



Computational Voltage-Profile and Power-Loss Sensitivity Analysis of a 20-kV Distribution Feeder in Makassar

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ABSTRACT

Radial 20-kV distribution networks are susceptible to voltage deterioration and increasing power losses as loading rises. This study presents a steady-state voltage-profile and power-loss sensitivity assessment of the Antang feeder in Makassar, Indonesia, using the Backward/Forward Sweep (BFS) method. The model was developed from secondary historical data for an actual Indonesian feeder, including an 11.32-km line length, 45 distribution substations, 50- and 70-mm² conductors, and a base load of 3,192.14 kVA. The 100% base case was calibrated against values documented in the earlier feeder study, namely active and reactive power losses of 47.2 kW and 118.8 kVAr and a maximum voltage drop of 1.84%. Uniform loading scenarios of 50%, 75%, 100%, and 125% were then applied to all PQ loads while retaining their power factors. Minimum voltage decreased from 0.9908 pu at 50% loading to 0.9770 pu at 125% loading. Active power losses increased from 11.80 to 73.75 kW and reactive losses from 29.70 to 185.63 kVAr. All simulated cases remained above the conservative 0.95-pu planning threshold used in this study. The results quantify steady-state voltage and loss sensitivity within the investigated loading range; they do not identify a voltage-collapse point because no Voltage Stability Index, Continuation Power Flow, or P-V curve analysis was performed. The historical 2021 dataset is therefore treated as a calibrated reference case rather than a statement of current 2026 operating conditions.

Keywords: 20-kV distribution network; voltage profile; power-loss sensitivity; load-flow analysis; Backward/Forward Sweep; radial feeder.

1. Introduction

The global transition toward more sustainable energy infrastructure has accelerated the integration of renewable energy sources, distributed generation, energy storage systems, and smart-grid technologies. These developments aim to improve energy efficiency, reduce carbon emissions, and enhance the reliability of electricity supply. However, increasing penetration of renewable resources and distributed energy resources (DERs) also makes power-system operation more complex, particularly in medium-voltage distribution networks that connect transmission systems to end users. Voltage-stability assessment has therefore become an important indicator of secure and reliable power-system operation [1].

Voltage stability is the ability of a power system to maintain acceptable voltage magnitudes at all buses under normal operating conditions and following disturbances or changes in loading. An inability to maintain the balance between active and reactive power may cause a progressive voltage decline and ultimately voltage collapse, leading to service interruptions or widespread outages. Growing electricity demand, changing load characteristics, and the increasing use of inverter-based generation have made

voltage stability a major concern in modern power-system operation [2].

Previous studies have employed load-flow analysis, voltage stability indices (VSIs), continuation power flow, network reconfiguration, and optimal distributed-generation placement to assess distribution-network performance. In the present study, however, the term voltage stability is avoided where it could imply collapse-margin analysis. The investigated quantities are steady-state bus-voltage magnitudes, voltage deviation from 1 pu, and active/reactive losses under controlled load scaling [3].

Previous studies have employed load-flow analysis, voltage stability indices (VSIs), continuation power flow, network reconfiguration, and optimal distributed-generation placement to assess or improve voltage stability. Advances in computational methods allow critical buses and lines to be identified efficiently, stability margins to be evaluated, and operating strategies to be compared. Recent reviews indicate that VSIs provide useful information for monitoring power-system conditions and detecting proximity to voltage collapse [4].

Computational optimization has also been applied to improve voltage profiles and reduce losses in distribution

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networks. Network reconfiguration, reactive-power control, and optimal placement of distributed generation can jointly enhance voltage stability and operating efficiency [5]. Computational studies enable multiple operating conditions to be evaluated without intrusive testing of an actual network and can therefore support the planning and operation of modern distribution systems [6].

Nevertheless, several limitations remain in the literature. Many studies focus on a single optimization technique or evaluate only one technical indicator, such as voltage magnitude or a stability index, without jointly examining voltage profiles, active and reactive losses, and network operating characteristics. The increasing complexity introduced by DERs also requires analytical frameworks that can evaluate multiple loading levels and network configurations. Comparative assessment of voltage-stability indicators under realistic operating conditions remains an important research challenge [7].

