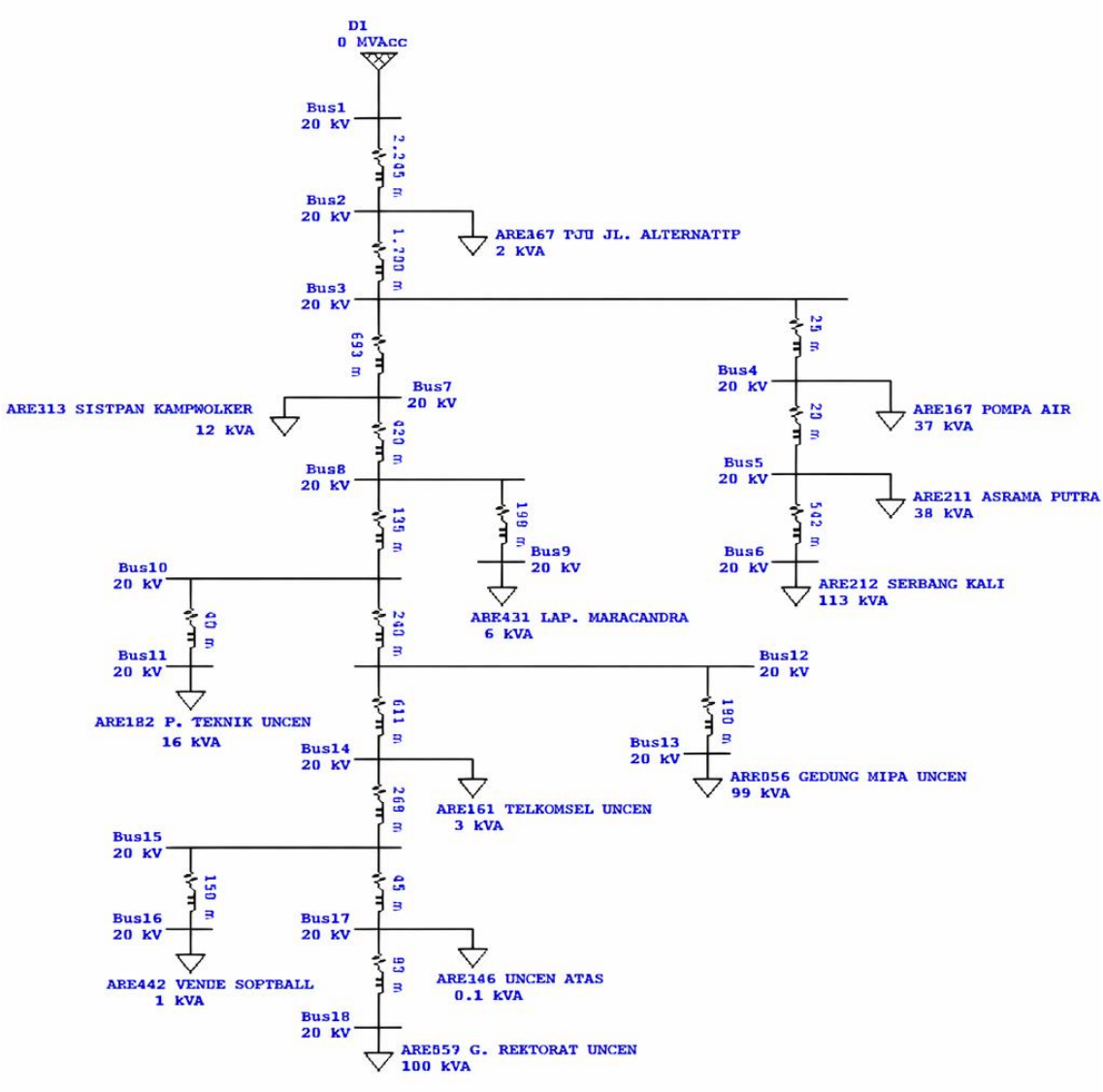


Figure 2. Determination of load bus points on the Edelweiss Feeder

Transformer loading data were obtained from the operational records of the Abepura ULP, including the peak load currents for each phase (R, S, and T) and the neutral current (Table 1). These data were used to evaluate the transformer loading levels and identify potential load imbalance conditions that may contribute to additional losses in the neutral conductor and grounding system (Table 2).

Table 1. Technical summary of the Edelweiss Feeder

Parameter	Value	Unit
Distribution system type	Radial feeder	–
Feeder name	Edelweiss	–
Operating voltage	20	kV
Utility operator	PT PLN (Persero) ULP Abepura	–
Number of analyzed buses	18	buses
Number of distribution transformers	12	units
Total installed transformer capacity	1,555	kVA
Total connected load	361.95	kW
Total apparent load	427	kVA
Conductor type	AAAC	–
Conductor cross-sectional area	150	mm²
Conductor resistance (R)	0.2162	Ω/km
Conductor reactance (X)	0.3305	Ω/km
Assumed power factor (cos ϕ)	0.85	–
Network configuration	Multi-branch radial	–
Primary analysis parameters	Voltage drop, active power loss, reactive power loss, transformer loading	–

