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Analysis of Power Losses and Voltage Drop in the Parungpanjang–Cilejit LAA Traction Substation for KRL Service Optimization

Mardito Adenovit Kusnanda Putra*, Budi Yanto Husodo
Universitas Mercu Buana, Indonesia
Email: dhito.workspace@gmail.com*

ABSTRACT

The increase in the frequency of electric rail train trips on the Tanah Abang–Rangkasbitung line, especially on the Parungpanjang–Cilejit road section, requires the Upper Flow Electricity system to operate at a higher capacity to maintain the continuity of traction electricity supply. This study aims to analyze the existing conditions of the Upper Flow Electricity system, identify the technical factors that affect power loss and voltage drops, and evaluate several alternative solutions that can be applied to improve the reliability of power distribution. It used quantitative approach based on manual calculations using technical parameters such as the length of the trajectory between substations, conductor resistance, load current, and nominal voltage. Two alternative solutions were analyzed, namely the insertion of traction substations at strategic points to shorten the supply distance, as well as improving the technical specifications of the upstream power grid through the replacement of conductor size and configuration and increasing substation capacity. The calculation results show that, in the existing condition on the 8-minute headway, the voltage drop reached 239.256 V (14.77%) and the power loss was 268.813 kW. The alternative application of substation insertion lowered the voltage drop to 103.243 V (6.37%) and the power loss to 111.323 kW, while the alternative of increasing technical specifications resulted in a voltage drop of 140.958 V (8.7%) and a power loss of 134.406 kW. Both alternatives show significant potential in reducing power loss and keeping voltage within safe limits, so they can serve as problem-solving steps on this line.

KEYWORDS *Traction Substation, Headway, Voltage Drop, Upstream Electricity, Power Loss*

INTRODUCTION

Rail-based transportation, especially Electric Rail Trains (KRL), has a strategic role in supporting the mobility of urban communities and buffer areas in Indonesia. The Tanah Abang-Rangkasbitung Line is one of the KRL lines that has experienced a significant increase in the number of trips and passenger volume every year, including on the Parungpanjang-Cilejit road which is a dense operational segment (Sugianto et al., 2023).

The increase in travel demand necessitated a reduction of headway to ≤10 minutes to increase carrying capacity. However, the reduction of headways has a direct impact on increasing the load on the Upper Flow Electricity (LAA) and Traction Substation electricity distribution systems. This condition can trigger voltage drops and power losses that exceed the recommended technical limits in electrical railway operations (Saputra, 2019).

The challenges of power loss and voltage drop in electric railway systems have been extensively documented in international literature, particularly in densely operated urban rail networks. Studies on metro systems in Tokyo, Paris, and Beijing have demonstrated that voltage drop becomes a critical limiting factor when train frequencies exceed certain thresholds, with voltage variations affecting traction motor performance and overall system reliability (Diyoke & Eya, 2023; Zhou et al., 2024; Zhu, 2025). Research by Abrahamsson et al. (2020) on Swedish railway electrification systems showed that inadequate substation spacing resulted in voltage drops exceeding 15% during peak hours, leading to reduced train speeds and increased energy consumption. Similarly, investigations of the Delhi Metro by Kumar and Singh (2021) revealed that power losses in overhead catenary systems could reach 8-12% of total energy consumption when conductor specifications were not optimized for high-frequency operations. However, most existing research has focused on AC electrification systems or metros with shorter inter-station distances, leaving a significant gap in understanding DC traction power optimization for suburban rail networks with long inter-substation distances typical of developing countries' railway infrastructure.

Despite these international precedents, there remains a critical research gap regarding DC traction power system optimization in suburban rail corridors with extended inter-substation distances (>7 km) operating under progressively reduced headways. The Parungpanjang-Cilejit section represents a unique case where legacy infrastructure designed for 15-minute headways must accommodate modern operational demands of 8-10 minute headways without comprehensive system upgrades. This situation is increasingly common in developing nations' railway networks but has received limited academic attention. Existing technical solutions documented in literature—such as substation insertion, conductor upgrading, or capacity enhancement—have typically been analyzed individually, but few studies have provided systematic comparative evaluations of multiple alternatives under identical operational scenarios, particularly for 1620 VDC systems common in Indonesian railway electrification.