Developments in computing provide opportunities for faster and more systematic voltage-stability assessment. Through computational modelling, alternative operating scenarios can be simulated to quantify the influence of loading changes on voltage profiles, losses, and distribution-network performance. Such analysis can support technical evaluation as well as operational decisions intended to improve reliability, efficiency, and sustainability.

A further methodological issue is the distinction between voltage-profile assessment and formal voltage-collapse analysis. Continuation Power Flow, P-V/Q-V curves, or validated voltage-stability indices are required when the objective is to determine maximum loading or proximity to collapse. The present study instead evaluates steady-state voltage-profile and loss sensitivity over a predefined 50–125% loading range. Accordingly, 125% loading must not be interpreted as the collapse limit of the Antang feeder.

The Indonesian distribution context makes this combined interpretation particularly relevant. Medium-voltage feeders commonly supply geographically dispersed distribution substations through radial paths, and demand growth may occur at different rates across residential, commercial, and public-service areas. A relatively long electrical distance between the source and remote buses can amplify the effect of current on voltage drop [8]. At the same time, a low load power factor increases reactive current without producing additional useful active power. Planning based only on the present minimum voltage may therefore postpone attention to losses and capacity utilization until the network has already become less efficient. Scenario-based load-flow analysis provides an early indication of this progression before an operational limit is exceeded.

A further methodological issue is the distinction between voltage-profile assessment and formal voltage-collapse analysis. Continuation power flow and bifurcation techniques are required when the objective is to determine the maximum loading point or the distance to a saddle-node bifurcation. By contrast, the present study evaluates how a calibrated radial feeder responds within a specified operational range. Its use of the term voltage stability is therefore bounded by steady-state voltage performance, deviation from the nominal value, and margin to the 0.95-pu

operating threshold. This definition prevents the investigated 125% scenario from being misinterpreted as the actual collapse limit of the Antang feeder [9].

The resulting contribution is not a new load-flow algorithm or a formal voltage-collapse method. It is a transparent case-based application that connects historical feeder data, explicit calibration targets, a reproducible BFS implementation, and consistently scaled load scenarios. This framing supports planning-oriented interpretation while making clear which conclusions require updated field measurements or more advanced stability tools.

Accordingly, this study analyzes the Antang 20-kV feeder in Makassar by evaluating steady-state bus-voltage profiles, active and reactive power losses, and load-growth sensitivity at 50%, 75%, 100%, and 125% loading. The principal contribution is a data-informed application of BFS to an Indonesian radial feeder while clearly distinguishing the historical base case from simulated sensitivity scenarios and avoiding claims of a voltage-collapse margin.

2. Methods and modelling

2.1. Methodological framework

This study adopts a computational steady-state approach to assess voltage-profile and power-loss sensitivity in a medium-voltage radial distribution system. BFS is used to solve load flow under multiple loading conditions; no dynamic voltage-stability, VSI, CPF, or P-V curve analysis is performed [10].

The procedure begins with secondary data for the Antang feeder, including the single-line information, distribution-transformer capacities and loads, conductor lengths and types, and previously reported base-case load-flow outputs. The historical dataset was documented in a 2021 feeder study based on information from PT PLN (Persero), Panakkukang Customer Service Unit. For the present paper, those published values are treated as secondary historical reference data rather than new PLN measurements or current SCADA data.

The Backward/Forward Sweep (BFS) method was selected because it is well suited to radial distribution networks with relatively high resistance-to-reactance ratios. The method provides reliable convergence and can accommodate changes in distribution-network structure [11].

BFS is also widely applied to distribution systems with distributed generation because it provides an efficient load-flow solution without requiring inversion of a large admittance matrix [12].

After the network model was constructed, the 100% case was calibrated to the historical reference values reported in the earlier feeder study: aggregate apparent load of 3,192.14 kVA, active loss of 47.2 kW, reactive loss of 118.8 kVAr, and maximum voltage drop of 1.84%. Calibration therefore means reproducing these documented aggregate targets with the reconstructed BFS model. It is not equivalent to validation against independent contemporary field measurements.