Table 2. Transformer loading data of Edelweiss Feeder

Substation Number	Rated Power (kVA)	Location	Load	
			P (kW)	S (kVA)
ABE367	50	Street Lighting (PJU) – Alternative Road	1.70	2
ABE368	160	Uncen Water Pump Station	31.45	37
ABE211	100	Kamwolker Male Dormitory	32.30	38
ABE212	200	Kamwolker Riverside	96.05	113
ABE313	100	Kamwolker Road Infill Area	10.20	12
ABE431	100	Mahacandra Field, Uncen	5.10	6
ABE182	200	Faculty of Engineering, Uncen	13.60	16
ABE056	160	Faculty of Mathematics and Natural Sciences (MIPA) Building, Uncen	84.15	99
ABE161	25	Telkomsel Facility, Uncen	2.55	3
ABE346	50	Upper Uncen Area	0.00	0
ABE057	160	Rectorate Building, Uncen	85.00	100
ABE442	250	Softball Venue, Uncen	0.85	1

2.2. Assumptions and Scope of Analysis

To ensure a consistent analytical framework and facilitate feeder-level performance evaluation, several assumptions were adopted in this study. First, the Edelweiss feeder was modeled as a balanced three-phase radial distribution system. The analysis was performed using aggregated load data at each transformer location rather than phase-by-phase measurements.

Consequently, phase voltage imbalance, negative-sequence components, harmonic distortion, and detailed neutral conductor losses were not explicitly modeled. The balanced-system assumption was considered appropriate for evaluating the overall feeder voltage profile and technical losses under normal operating conditions.

Second, a uniform power factor of 0.85 was applied throughout the feeder. This value reflects the standard operational power factor commonly used in medium-voltage distribution studies and is consistent with the planning assumptions adopted by PLN for feeder performance evaluation. The corresponding reactive power component was calculated using sin ϕ = 0.527. Although actual power factor values may vary among customer groups and transformer locations, the use of a uniform value allows a consistent comparison of voltage drop and loss behavior across all feeder segments.

Third, the load data were obtained from the operational records of PT PLN (Persero) ULP Abepura and represent peak loading conditions recorded at each distribution transformer during the study period. The analysis therefore reflects a worst-case operating scenario in which feeder currents, voltage drops, and technical losses are expected to approach their highest practical values. Seasonal load variations, daily demand fluctuations, and short-term transient conditions were not considered in the present study.

Finally, conductor parameters were assumed to remain constant along each segment, with resistance and reactance values determined according to the technical specifications of the installed AAAC conductors and relevant SPLN standards. Environmental influences such as conductor temperature variation, weather conditions, and conductor aging effects were not incorporated into the calculations.

2.3. Calculation Procedure

The calculations are based on Ohm's and Kirchhoff's laws to quantify the voltage drop and technical losses along each feeder segment. Recent work on radial distribution systems shows that line losses are governed by the branch current through line resistance and reactance, while the voltage drop is driven by line impedance and feeder length. Conductor sizing is then constrained by the current-carrying capacity, particularly for AAAC conductors. Transformer loading is best expressed in kVA, and the power factor remains a key determinant because a low PF increases the current demand, conductor size, and voltage regulation burden (Ayalew *et al.*, 2022; Usman *et al.*, 2022).

2.3.1. Load Current, Power Factor, and Loading Level

The load current in a balanced three-phase system is derived from the fundamental relationship between the apparent power and line voltage, and can be expressed as (Adekitan, 2020; Abdelkarim *et al.*, 2022):

$$I_i = \frac{S_i \times 10^3}{\sqrt{3} V_{LL}} \quad (1)$$

where, I_i is the load current at transformer i (A); Si is the apparent power of transformer i (kVA); and V_LL is the line-to-line voltage (V). This relationship indicates that, for a given operating voltage, an increase in the apparent power will directly result in a higher current flowing through the conductors (Ding and Rakov, 2022). The power factor relates the active power component to the apparent power and is defined as (Medina *et al.*, 2022):

$$Cos\ \varphi_i = \frac{P_i}{S_i} \quad (2)$$

where P_i is the active power demand (kW), S_i is the apparent power demand (kVA), and φ_i is the power factor angle of load point i.

The corresponding reactive power was calculated as (Nobile, Cacciato and Vasta, 2022):

$$Q_i = P_i tan\varphi_i \quad (3)$$

where Q_i is the reactive power demand (kVAR). The calculated values of $\cos\varphi_i$ and Q_i were subsequently used in determining the voltage drop and reactive power losses along the feeder.

In transformer operation, the loading level is more relevant than the absolute power values and is therefore expressed as (Kosobudzki *et al.*, 2025):

$$L_i = \frac{S_i}{S_{rate,i}} \times 100\% \quad (4)$$

where L_i is the transformer loading level (%), S_i is the actual apparent load (kVA), and $S_{rated,i}$ is the rated transformer capacity (kVA). This parameter was used to assess the utilization level of each transformer and to identify substations operating under relatively high loading conditions. This formulation allows for the evaluation of whether the transformer operates within or beyond its nominal capacity.