On the Parungpanjang-Cilejit route, the distance between the Parungpanjang and Cilejit Traction Substations is ±7,011 km. The LAA system on this cross section uses a 300 mm² cross-sectional Bare Copper Conductor (BCC) feeder wire with a resistance of 0.0611 Ω/km, and a 0.2 CuMg trolley wire with a cross-section of 110 mm² with a resistance of 0.2 Ω/km. The nominal voltage of the system is 1620 VDC with a silicon rectifier (SR) capacity of 3000 kW for each substation. This specification is designed for a normal 15-minute headway, so that when the headway is shortened to 12, 10 and 10 minutes, the load current increases significantly, potentially causing power loss and critical voltage drops (Wibowo & Haryatmi, 2022).

The phenomenon of voltage drop occurs due to the resistance of the conductor which causes a decrease in the voltage between the source and the load. Power loss occurs because the flowing current produces heat according to the law of Joule. In a DC system such as LAA, the power loss is calculated by:

$$P_{loss} = I^2 \times R \quad (1)$$

and the voltage drop is calculated by:

$$\Delta V_{maks} = \frac{2R_0 + R_{tot}\,L}{4} \times I \quad (2)$$

Where, The value of power loss and voltage drop is influenced by the length of the track, the cross-sectional area of the conductor, and the conducting material (Hananto, 2021).

If the voltage drop exceeds 10% of the nominal voltage, the risk of KRL operational disruption increases, including a decrease in train acceleration, disturbance of traction system stability, and tripping equipment (Apriani & Jailani, 2022). Therefore, a thorough technical evaluation is needed to ensure that the power distribution system is able to accommodate the needs of operation on short headways.

Based on this background, this research aims to: (1) analyze the actual condition of power loss and voltage drop in the LAA traction substation system on the Parungpanjang-Cilejit crossing under various operational headway scenarios (20, 15, 12, 10, and 8 minutes); (2) identify the technical and operational factors that cause excessive power loss and voltage drops through systematic parameter analysis; and (3) evaluate two alternative technical solutions—namely the insertion of traction substations at strategic points and the improvement of technical specifications of the LAA network—through comparative quantitative analysis to determine the most effective approach for ensuring system reliability and compliance with safety standards. The results of this study are expected to be technical considerations for operators and regulators to improve the reliability of power distribution systems in solid crosses, so that KRL travel services remain reliable, efficient, and meet safety standards.

METHOD

This research is quantitative research with a descriptive analysis approach. This approach is used to calculate, analyze, and compare the value of power loss and voltage drop in the Upper Flow Electricity (LAA) system on the Parungpanjang-Cilejit crossing, both under existing conditions and in two alternative solution scenarios. The quantitative approach was chosen because it can provide measurable, objective, and verifiable measurement results.

The research was carried out during the period March-July 2025. Field data collection was carried out along the Parungpanjang – Cilejit crossing, which is part of the operational route of the Tanah Abang-Rangkasbitung KRL. Primary data were obtained through direct field measurements conducted during actual train operations, while secondary data were acquired from official technical documentation maintained by PT Kereta Api Indonesia (Persero) and the Directorate General of Railways (DJKA), Ministry of Transportation. Data from PT KAI included historical train operation schedules, current loading patterns across different time periods, and existing LAA network specifications including conductor types, lengths, and configurations. DJKA provided regulatory standards, safety guidelines, and technical requirements for railway electrification systems in Indonesia, particularly those stipulated in Minister of Transportation Regulation No. PM 50 of 2018 concerning Technical Requirements for Railway Electrical Installations. These data sources were triangulated to ensure accuracy and reliability of the technical parameters used in subsequent calculations. The data processing and analysis process is carried out at the electrical laboratory of Mercu Buana University and is supported by technical data from PT Kereta Api Indonesia (Persero).