The simulation outputs were evaluated in terms of bus voltages, active and reactive losses, and voltage-deviation

characteristics. This analysis was used to identify the most demanding operating condition within the investigated loading range.

The final stage comprised interpretation of the simulation results and assessment of the influence of load variation on feeder performance. The overall research workflow is shown in Fig. 1 below:

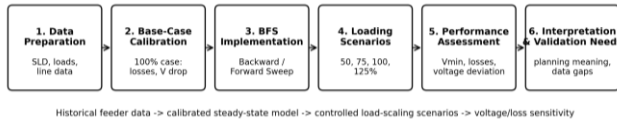


Fig.1. High-resolution methodological workflow for the steady-state voltage-profile and power-loss sensitivity assessment.

Data preparation was treated as a separate modelling step because the source information combined feeder characteristics, transformer loading, conductor data, and previously reported load-flow outputs. Each distribution substation was assigned to its corresponding bus, and each line segment was ordered according to the radial parent-child relationship. This ordering is essential for BFS because downstream currents must be accumulated toward the source before bus voltages are updated away from the source. The topology was kept identical in all scenarios so that differences in the outputs can be attributed to loading rather than to a change in network configuration.

Model calibration was assessed by agreement with the documented 100% historical operating condition. Once the aggregate load, total losses, and maximum voltage drop were reproduced, the 50%, 75%, and 125% scenarios were obtained using common P and Q multipliers at every PQ bus. This controlled construction preserves each represented power factor but does not reproduce non-uniform real-world growth.

Quality control included a fixed 1.0-pu slack voltage, convergence at the stated tolerance, physically consistent voltage declines along loaded radial paths, and monotonic loss increase with loading. These are internal consistency checks rather than independent model validation. A stronger validation would compare simulated bus voltages and feeder losses against updated field or SCADA measurements at matched operating conditions.

2.2. System description

The case study is the Antang feeder, a 20-kV radial distribution network supplied from the Tello substation and serving the Perumnas Antang area of Makassar. The feeder is operated within the service area of the Panakkukang Customer Service Unit and was selected because of its relatively long network and continuing load growth. Historical data indicate a total feeder length of 11.32 km and an aggregate load of 3,192.14 kVA [11].

The Antang feeder contains 45 distribution substations of varying capacities and uses conductors with cross-sectional areas of 50 and 70 mm². The Tello substation was represented as the slack bus at 1.0 pu, while the distribution substations were represented as PQ buses according to their connected loads. The radial structure enables the BFS method to be applied without a computationally expensive admittance-matrix inversion.

The source dataset provides phase-specific loads at each distribution substation. To remain consistent with the balanced three-phase assumption adopted in this model, the phase loads were aggregated into an equivalent three-phase load at the corresponding bus. This treatment preserves the total feeder demand but does not represent phase unbalance.

The principal model components and parameters are as follows:

1. Tello substation as the 20-kV slack bus with a reference voltage of 1.0 pu.
2. Forty-five distribution substations represented as load buses.
3. An 11.32-km radial feeder using 50- and 70-mm² conductors.
4. A base feeder load of 3,192.14 kVA at the 100% loading condition.
5. Constant-power loads with unchanged power factors across loading scenarios.

The resistance and reactance of each line section were used to calculate branch currents, voltage drops, and power losses. The base case was calibrated to the previously reported active power loss of 47.2 kW, reactive power loss of 118.8 kVAR, and maximum voltage drop of 1.84% [11].

The analysis was conducted under steady-state conditions at 50 Hz. Transients, harmonics, short-circuit events, conductor-temperature variation, and phase unbalance were excluded. The results therefore represent a balanced three-phase steady-state equivalent.

Four loading levels were evaluated: 50%, 75%, 100%, and 125%. At each level, the active and reactive power at every load bus were multiplied by a common loading factor. The 100% case represents the historical base condition, while the remaining cases provide a load-sensitivity assessment [13, 14].

The system boundary extends from the 20-kV bus at the Tello substation to the most remote distribution substation on the Antang feeder. The low-voltage network, transmission system, distributed generation, and renewable energy sources were not explicitly modelled.

The resulting feeder model was used for the steady-state voltage-profile and power-loss sensitivity assessment described in the following subsections.