2.3.2. Voltage Drop in a Three-Phase System

Voltage variation along a feeder is influenced not only by resistance but also by reactance and the phase angle between the current and voltage (Ayalew *et al.*, 2022). Considering these components, the voltage drop in a three-phase system can be expressed as (Ding and Rakov, 2022):

$$\Delta V_i = \sqrt{3} I_i (R\ l_i Cos\ \varphi + X\ l_i Sin\ \varphi) \quad (5)$$

where ΔV_i is the voltage drop across segment i (V), R is the conductor resistance (Ω/km), X is the conductor reactance (Ω/km), and l_i is the conductor length (km). For the Edelweiss feeder, the conductor parameters were taken as $R = 0.2162\ \Omega/\mathrm{km}$ and $X = 0.3305\ \Omega/\mathrm{km}$, corresponding to the AAAC conductor used throughout the feeder. Segment lengths were obtained directly from the single-line diagram shown in Figure 2.

Because the feeder operates in a radial configuration, the current flowing through upstream segments represents the accumulation of local and downstream loads. Therefore, the current at each bus was calculated as (Kosobudzki *et al.*, 2025):

$$I_{bus,j} = I_{local,j} + \sum I_{dwonstream} \quad (6)$$

where $I_{\mathrm{bus},j}$is the cumulative current flowing through bus j.

The receiving-end voltage is then obtained as follows:

$$V_{r,j} = V_{s,j} - \Delta V_j \quad (7)$$

where $V_{s,j}$ and $V_{r,j}$ denote the sending-end and receiving-end voltages, respectively.

The voltage-drop percentage was then calculated as:

$$\%\Delta V_j = \frac{\Delta V_j}{V_{s,j}} \times 100\% \quad (8)$$

This normalization facilitates a comparison with acceptable tolerance limits in distribution systems (Mathenge, Mharakurwa and Mogaka, 2024).

2.3.3. Power Losses in the Line

Power losses in conductors do not occur randomly; they follow the mechanism of energy dissipation owing to electrical resistance (Sadiq and Antar, 2024). The active power loss in a three-phase system is expressed as:

$$P_{loss,j} = 3I_{bus,j}^2 R_j \quad (9)$$

This formulation indicates that an increase in the current leads to a quadratic increase in the power losses, highlighting the sensitivity of losses to the loading conditions. Meanwhile, the reactive power loss associated with line reactance is expressed as:

$$Q_{loss,} = 3I_{bus,j}^2 X_j \quad (10)$$

The total feeder losses were determined by summing the losses of all conductor segments:

$$P_{loss,total} = \sum_{j=1}^{n} P_{loss.j} \quad (11)$$

$$Q_{loss,total} = \sum_{j=1}^{n} Q_{loss.j} \quad (12)$$

For each feeder segment, the branch current, conductor impedance, and segment length were substituted into Equations (5) - (12) to calculate the voltage drop, receiving-end voltage, active power loss, and reactive power loss. The calculations were performed sequentially from Bus 1 to Bus 18 following the radial topology of the Edelweiss feeder.

2.4. Network Performance Evaluation Parameters

The primary indicators used to evaluate the performance of the Edelweiss feeder are defined as follows:

- Voltage Drop Percentage (%ΔV): This parameter must remain within the SPLN tolerance limits (maximum 10% of the nominal voltage).
- Power Loss Percentage ($\%P_{loss}$): This is defined as the ratio between the total power losses in the network and the total power supplied from the substation.
- Transformer Loading Level (%loading): Expressed as the ratio of the actual load current to the transformer's rated current. Values exceeding 80% are typically considered heavy loading conditions that warrant closer attention.
- Load imbalance: Assessed based on the magnitude of the current flowing through the neutral conductor of the distribution transformer.

3. RESULTS AND DISCUSSION

The analysis of the Edelweiss feeder reveals the technical performance of the distribution network within the Abepura ULP area. The collected data indicate a strong correlation between transmission distance, load density, and the voltage quality received by end-users.

3.1. Topology Analysis and Conductor Specifications

Along the main feeder, power flows from Bus 1 to Bus 2 and Bus 3, then branches toward the right through Bus 4–Bus 5–Bus 6 and downward through Bus 7–Bus 8–Bus 10–Bus 11–Bus 12–Bus 13–Bus 14–Bus 15–Bus 16–Bus 17–Bus 18. From this configuration, Bus 3, Bus 7, Bus 8, Bus 12, and Bus 15 function as branching nodes, whereas terminal buses receive voltage after passing through multiple conductor segments. From an operational perspective, load points located farther from the source tend to represent the most critical locations for evaluating voltage drop and power losses, because in radial feeders the downstream voltage profile follows the electrical distance from the source.

The loads identified in the diagram are concentrated in several branches, particularly at ARE212 Serbang Kali (113 kVA), ARE657 Uncen Rectorate (100 kVA), and ARD56 MIPA Building Uncen (99 kVA). In contrast, smaller loads were observed at locations such as ARE146 Upper Uncen (0.1 kVA) and ARE442 Vende Softball (1 kVA). This composition indicates an uneven load distribution across branches, where segments serving larger loads carry higher currents and are likely to become dominant contributors in the power loss analysis (Ma, Fang and Kong, 2020; Mahdavi *et al.*, 2021).