The target of the research is the Upper Flow Electricity system on the Parungpanjang-Cilejit crossing, focusing on technical parameters in the form of distance between traction substations, conductor resistance, load current, nominal voltage, and network configuration. The research objectives include existing conditions and evaluation results from the application of alternative technical solutions.

The subject of this study is the Upper Flow Electricity network that connects the Parungpanjang Traction Substation and the Cilejit Traction Substation. The specifications of the conductors that are the object of measurement include Bare Copper Conductor (BCC) 300 mm^2 and CuMg 0.2–110 mm^2.

The problem identification process of the researcher identifies problems in the form of high power loss values and voltage drops that occur in short headway conditions.

1. Technical data collection: Technical data is collected through field measurements, data retrieval from official documents of PT KAI and DJKA, and interviews with traction substation technicians.
2. Calculation of existing conditions: The calculation of power loss and voltage drop is carried out using the basic equation of direct current (DC) electricity with parameters measured directly in the field.
3. Alternative simulation Solution: Two alternatives were mathematically tested: (1) insertion of traction substations at strategic points, (2) application of double feeder configuration and increased capacity of silicon rectifier.result analysis and scenario comparison

The results of the calculations were compared to identify the potential reduction of power loss and reduction of voltage drops in each scenario.

Research Data and Instruments

a. The instruments used in this study include:
b. Amperemeters for current measurement.
c. Voltmeter for voltage measurement.
d. Data on the number of trips and KRL travel time from PT KAI
e. Technical documents for KRL load from PT KCI and LAA network from PT KAI.

Data Collection Techniques

The data collection technique is carried out by:

a. Direct field measurements of current and voltage.
b. Observation of the physical condition of the LAA tissue.
c. Documentation study to obtain data on distance, KRL load, conductor specifications, and substation capacity.

Data Analysis Techniques

The data is analyzed with the following steps:

1. Calculate the total resistance of the network based on the specifications of the conductor and the length of the trajectory and the flowing current with the equation:

$$R_{TOTAL} = \frac{R_F \times R_T}{R_F + R_F} \qquad (3)$$

Where RF is the resistance of the feeder wire and RT is the resistance of *the trolley wire*

$$I = \frac{S}{V} \qquad (4)$$

Where I is the flowing current, S is the load power of the KRL and V is the rated voltage.

2. Calculating the supply distance of the LAA substation with the equation:

$$D = {}^{1}/_{2}\,(B - A) + {}^{1}/_{2}\,(C - B) \qquad (5)$$

Where D is the supply distance of the substation and A, B and C are the starting point of the substation

3. Calculate the capacity of substation needs on the load of KRL operating with Headway 20, 15, 12, 10, 8 minutes with the equation:

$$Pm = C \times D \times \left(\frac{60}{H}\right) \times N \times R \times \left(\frac{W}{1000}\right) \qquad (6)$$

Pm = Maximum Load One Hour (kW)

C = Arrangement of KRL Network in 1 time = 2 KRL Sets
H = *Headway* (minutes)
N = Track Type = 2 (*double track*)
R = Train consumption ratio (50 kWH/1000 ton km)
In = Total weight of KRL + full passengers with an average weight of 60kg = 470,000 kg / 470 tons

$$P_1 = Pm + Cm\sqrt{Pm} = Pm + 1.7\sqrt{Im} \times \sqrt{Pm} \quad (7)$$

$$P_2 = 1{,}62\ kV \times 2\ Im\ (1 - \alpha) \ldots\ldots\ldots\ldots\ldots (8)$$

$$P_t = \frac{P_1}{2{,}5}; jika\ P_1 > P_2$$

$$P_t = \frac{P_2}{2{,}5}; jika\ P_2 > P_1$$

P1 = Instantaneous peak load by headway (kW)
P2 = Instantaneous peak load based on maximum current (kW)
Pt = Required load (kW)
Pm = Maximum load one hour (kW)
Cm = Electrification factor DC = 1.7√Im
In = Maximum flow of KRL (A)
A = Current divider ratio 0.08

4. Calculating voltage drop with equation:
   ΔV_max = (2 · R_0+ R_Total·L)/4 ×I
   Maximum = Maximum voltage drop (V)
   R0 = Internal Resistance Gardu LAA (Ω)
   RTotal = Resistance Total (Ω)
   L = Distance between LAA Parungpanjang – Cilejit substations (7,011 km)
   I = Maximum current when KRL passes (A)
5. Calculate power loss with the equation:
   P_loss=I^2×R
6. Compare the results of the calculation between the existing conditions and the two alternative solutions.
7. Draw conclusions about the potential of the two solutions as a step to solve the problem.