Electrically, the feeder response is governed by the location as well as the magnitude of demand. Current supplied to a downstream substation also flows through every upstream segment on its path from the source [15]. A load near the end of the feeder can therefore contribute to voltage drop and losses over several consecutive branches, whereas an equal load located close to the slack bus affects a shorter path. The aggregate feeder length alone cannot fully describe this behavior; the radial topology and distribution of demand determine which segments carry the largest cumulative current. This is one reason bus-level load-flow analysis is more informative than estimating voltage drop from a single equivalent line.

The two conductor cross-sections represented in the model imply that branch impedance is not spatially uniform. Sections with smaller cross-sectional area generally have

greater resistance per unit length and can make a larger contribution to voltage drop and active loss when heavily loaded. Reactive loss is similarly associated with branch reactance and squared current. The calibrated model retains these line characteristics rather than replacing the feeder with one lumped impedance. As a result, the calculated minimum voltage reflects the cumulative electrical path to the most affected bus under each scenario.

The balanced equivalent should nevertheless be interpreted carefully. Aggregating phase-specific loads preserves total apparent demand, but it removes neutral-current effects and phase-dependent voltage differences. In an actual feeder, the lowest phase voltage may be below the balanced positive-sequence result even when the three-phase average is acceptable. The present model is appropriate for feeder-level screening and scenario comparison, while an unbalanced model is required for phase-specific operational decisions.

2.3. Mathematical modelling

The mathematical model evaluates medium-voltage distribution-system operation through steady-state load-flow calculations. The calculated outputs include active and reactive power, voltage magnitude, voltage angle, and branch losses. These quantities are used for voltage-profile and loss-sensitivity assessment; they are not presented as a bifurcation-based voltage-stability margin.

The active-power balance at bus i is expressed as [16]:

$$P_i = V_i \sum_{j=1}^n V_j (G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij}) \quad (1)$$

where:

- P_i = active power at bus i (pu);
- V_i = voltage magnitude at bus i (pu);
- V_j = voltage magnitude at bus j (pu);
- G_{ij} = conductance between buses i and j (pu);
- B_{ij} = susceptance between buses i and j (pu);
- θ_{ij} = voltage-angle difference between buses i and j (rad);
- n = number of system buses.

The reactive-power balance at bus i is given by

$$Q_i = V_i \sum_{j=1}^n V_j (G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij}) \quad (2)$$

where:

- Q_i = reactive power at bus i (pu).

Equations (1) and (2) determine the operating state at each bus and form the basis of the load-flow calculation [16].

The load flow was solved using the BFS method. The calculation comprises two iterative stages: a backward sweep and a forward sweep [12].

During the backward sweep, the load current at bus i is calculated as:

$$I_i = \left(\frac{P_i + jQ_i}{V_i} \right)^* \quad (3)$$

where:

- I_i = load current at bus i ;

P_i = active load power;

Q_i = reactive load power;

V_i = bus voltage;

$*$ = complex conjugate.

The branch current is obtained by summing all downstream load currents connected to branch k :

$$I_{br,k} = \sum I_i \quad (4)$$

where:

$I_{br,k}$ = current in branch k .

During the forward sweep, the downstream bus voltage is updated using:

$$V_{i+1} = V_i - I_{br,k} (R_k + jX_k) \quad (5)$$

where:

V_{i+1} = downstream bus voltage;

R_k = line resistance;

X_k = line reactance.

$$|V_i^{k+1} - V_i^k| \leq \epsilon \quad (6)$$

where:

ϵ = convergence tolerance;

k = iteration index.

The total active power loss is calculated as:

$$P_{loss} = \sum_{k=1}^m I_k^2 R_k \quad (7)$$

where:

P_{loss} = total active power loss;

I_k = current in line k ;

R_k = resistance of line k ;

m = number of distribution lines.

The total reactive power loss is calculated as:

$$Q_{loss} = \sum_{k=1}^m I_k^2 X_k \quad (8)$$

where:

Q_{loss} = total reactive power loss;

X_k = reactance of line k .