Conductor specifications can only be clearly interpreted at the system and segment levels, rather than in terms of material properties or cross-sectional details of the conductor. It is evident that all buses operate at a 20 kV voltage level, and each conductor segment is labeled with its corresponding length (Minetti, Procopio and Bonfiglio, 2025). However, parameters such as conductor type, cross-sectional area, material (copper or aluminum), insulation class, installation method, and ampacity are not specified in the single line diagram and therefore cannot be determined without a separate cable schedule or technical documentation (Gautam, Patel and Mansani, 2022). According to IEC standards, conductor parameters are classified based on the nominal cross-sectional area and electrical characteristics rather than solely on topological representation. For instance, IEC 60228 defines nominal conductor cross-sections ranging from 0.5 mm^2 to 3,500 mm^2 for power cables, whereas IEC 60364-5-52 addresses conductor sizing and voltage drop considerations.

3.2. Cogging Torque Reduction Performance

Table 3 and Table 4 indicate that the Edelweiss feeder operates as a 20 kV radial system with staged power flow from upstream to downstream buses, where the voltage behaviour is governed by the accumulation of branch currents and line impedance along the feeder path (Mathenge, Mharakurwa and Mogaka, 2024). In such configurations, the voltage drop is evaluated progressively from the substation toward the far-end load, with the most distant buses representing the most sensitive points for voltage deviation owing to cumulative impedance effects (Babu and Dhal, 2024).

Table 3. Voltage drop of the Edelweiss Feeder

Bus	Substation Number	Load Current	Cos φ	Sin φ	impedances 150 mm		Channel Length (kms)	ΔV (Volt)
					R	X		
Bus 2	**ABE367**	**12,34**	**0,85**	**0,527**	**0,2162**	**0,3305**	**2,357**	**18,032**
Bus 3	ABE313+ABE368	12,28	0,85	0,527	0,2162	0,3305	1,785	13,589
Bus 4	ABE368	5,43	0,85	0,527	0,2162	0,3305	0,026	0,088
Bus 5	ABE211	4,36	0,85	0,527	0,2162	0,3305	0,021	0,057
Bus 6	ABE212	3,26	0,85	0,527	0,2162	0,3305	0,569	1,150
Bus 7	ABE313	6,85	0,85	0,527	0,2162	0,3305	0,728	3,091
Bus 8	ABE431+ABE182	6,50	0,85	0,527	0,2162	0,3305	0,441	1,777
Bus 9	ABE431	0,17	0,85	0,527	0,2162	0,3305	0,208	0,022
Bus 10	ABE182+ABE161	6,33	0,85	0,527	0,2162	0,3305	0,142	0,557
Bus 11	ABE182	0,46	0,85	0,527	0,2162	0,3305	0,042	0,012
Bus 12	ABE161+ABE056	5,87	0,85	0,527	0,2162	0,3305	0,252	0,917
Bus 13	ABE056	2,86	0,85	0,527	0,2162	0,3305	0,189	0,335
Bus 14	ABE161	3,01	0,85	0,527	0,2162	0,3305	0,642	1,198
Bus 15	ABE442+ABE346	2,92	0,85	0,527	0,2162	0,3305	0,281	0,509
Bus 16	**ABE442**	**0,00**	**0,85**	**0,527**	**0,2162**	**0,3305**	**0,158**	**0,001**
Bus 17	ABE346	2,92	0,85	0,527	0,2162	0,3305	0,047	0,085
Bus 18	ABE057	0,03	0,85	0,527	0,2162	0,3305	0,087	0,002
				Total				**41,422**

Table 4. Sending-End and Receiving-End voltages of the Edelweiss Feeder

Bus	ΔV (Volt)	V sending	V receiving	ΔV (%)
Bus 1	0,000	20.000,00	20.000,00	0,0000
Bus 2	18,032	20,000.00	19,981.97	0,0009
Bus 3	13,589	19,981.97	19,968.38	0,0006
Bus 4	0,088	19,968.38	19,968.29	0,0000
Bus 5	0,057	19,968.29	19,968.23	0,0000
Bus 6	1,150	19,968.23	19,967.08	0,0001
Bus 7	**3,091**	**19,967.08**	**19,963.99**	**0,0001**
Bus 8	1,777	19,963.99	19,962.22	0,0001
Bus 9	0,022	19,962.22	19,962.19	0,0000
Bus 10	0,557	19,962.19	19,961.64	0,0000
Bus 11	0,012	19,961.64	19,961.62	0,0000
Bus 12	0,917	19,961.62	19,960.71	0,0000
Bus 13	0,335	19,960.71	19,960.37	0,0000
Bus 14	1,198	19,960.37	19,959.17	0,0001
Bus 15	0,509	19,959.17	19,958.67	0,0000
Bus 16	0,001	19,958.67	19,958.67	0,0000
Bus 17	0,085	19,958.67	19,958.58	0,0000
Bus 18	0,002	19,958.58	19,958.58	0,0000

From a loading perspective, the total recorded load current of 41.422 A suggests that the network operated under relatively controlled conditions. However, this value alone is insufficient to determine the percentage of transformer loading because the transformer nameplate capacity is not provided. Accurate transformer loading evaluation requires a comparison with the installed capacity to assess whether the peak loading remains within safe operational limits and future load growth projections (Usman *et al.*, 2022).