RESULT AND DISCUSSION

The voltage drop on the Parungpanjang – Cilejit road plot calculates based on the distance of the KRL headway where the voltage drop at the headway of 12 minutes, 10 minutes and 8 minutes is 178 Volts, 203 Volts and 239 Volts or above 10% of the Rail Voltage. This is not in accordance with the Regulation of the Minister of Transportation of the Republic of Indonesia Number PM 50 of 2018 concerning Technical Requirements for Railway Electrical Installations where the maximum voltage drop is 10% or 162 Volts. And the power losses that occur are very volatile following the headway where the largest power loss is 268,813 kW at the 8-minute headway.

Table 1. Calculation Results of Existing LAA Network Conditions

H (minutes)	I (A)	ΔV (V)		Ploss (kW)
20	1468,365	146,590	9,049%	100,910
15	1527,872	152,531	9,415%	109,254
12	1787,665	178,467	11,016%	149,567
10	2036,975	203,356	12,553%	194,194
8	2396,585	239,256	14,769%	268,813

The maximum allowable voltage drop is 10% of the real voltage of 1620 VDC or equal to 162 VDC. Then the maximum distance allowed to obtain a voltage drop value of 10% at the highest peak load is:

$$\Delta V_{max} = \frac{2 \cdot R_0 + R_{Total} \cdot L}{4} \times I$$

$$162\ Vdc = \frac{2 \cdot 0{,}0356 + 0{,}046801992 \cdot L}{4} \times 2396{,}585331\ A$$

$$\frac{162 \times 4}{2396{,}585331} = 0{,}0712 + 0{,}046801992 \cdot L$$

$$L = \frac{0{,}270384698 - 0{,}0712}{0{,}046801992}$$

L= 4,255902172 km

So the maximum distance to get a voltage drop value below 10% is 4.2 km or less. More than 4.2 km, the potential voltage drop that occurs is above 10%.

The maximum allowable voltage drop is 10% of the real voltage of 1620 VDC or equal to 162 VDC. Then the maximum total wire resistance value to obtain a voltage drop value of 10% at the highest peak load is:

$$\Delta V_{max} = \frac{2 \cdot R_0 + R_{Total} \cdot L}{4} \times I$$

$$R_{Total} = \frac{\left(\frac{4 \times \Delta V}{I}\right) - 2 \cdot R_0}{L}$$

$$R_{Total} = \frac{\left(\frac{4 \times 162}{2396{,}585331}\right) - 2 \cdot 0{,}0356}{7{,}011}$$

$$R_{Total} = \frac{(0{,}270378) - 0{,}0712}{7{,}011}$$

$$R_{Total} = 0{,}0284\ \Omega/km$$

So the maximum wire resistance value to get a voltage drop value below 10% is 0.0284 Ω/km and should not be more.

Table 2. Simulation of LAA Network Calculation Results of Substation Insertion Condition

H (minutes)	I (A)	ΔV (V)		Ploss (kW)
20	1468,365	98,295	6,07%	100,910
15	1468,365	98,295	6,07%	100,910
12	1468,365	98,295	6,07%	100,910

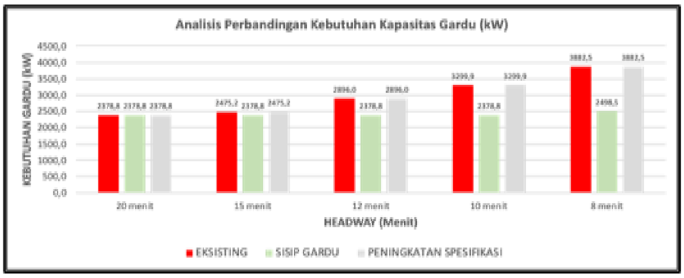
10	1468,365	98,295	6,07%	100,910
8	1542,272	103,243	6,37%	111,323