Steady-state voltage performance was additionally summarized using system voltage deviation, expressed as [17]:

$$VD = \sum_{i=1}^n |V_i - V_{ref}| \quad (9)$$

where:

VD = system voltage deviation;

V_i = voltage at bus i ;

V_{ref} = reference voltage, equal to 1 pu.

A smaller VD indicates a voltage profile closer to the 1-pu reference. In this paper, VD is a descriptive voltage-

profile metric rather than an independent Voltage Stability Index.

The same mathematical model was solved for each loading level so that changes in voltage profile, active and reactive losses, and voltage deviation could be compared consistently.

2.4. Numerical implementation and convergence procedure

The BFS implementation begins by initializing every PQ-bus voltage at the slack-bus value. For a given iteration, the complex current demanded at each bus is calculated from its specified active and reactive power and the voltage obtained in the preceding iteration [18]. Starting at the terminal buses, these load currents are added recursively to obtain the current in each parent branch. The backward traversal ends at the source and ensures that the current of an upstream branch includes all loads and losses supplied through its downstream subtree.

The forward sweep then starts at the slack bus. For each branch, the voltage drop is calculated from the complex branch current and series impedance, and the receiving-end voltage becomes the reference for updating the next downstream bus. A complete backward and forward traversal constitutes one iteration. Because load current depends on bus voltage, the two sweeps are repeated until the largest voltage-magnitude change between consecutive iterations is smaller than 10^{-6} pu. The same tolerance and initialization are used for all loading levels to maintain numerical comparability.

After convergence, branch active and reactive losses are computed from squared current and the corresponding resistance and reactance. Summing the branch quantities gives the feeder totals reported in the results. The minimum bus voltage is obtained by scanning all load buses; the slack bus is retained as the maximum value of 1.0 pu because source-voltage regulation is outside the model boundary. The maximum voltage deviation is subsequently calculated relative to this reference. These post-processing steps use the converged state rather than intermediate iteration values.

BFS is computationally suitable for this case because the Antang network is radial and can be traversed directly using its parent-child ordering. Unlike a conventional Newton-Raphson formulation, the method does not require repeated factorization of a full nodal Jacobian. This characteristic is useful for scenario studies in which the same topology is solved repeatedly at different load levels [19, 20]. It also makes the calculation sequence transparent: demand determines load current, downstream currents determine branch current, branch current and impedance determine voltage drop, and the updated voltage again determines current.

Convergence of the numerical solution should not be equated with physical voltage-stability margin. An iterative load-flow solution may converge at an unacceptable voltage, while formal collapse-margin analysis requires additional methods. Accordingly, each converged case is evaluated against its voltage profile and losses. The 0.95-pu value is used as a conservative planning-screening threshold. Indonesia's Distribution Rule (Permen ESDM No. 04/2009)

states that normal distribution-system voltage should be maintained within +5% and -10% of nominal; therefore, the 0.95-pu criterion used here is intentionally more conservative than the -10% regulatory lower bound [22 - 24].

2.5. Boundary conditions and model assumptions

The boundary conditions were defined to make the Antang feeder model reproducible and comparable across scenarios. Historical data define the base case, while network parameters and load power factors remain unchanged during load scaling.

The feeder was modelled as a balanced three-phase radial 20-kV network under steady-state conditions. The analysis focuses on voltage-profile and power-loss changes caused by loading, while transients, harmonics, short circuits, and phase unbalance are excluded.

The nominal frequency was held constant, and line resistance and reactance were assumed not to vary during the simulations. These assumptions are commonly adopted in distribution load-flow and voltage-stability studies [25-27].

The aggregate base load of 3,192.14 kVA was represented using constant-power loads. Active and reactive power at each bus were uniformly scaled to produce the 50%, 75%, 100%, and 125% cases, while the bus power factors were maintained.

BFS was implemented with a specified convergence tolerance, and the iterations were terminated when the voltage change between successive iterations fell below that limit. This approach provides a stable and efficient solution for radial distribution networks [28 - 30].

The principal boundary conditions and model parameters are summarized in Table 1.

Table 1
Technical boundary conditions and parameters of the modelled feeder.