The voltage drop distribution shown in Table 3 is strongly dominated by Bus 2 and Bus 3, which together contribute 31.621 V, equivalent to approximately 76.34% of the total feeder voltage drop. This dominance can be explained by the combined effect of current accumulation and electrical distance. In a radial distribution system, the current flowing through the first feeder segments is not associated with a single downstream load; instead, it represents the aggregated demand of all connected loads located beyond that point. Consequently, Bus 2 and Bus 3 carry the highest branch currents in the network, reaching 12.34 A and 12.28 A, respectively, while simultaneously exhibiting the longest upstream conductor sections (2.357 km and 1.785 km).

According to the voltage-drop relationship, both current magnitude and line impedance contribute directly to voltage reduction. Although several downstream segments possess comparable conductor parameters, their currents decrease substantially after load extraction at successive branching nodes. For example, current levels decline from approximately 12 A in the Bus 2–Bus 3 corridor to less than 7 A in most downstream branches and to below 1 A at terminal buses such as Bus 9, Bus 11, and Bus 18. As a result, the electrical impact of impedance becomes progressively smaller along the feeder, producing only marginal voltage reductions despite additional line length.

Therefore, the dominance of Bus 2 and Bus 3 reflects the cumulative nature of power flow in a radial distribution system rather than merely their physical distance from the source. These segments serve as the primary energy transfer corridors supplying all downstream loads, including the major demand centers at ABE212 (113 kVA), ABE057 (100 kVA), and ABE056 (99 kVA). Because voltage drop is directly proportional to both current and impedance, the coexistence of high current accumulation and relatively long conductor sections causes these two buses to become the principal contributors to the overall feeder voltage reduction (Amoah and Essilfie, 2025). This finding suggests that electrical distance, defined as the combined effect of current flow and impedance, provides a more comprehensive explanation of voltage drop behaviour than geometric line length alone.

Beyond Bus 3, the contribution to the voltage drop decreased sharply. Lateral buses such as Bus 4 (0.088 V), Bus 5 (0.057 V), Bus 9 (0.022 V), Bus 11 (0.012 V), Bus 16 (0.001 V), and Bus 18 (0.002 V) exhibited only minimal voltage reductions. From a technical standpoint, this pattern reflects two dominant factors: short segment lengths and low local current levels (Babu and Dhal, 2024; Mathenge, Mharakurwa and Mogaka, 2024). Consequently, the voltage variation along the Edelweiss feeder is primarily governed by the main feeder corridor rather than by smaller lateral branches supplying minor loads.

The ΔV (%) column in the table appears to be expressed as a decimal ratio rather than as a percentage. For example, a voltage drop of 18.032 V on a 20 kV base corresponds to approximately 0.0902%, whereas the final drop at Bus 18 of 41.42 V corresponds to approximately 0.2071% of the nominal voltage. From an operational perspective, these values are very small and remain well below

the commonly accepted ±10% limit used in radial feeder studies to maintain an acceptable voltage quality at load points (Ayalew *et al.*, 2022; Ding and Rakov, 2022).

Overall, the feeder maintained a highly stable voltage profile; however, opportunities for improvement remained in the upstream segments, particularly at Bus 2 and Bus 3, as these sections contribute most significantly to the cumulative voltage drop. From a planning perspective, these locations are more appropriate as priority points for conductor reassessment, load redistribution, or reactive power compensation than shorter branches, where the voltage drop is negligible.

3.3. Quantification of Technical Power Losses

The distribution of power losses in Table 5 is uneven across the buses and tends to be concentrated in the upstream segments of the feeder. Bus 2 records an active power loss of 4.512 kW and a reactive power loss of 2.9515 kVAR, followed by Bus 3 with 2.5622 kW and 1.6761 kVAR. These two buses alone account for approximately 96.8% of the total active power loss (7.3103 kW) and 96.7% of the total reactive power loss (4.7821 kVAR). This pattern is consistent with the characteristics of radial distribution networks, where upstream segments carry the cumulative current from all downstream loads, resulting in a significant increase in power losses owing to the quadratic relationship between current and losses (I2R) (Albuquerque, 2021; Amoah and Essilfie, 2025).