In table 2. The simulation of the results of the calculation of the LAA network in the substation insertion scenario conditions shows that the voltage drop in the Parungpanjang – Cilejit road plot is consistently calculated at 98,295 V – 103,243 V or 6.08% - 6.37% which means that it is below the permissible standard, which is a maximum of 10% in accordance with regulations.

Table 3. Simulation of LAA Network Calculation Results by Improving Technical Specifications

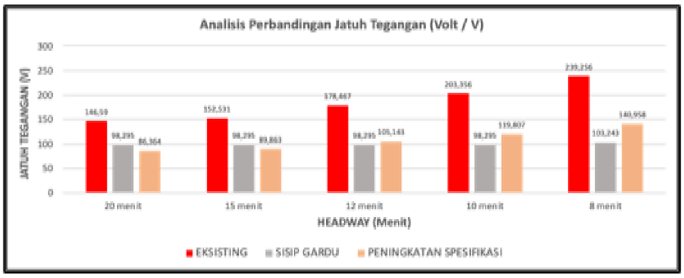
H (minutes)	I (A)	ΔV (V)		Ploss (kW)
20	1468,37	86,36	5,331%	50,455
15	1527,87	89,86	5,547%	54,627
12	1787,67	105,14	6,490%	74,784
10	2036,98	119,81	7,395%	97,097
8	2396,59	140,96	8,701%	134,406

In table 3. The simulation of the results of the calculation of the LAA network in the conditions of the technical specification increase scenario shows that the voltage drop on the Parungpanjang – Cilejit road plot is calculated quite fluctuating according to the headway, which is rated at 86.36 V – 140.96 V or 5.3 % - 8.7 % which means that it is below the permissible standard, which is a maximum of 10% in accordance with regulations.



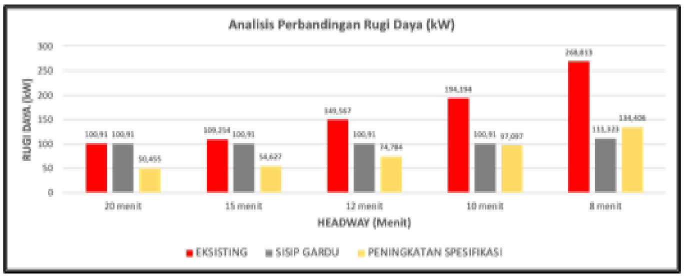
Graph 1. Comparative Analysis Chart of Substation Capacity Needs

Graph 1 found that under existing conditions, the power requirement exceeds the maximum capacity of SR 3000 kW when the headway < 12 minutes, even reaching 129% at the 8-minute headway. This shows that the substation is overloaded when the frequency of travel is high. The addition of substations (inserts) improves distribution, lowering the load of each substation to the range of 79–83%. Meanwhile, in the condition of increasing specifications, the loading capacity remains high but accommodates the SR capacity which is increased to 4000 kW, so that operations remain safe even at tight headways.



Graph 2. Voltage Drop Comparison Analysis Chart

Graph 2 shows that under existing conditions, the voltage drop exceeds the 10% regulatory limit of 1620 VDC at the 12-≤minute headway, with the highest value reaching 239.256 V (14.77%) at the 8-minute headway. This condition indicates a potential decline in train traction performance in the farthest segment of the substation. On the other hand, in the scenario of substation insertion and an increase in technical specifications, the entire voltage drop value is below the 10% threshold, ranging from 5.33%–8.70%. These improvements demonstrate the effectiveness of both alternative solutions in maintaining voltage stability, reducing the risk of operating interruptions, and ensuring that the power supply remains within recommended standards along the track.