Component	Parameter	Value
Study object	Feeder	Antang, Makassar
Nominal voltage	Vnom	20 kV
System frequency	f	50 Hz
Network configuration	Type	Radial
Feeder length	L	11.32 km
Distribution substations	Number	45
Base load	Sbase	3,192.14 kVA
Conductors	Cross-section	50 and 70 mm ²
Operating condition	System	Steady state
Power system	Phases	Balanced three-phase
Reference bus	Slack bus	Tello substation, 1 pu
Load buses	PQ buses	45 substations
Load variation	Factor	50%, 75%, 100%, 125%
Convergence criterion	epsilon	10^{-6}
Load-flow method	Solver	Backward/Forward Sweep

3. Results and Discussion

3.1. Distribution-system performance

The Antang feeder model was analyzed using BFS at 50%, 75%, 100%, and 125% loading. The 100% case was calibrated to the historical feeder data, whereas the other cases represent uniform changes in active and reactive power at every load bus.

3.1.1. Voltage profile

The minimum voltage decreased progressively as loading increased: 0.9908 pu at 50%, 0.9862 pu at 75%, 0.9816 pu at the 100% historical base case, and 0.9770 pu at 125%. All values remain above the conservative 0.95-pu planning threshold used in this study.

Table 2

Simulated voltage profile of the Antang feeder.

Loading Condition	Minimum Voltage (pu)	Maximum Voltage (pu)
50%	0.9908	1.0000
75%	0.9862	1.0000
100%	0.9816	1.0000
125%	0.9770	1.0000

The voltage reduction is attributable to higher current and cumulative branch impedance along the radial path. The 0.0138-pu reduction between the 50% and 125% scenarios indicates reduced steady-state voltage headroom, but it does not quantify distance to voltage collapse.

The near-linear decline in minimum voltage over the investigated range is a local sensitivity characteristic of the uniformly scaled model. It should not be extrapolated to a collapse point. At higher or spatially concentrated loading, constant-power behavior and branch-specific impedance can produce a more nonlinear voltage response.

At the 100% historical reference condition, a minimum voltage of 0.9816 pu corresponds to the calibrated 1.84% maximum drop. Raising all loads to 125% increases the maximum drop to 2.30%. Both remain inside the conservative 0.95-pu screening boundary and the broader Indonesian normal-voltage band cited in the revised methodology; nevertheless, the increased loss and reduced headroom remain relevant to planning.

The minimum-voltage value alone does not identify the electrically weakest substation. The source manuscript and available processed tables do not preserve the bus/substation ID associated with the 0.9770-pu minimum. That identifier should be exported directly from the BFS result table or original feeder model before resubmission. A feeder single-line diagram with bus/substation labels should also be added when the verified topology file is available; no bus ID or topology has been invented in this revision.

3.1.2. Power losses

The 100% base case produced active and reactive power losses of 47.2 kW and 118.8 kVAr, respectively, consistent with the calibration data for the Antang feeder. Losses at the other loading levels changed with the corresponding network current, as shown in Table 3.

Table 3

Antang feeder power losses under the investigated loading scenarios.

Loading Condition	Active Loss (kW)	Reactive Power Loss (kVAr)
50%	11.80	29.70
75%	26.55	66.83
100%	47.20	118.80
125%	73.75	185.63

Active power losses increased from 11.80 kW at 50% loading to 73.75 kW at 125% loading, while reactive power losses increased from 29.70 to 185.63 kVAr. The faster-than-linear increase is consistent with the quadratic I²R and I²X relationships in distribution lines.

The tabulated loss values follow the squared-loading relationship exactly relative to the calibrated base case: reducing demand to 50% produces 25% of the base losses, increasing it to 75% produces 56.25%, and increasing it to 125% produces 156.25%. This pattern results from the scenario construction and the retained power factor, for which branch current is treated as proportional to the load multiplier. It is therefore a controlled sensitivity result rather than independent evidence of a newly observed field relationship. Its value lies in quantifying how rapidly feeder losses would increase if the present load distribution and electrical parameters remained unchanged.

At 125% loading, the feeder carries only 25% more specified demand than the base case, but the active and reactive losses are 56.25% higher. The incremental burden is consequently disproportionate to the useful load increase. Active loss represents energy converted to heat in conductors and must be supplied by the upstream system. Reactive loss does not directly represent billed energy consumption, but it increases reactive-power requirements and contributes to current and voltage drop. Both quantities should therefore be considered when evaluating whether continued operation without reinforcement remains technically and economically attractive.