Table 5. Power loss values of the Edelweiss Feeder

Bus	Substation Number	Impedances 150 mm		ΔV (Volt)	Power Losses	
		R	X		P (kW)	Q (kVAR)
Bus 2	ABE367	0,2162	0,3305	0,000	4,5120	2,9515
Bus 3	**ABE313+ABE368**	**0,2162**	**0,3305**	**18,032**	**2,5622**	**1,6761**
Bus 4	ABE368	0,2162	0,3305	13,589	0,0001	0,0001
Bus 5	ABE211	0,2162	0,3305	0,088	0,0000	0,0000
Bus 6	ABE212	0,2162	0,3305	0,057	0,0184	0,0120
Bus 7	ABE313	0,2162	0,3305	1,150	0,1326	0,0867
Bus 8	ABE431+ABE182	0,2162	0,3305	3,091	0,0438	0,0287
Bus 9	ABE431	0,2162	0,3305	1,777	0,0000	0,0000
Bus 10	ABE182+ABE161	0,2162	0,3305	0,022	0,0043	0,0028
Bus 11	ABE182	0,2162	0,3305	0,557	0,0000	0,0000
Bus 12	ABE161+ABE056	0,2162	0,3305	0,012	0,0117	0,0076
Bus 13	ABE056	0,2162	0,3305	0,917	0,0016	0,0010
Bus 14	**ABE161**	**0,2162**	**0,3305**	**0,335**	**0,0199**	**0,0130**
Bus 15	ABE442+ABE346	0,2162	0,3305	1,198	0,0036	0,0024
Bus 16	ABE442	0,2162	0,3305	0,509	0,0000	0,0000
Bus 17	ABE346	0,2162	0,3305	0,001	0,0001	0,0001
Bus 18	ABE057	0,2162	0,3305	0,085	0,0000	0,0000
	Total			**41,422**	**7,3103**	**4,7821**

When comparing the ΔV values in Table 2 and Table 3, it can be observed that segments with the highest voltage drop do not necessarily produce the largest local power losses, although both remain correlated through the magnitude of the current flow. For instance, Bus 3 exhibits a relatively high

ΔV (18.032 V), its power loss remains lower than that of Bus 2. This suggests that the topological position plays a more decisive role than the segment length alone; Bus 2 is located closer to the source and carries the aggregated current from the entire downstream network, leading to more dominant power dissipation in the conductor. In distribution load flow studies, this condition commonly arises because each downstream branch contributes additional current to the upstream segments (Mathenge, Mharakurwa and Mogaka, 2024).

Conversely, buses with relatively small loads or located on short lateral branches, such as Bus 4, Bus 5, Bus 9, Bus 11, Bus 16, and Bus 18—exhibit power losses that were nearly negligible. These values do not necessarily indicate higher local efficiency but rather reflect the low current magnitude flowing through these segments. With uniform impedance values (R = 0.2162 Ω/km and X = 0.3305 Ω/km), variations in power losses are entirely governed by current distribution rather than changes in conductor characteristics. This condition reinforces the notion that in networks with homogeneous conductor parameters, the dominant factors influencing power losses are the load distribution patterns and the relative position to the source (Ding and Rakov, 2022).

The total active power loss of 7.3103 kW in this 20 kV system can be considered relatively low compared to typical feeder capacities, which generally range from hundreds of kVA to several MVA. However, the concentration of losses in upstream segments suggests that targeted evaluation is more appropriate than a system-wide intervention. Measures such as network reconfiguration, conductor uprating in upstream sections, and installation of reactive power compensation are commonly considered to reduce the total current flowing through these critical segments (Baran and Wu, 1989).

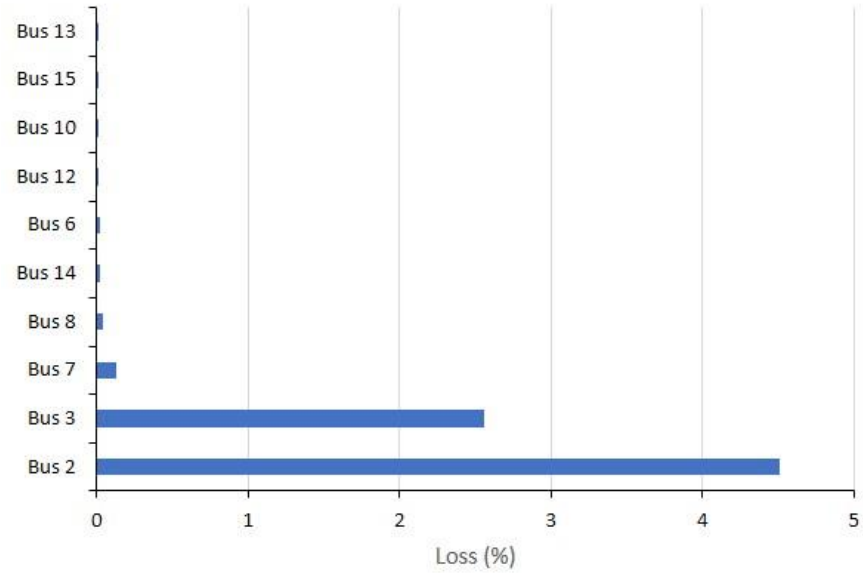


Figure 3. Distribution of active power losses along the Edelweiss Feeder

Figure 3 illustrates the highly concentrated nature of technical losses within the Edelweiss feeder. Bus 2 and Bus 3 account for approximately 96.8% of the total active power loss, whereas all downstream segments contribute only a small fraction of the overall losses. The loss distribution presented in Figure 3 provides a clearer visualization of the dominance of upstream segments in

determining overall feeder efficiency. Although the Edelweiss feeder consists of numerous downstream branches, active power losses are overwhelmingly concentrated at Bus 2 and Bus 3. Together, these segments contribute 7.0742 kW out of the total 7.3103 kW loss, corresponding to approximately 96.8% of the feeder losses. In contrast, all remaining buses collectively contribute less than 3.2%. This finding highlights that technical losses are not uniformly distributed throughout the network but are strongly influenced by current accumulation in segments located close to the source. Such behaviour is characteristic of radial distribution systems, where upstream conductors carry the combined current demand of all downstream loads, resulting in disproportionately higher I^2R losses. Consequently, loss-reduction measures should prioritize these critical upstream sections because improvements implemented in Bus 2 and Bus 3 are expected to produce substantially greater benefits than interventions applied to lightly loaded downstream branches.