Graph 3. Power Loss Comparison Analysis Chart

Graph 3 shows that the highest power loss under existing conditions reached 268,813 kW during an 8-minute headway. Meanwhile, in the substation insertion scenario, this value dropped significantly to 111,323 kW, and in the increase in technical specifications, it was recorded at 134,406 kW. Both approaches generally provide a significant reduction in power loss compared to existing conditions. This difference indicates an increase in power distribution efficiency which has a positive impact on energy savings, reduction of heat in conductors, and an increase in the reliability of traction electricity supply on the Parungpanjang-Cilejit route.

Table 4. Comparative Analysis of Two Alternative Solutions

Aspects	Alternatives to Substation Inserts	Alternatives to Technical Specification Enhancement
Technical Objectives	Reduce LAA network distance	Reduces resistance values and increases substation capacity
LAA Network Distance	Maximum 4.2 km	Does not change the distance
Voltage Drop Value	98 – 103 V	86 – 140 V
Resistance Value	0,0468 Ω	0,0234 Ω

Current Stability	1.542 A	2.396 A
Effects on Power Losses	100 – 111 kW	50 – 134 kW
Infrastructure Constraints	Requires new land clearing.	Crossing geography constraints for LAA networks
Implementation Time Requirements	Longer (related to construction and licensing and carried out by the Railway Engineering Center)	Faster (replacement of existing components and can be done by PT KAI's internal)
Conformity to PM 50/2018	Ideal because it meets the maximum voltage drop requirement of 10%	Idela because it meets the requirements for a maximum voltage drop of 10%
Technical Risks	Complexity of operational synchronization and installation of new substations.	Must shut *down* during the work process and disrupt train travel operations
Estimated Cost	158 – 188 billion	316 – 376 billion
Impact of Effectiveness	Tall	Keep

The practical implementation challenges of these proposed solutions must be carefully considered within the broader context of Indonesian railway infrastructure development. The substation insertion alternative, while technically effective, faces significant land acquisition challenges in the densely populated corridor between Parungpanjang and Cilejit, where available land is scarce and expensive. The estimated 158-188 billion IDR cost does not fully account for potential delays due to community negotiations, environmental impact assessments, and coordination with local governments—processes that can extend project timelines by 18-24 months based on similar railway projects in Indonesia (Githinji & Were, 2018; Salim & Negara, 2018; Sim et al., 2024). Furthermore, the construction phase would require temporary operational adjustments, including possible speed restrictions or single-track operations that could temporarily reduce line capacity during peak implementation periods.

Comparatively, similar urban rail electrification challenges have been addressed differently in other Asian countries. The Bangkok Mass Transit System (BTS) faced analogous voltage drop issues during capacity expansion and opted for a hybrid approach combining conductor upgrades with strategic substation additions, achieving voltage stabilization while minimizing service disruptions (Adetona & Udeze, 2024; Latif et al., 2023; Wu & Igarashi, 2024). Singapore's Mass Rapid Transit (MRT) implemented a phased technical specification enhancement program that upgraded conductor systems during overnight maintenance windows, avoiding daytime service interruptions but requiring three years for complete network implementation. The Delhi Metro Rail Corporation addressed similar challenges on their 25 kV AC system by installing additional traction substations at 7-8 km intervals, but their AC system architecture differs fundamentally from the DC system analyzed in this study. These international precedents suggest that the optimal solution for the Parungpanjang-Cilejit corridor may require adapting global best practices to local Indonesian contexts, considering factors such as budget constraints, implementation timelines, and operational continuity requirements that are unique to PT KAI's operational environment.

CONCLUSION

This study identifies critical voltage drops and power losses exceeding regulatory limits in the existing Upper Flow Electricity system on the Parungpanjang-Cilejit route, and evaluates two effective solutions: traction substation insertion and technical specification enhancement. For practical implementation, short-term monitoring, medium-term evaluation of the substation option for its superior stability and cost, and long-term infrastructure planning are recommended. Future research should address the study's limitations by incorporating dynamic modeling, exploring energy storage and smart grid technologies, and expanding the analysis to other network sections to support sustainable railway electrification in Indonesia.

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