The results also clarify why voltage alone can understate emerging inefficiency. Between the 100% and 125% cases, the minimum voltage changes by 0.0046 pu, whereas active loss rises by 26.55 kW and reactive loss by 66.83 kVAr. A feeder may thus appear comfortably inside its voltage band while its marginal losses are already increasing rapidly. Energy-loss monitoring, power-factor assessment, and conductor loading can provide earlier planning signals than a voltage-limit alarm considered in isolation.

3.1.3. Steady-State Voltage-Profile Assessment

Steady-state voltage performance was assessed using minimum bus voltage and maximum deviation from the 1-pu reference. The maximum deviation is defined as one minus the minimum system voltage.

Table 4

Maximum voltage deviation of the Antang feeder.

Loading Condition	Maximum Voltage Deviation (pu)
50%	0.0092
75%	0.0138
100%	0.0184
125%	0.0230

Maximum voltage deviation increased from 0.0092 pu at 50% loading to 0.0230 pu at 125%. This shows progressively

larger departure from nominal voltage as loading rises, while all simulated cases remain above the study screening threshold.

The 125% scenario produced the lowest minimum voltage and highest losses in the investigated range. The result identifies it as the most demanding simulated steady-state scenario, not as the feeder voltage-collapse point.

Because VD is defined directly from V_{min} , it is not an independent Voltage Stability Index. More advanced VSI, CPF, or P-V/Q-V analyses would be required to estimate a critical loading factor or collapse margin.

Using the study screening threshold, the 100% case has 0.0316 pu of headroom and the 125% case has 0.0270 pu. The 25% load increase therefore consumes 0.0046 pu of that conservative planning headroom. This deterministic result does not include uncertainty in demand, conductor impedance, source voltage, phase unbalance, or power factor.

3.2. Sensitivity analysis

Sensitivity was assessed by uniformly scaling active and reactive load at every represented PQ bus to 50%, 75%, 100%, and 125% of the historical base case. Network topology, line impedance, and each bus power factor were kept fixed.

The minimum voltage decreased from 0.9908 to 0.9770 pu as loading increased from 50% to 125%. Thus, a 75-percentage-point loading increase produced an additional maximum voltage deviation of 0.0138 pu.

Power losses were more sensitive to loading. Relative to the base case, active power losses were 75% lower at 50% loading but approximately 56.25% higher at 125% loading. Load growth therefore affects not only voltage performance but also energy-delivery efficiency [31,32].

Table 5
Influence of load variation on the principal Antang feeder parameters.

Loading	Minimum Voltage (pu)	Active Power Loss (kW)
50%	0.9908	11.80
75%	0.9862	26.55
100%	0.9816	47.20
125%	0.9770	73.75

Table 5 shows that the 125% case has both the lowest voltage and the highest active loss, making it the most demanding condition within the tested steady-state range.

The sensitivity analysis does not identify a voltage-collapse point because loading was limited to 125% and no VSI, CPF, or P-V curve was computed.

From an operational perspective, the results support monitoring load growth at remote substations, evaluating load power factors, and considering reactive-power compensation or reconductoring if demand continues to increase.

The sensitivity comparison also separates two types of response. Minimum voltage changes approximately in proportion to the load multiplier over the tested interval, while losses change in proportion to its square. This difference explains why loss reduction may provide a strong

economic motivation for intervention before voltage becomes unacceptable. It also indicates that measures which reduce branch current can produce multiple benefits. Improving power factor [20], shifting coincident peak demand, supplying part of the load closer to consumption, or increasing conductor capacity can reduce losses and voltage drop simultaneously, although each measure has different costs and operating constraints.

Uniform scaling provides a controlled feeder-wide benchmark but does not represent realistic spatial growth. A load increase concentrated at the most electrically remote PQ bus would generally produce a larger minimum-voltage reduction and greater losses along the full upstream path than an equal increase close to the slack bus. Conversely, near-source growth traverses fewer line sections and can have a smaller influence on the remote-bus voltage. A numerical locational-sensitivity case cannot be added reliably from the present manuscript because the bus-by-bus loading/topology file and the ID of the weakest bus are not included in the available source. The next model revision should therefore compare at least two equal-kVA increments: one at the verified remote/weak bus and one at a near-source bus.