3.4. Impact of Load Imbalance on Power Losses

The current distribution presented in Table 3 indicates substantial variation among feeder segments, with upstream buses carrying considerably higher currents than downstream lateral branches. For example, the load currents at Bus 2 and Bus 3 exceed 12 A, whereas several downstream buses carry less than 1 A. This pattern reflects the radial configuration of the Edelweiss feeder, in which upstream segments accumulate the demand of multiple downstream loads. Consequently, current flow is not uniformly distributed throughout the network, resulting in unequal contributions to voltage drop and technical power losses (Tantu and Biramo, 2024).

The effect of this current concentration is clearly observed in Table 5, where Bus 2 and Bus 3 account for more than 96% of the total active and reactive power losses. Because conductor losses are proportional to the square of the current (I^2R), segments carrying larger cumulative currents experience disproportionately higher energy dissipation than lightly loaded branches. Therefore, the observed loss concentration is primarily associated with feeder topology and current aggregation rather than with conductor characteristics, which remain uniform throughout the analyzed network.

A similar trend can be observed in the voltage profile. Segments carrying higher currents generally exhibit larger voltage drops, even when their physical lengths are not the longest in the feeder. This finding suggests that current magnitude exerts a stronger influence on voltage variation than geometric distance alone. Previous studies on radial distribution systems have similarly reported that voltage profiles and technical losses are largely governed by branch-current distribution and electrical distance from the source (Babu and Dhal, 2024; Amoah and Essilfie, 2025).

It should be noted that the present analysis is based on aggregated bus current data and does not include phase-specific currents, neutral currents, or voltage-unbalance measurements. Therefore, the existence and magnitude of phase load imbalance cannot be directly quantified from the available dataset. While phase imbalance is widely recognized as a contributor to additional losses in distribution systems, the results of this study more directly support the conclusion that the dominant mechanism behind the observed losses is the accumulation of downstream load currents in upstream feeder segments (Mathenge, Mharakurwa and Mogaka, 2024).

From an operational perspective, the findings indicate that efforts to reduce losses should prioritize the heavily loaded upstream sections of the feeder. Measures such as load redistribution, feeder reconfiguration, conductor uprating, and reactive power compensation are likely to provide greater

benefits than interventions targeting lightly loaded lateral branches. Future studies incorporating phase-resolved current measurements and neutral current analysis would enable a more rigorous assessment of load imbalance effects and their contribution to technical losses in the Edelweiss feeder.

3.5. Line Impedance Dynamics and the Influence of Distance

The Edelweiss feeder uses uniform conductor parameters (R = 0.2162 Ω/km and X = 0.3305 Ω/km), indicating that differences in voltage drop and power losses are primarily governed by line length and current distribution rather than variations in conductor characteristics. According to the voltage drop formulation, the impedance contribution increases with distance; however, the results in Table 2 show that this relationship is strongly influenced by the magnitude of current flowing through each segment (Ding and Rakov, 2022; Mathenge, Mharakurwa and Mogaka, 2024).

This effect is most evident in the upstream sections of the feeder. Bus 2 and Bus 3 record the highest voltage drops, 18.032 V and 13.589 V, respectively, because these segments carry the cumulative current of downstream loads. By contrast, several downstream branches with comparable or longer electrical paths exhibit substantially lower voltage drops owing to their smaller current levels. For example, Bus 7 produces a voltage drop of 3.091 V despite a relatively short line length of 0.728 km, highlighting that voltage behaviour is determined by the combined effect of impedance and current rather than distance alone. These findings are consistent with radial load-flow theory, which identifies branch current and cumulative impedance as the primary drivers of voltage variation (Ismail *et al.*, 2020; Ayalew *et al.*, 2022; Babu and Dhal, 2024).

A similar pattern is observed in the loss distribution. Although all feeder segments share identical impedance values, active and reactive power losses are concentrated in Bus 2 and Bus 3, where current levels are highest. This behaviour reflects the quadratic relationship between current and losses (I^2R), indicating that electrical distance should be interpreted as the combined influence of network impedance and current flow rather than physical length alone. Consequently, the relatively small total voltage drop of 41.422 V and total active power loss of 7.3103 kW suggest that feeder performance is mainly controlled by current accumulation in critical upstream segments. From an operational perspective, efforts to reduce losses should therefore prioritize current reduction through load redistribution and reactive power compensation rather than focusing solely on conductor length.

3.6. Comparison with Other Feeders in Abepura

Several previous studies conducted within the Abepura distribution area provide useful contextual references for interpreting the performance of the Edelweiss feeder. However, direct performance comparisons should be approached cautiously because feeder characteristics, network configurations, transformer capacities, loading conditions, and evaluation methodologies differ among studies.