The constant-power-factor assumption is also important. If power factor deteriorates during peak loading, reactive current increases, causing larger current magnitude, voltage drop, and I^2R/I^2X losses than in the constant-power-factor scenarios. Accordingly, the current 125% case may be optimistic for a future peak if reactive demand grows faster than active demand. Field measurements of P, Q, V, I, and power factor at representative substations are required to quantify this effect.

3.3. Limitations and future work

The study uses a balanced three-phase steady-state model and does not represent phase-load unbalance, transients, harmonics, short-circuit events, or dynamic voltage recovery. The underlying feeder dataset was documented in 2021. It is retained because it provides a traceable historical benchmark for testing the computational method and controlled load-growth scenarios, but it is not claimed to represent the feeder's actual 2026 operating state.

Loading was scaled uniformly at a constant power factor. The model does not incorporate daily load variation, distributed generation, rooftop photovoltaic generation, energy storage, or transformer tap-control actions [28].

The base case was calibrated to previously reported aggregate losses and voltage drop, not revalidated against current PLN measurements. This limits operational interpretation. Updated SCADA/field measurements should be used to refresh bus loads, conductor/tap status, voltage profile, feeder losses, and the weakest-bus location before any current planning recommendation is implemented.

Future studies should use updated SCADA or peak and off-peak measurements, implement an unbalanced three-phase model, and cross-validate BFS results using ETAP or OpenDSS [1].

Distributed generation, power-factor variation, network reconfiguration, capacitor placement, and reconductoring should be evaluated to improve the voltage profile and reduce feeder losses [3].

Uncertainty analysis is another necessary extension. Load allocation, conductor impedance, transformer demand, and source voltage contain measurement uncertainty [29]. Monte Carlo sampling or bounded sensitivity cases could quantify the range of possible minimum voltages and losses rather than reporting only deterministic point estimates [30].

Finally, future validation should compare simulated and measured voltage at several buses rather than feeder-level losses only. Bus-level error metrics would reveal whether the model reproduces the spatial profile, while measurements across multiple time periods would test performance under changing load composition [28].

4. Conclusion

This study applied the Backward/Forward Sweep method to a steady-state voltage-profile and power-loss sensitivity assessment of the Antang 20-kV feeder in Makassar using secondary historical data. The reconstructed model represents an 11.32-km radial feeder with 45 distribution substations, 50- and 70-mm² conductors, and a historical base load of 3,192.14 kVA. The 100% case was calibrated to previously documented aggregate values of 47.2 kW active loss, 118.8 kVAr reactive loss, and 1.84% maximum voltage drop. Increasing the common load multiplier from 50% to 125% reduced minimum voltage from 0.9908 to 0.9770 pu and increased active loss from 11.80 to 73.75 kW and reactive loss from 29.70 to 185.63 kVAr. The 125% case is the most demanding tested condition, but it is not a voltage-collapse point because no VSI, CPF, or P-V/Q-V analysis was performed. The results show that losses are substantially more sensitive to loading than minimum voltage within the tested range. The study's 0.95-pu threshold is a conservative planning screen; local distribution rules allow a broader normal voltage range. Because the dataset dates from 2021, the results should be treated as a historical computational benchmark rather than a statement of current feeder performance. Updated field validation, identification of the weakest bus, a verified SLD, non-uniform/location load-growth scenarios, power-factor sensitivity, and an unbalanced three-phase model are recommended before operational decisions are made.

CRedit authorship contribution statement

Irawati Amir: Conceptualization, Methodology, Writing - original draft, Validation, Visualization. **Maria Ninisantri Barung:** Data curation, Software, Formal analysis, Supervision, Writing - review and editing.

Declaration of competing interest

No conflict of interest.

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Data availability

The Antang feeder base data were obtained from an earlier study based on information from PT PLN (Persero), Panakkukang Customer Service Unit. The processed model

data and scenario results are available from the corresponding author upon reasonable request.

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