The Bougenville feeder has been reported to experience substantially higher voltage drop and power-loss levels prior to network reconfiguration, with noticeable improvements achieved after system restructuring. These findings demonstrate the potential benefits of topology optimization in reducing technical losses and improving voltage profiles.

Although the total voltage drop (41.422 V) and active power loss (7.3103 kW) observed in the Edelweiss feeder appear lower than the values reported for Bougenville, the two systems operate under different loading and network conditions. Therefore, the comparison should be interpreted as a qualitative indication rather than evidence of superior performance.

A similar limitation applies to comparisons with the DPR Kota feeder, where the analysis focused primarily on transformer loading and neutral-conductor losses under both peak and off-peak operating conditions. The available Edelweiss dataset does not include equivalent transformer loading indices or detailed neutral-current measurements. Consequently, differences between the two feeders are more appropriately interpreted as reflecting distinct operational characteristics rather than relative efficiency levels.

The Melati feeder study highlights the importance of phase-load imbalance as a contributor to neutral-current losses and network inefficiencies. While the present study identifies non-uniform current distribution and loss concentration within the Edelweiss feeder, detailed phase-by-phase measurements were not available. As a result, the extent to which phase imbalance contributes to the observed losses cannot be quantitatively compared with the findings reported for the Melati feeder.

Taken together, these comparisons suggest that the Edelweiss feeder operates with a stable voltage profile and relatively modest technical losses under the observed operating conditions. Nevertheless, the available evidence is insufficient to establish a definitive ranking of feeder performance within the Abepura distribution network. A more rigorous comparative assessment would require normalized indicators, such as loss percentage relative to transmitted power, feeder length, transformer capacity, and peak loading level, evaluated under comparable operating conditions.

3.7. Optimization Recommendations

Based on the observed concentration of voltage drop and technical losses in the upstream sections of the Edelweiss feeder, particularly at Bus 2 and Bus 3, optimization measures should be prioritized according to their implementation horizon and investment requirements.

3.7.1. Short-Term Operational Actions

The most practical and cost-effective measure is phase load balancing across distribution transformers exhibiting uneven loading conditions. Although the present study does not explicitly quantify phase imbalance, the non-uniform current distribution observed throughout the feeder suggests that balancing customer connections among phases R, S, and T could reduce neutral currents and improve current sharing. As technical losses are proportional to the square of current (I^2R), even modest reductions in phase current disparity may contribute to measurable loss reduction.

A second operational measure involves targeted feeder reconfiguration. Partial transfer of downstream loads from the Edelweiss feeder to adjacent feeders with available spare capacity, such as Melati or Bougenville, may reduce current accumulation in the heavily loaded upstream segments. Since more than 96% of total feeder losses are concentrated at Bus 2 and Bus 3, reducing current flow through these sections is expected to provide the greatest immediate benefit.

In addition, periodic monitoring of transformer loading and voltage profiles should be strengthened. Continuous assessment of loading trends would enable early identification of emerging overload conditions and support preventive operational decision-making before significant voltage quality deterioration occurs.

3.7.2. Medium-Term Infrastructure Improvements

For medium-term planning, reactive power compensation should be considered at locations characterized by significant inductive loads. The installation of shunt capacitor banks can improve the power factor, reduce reactive current demand, and consequently decrease both active and reactive power losses. This strategy is particularly relevant for university facilities, commercial buildings, and public service loads connected to the feeder.

Another potential improvement involves conductor uprating in critical segments with the highest current accumulation. Replacing existing conductors with larger cross-sectional AAAC conductors would reduce effective line resistance and mitigate future increases in voltage drop and technical losses associated with load growth. Because losses are concentrated in the upstream corridor, conductor replacement should be prioritized in these sections rather than across the entire feeder.

If future load expansion significantly increases feeder loading, the installation of an additional distribution transformer or the creation of a new load supply point may be justified. Such an approach would shorten the effective electrical distance between the source and load centers, reduce current concentration in the main feeder, and improve long-term voltage regulation performance.

4. CONCLUSION

This study evaluated the voltage profile and technical power losses of the 20 kV Edelweiss feeder using actual operational data and segment-based calculations. The results show that the feeder maintains a highly stable voltage profile, with a total voltage drop of 41.422 V (0.207% of the nominal voltage), which remains well within the acceptable operating limits. Technical losses are concentrated in the upstream sections of the feeder, particularly at Bus 2 and Bus 3, which account for more than 96% of the total active power loss of 7.3103 kW. These findings indicate that loss distribution is governed primarily by current accumulation and electrical distance associated with feeder topology rather than by conductor length alone. From an operational perspective, loss-reduction efforts should prioritize upstream segments through load redistribution, impedance reduction, and reactive power management, where the greatest technical benefits can be achieved.

This study is based on a static operating condition and utilizes aggregated bus load data without detailed phase-by-phase measurements. Consequently, the effects of phase imbalance, temporal load variations, and network reconfiguration scenarios could not be quantified directly. Future studies should incorporate three-phase load flow analysis, time-varying load profiles, and simulation-based optimization to provide a more comprehensive assessment of feeder performance and loss mitigation strategies.

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