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Research Article

Optimization of Electric Multiple Unit Headway

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Abstract: The needs of the people of JABODETABEK, Indonesia, for fast, safe, and comfortable means of transportation, such as electric rail trains, are increasing. In 2023, the narrowing of the headway on the East Bekasi-Cikarang station route will cause frequent tripping of the traction substation. This is due to the increasing frequency of multiple electric unit trips and the lack of power capacity at the traction substations to supply electrical power. In addition to that, there is a voltage drop in the overhead power network because the distance between the traction substations is too long. The fastest headway is 3 minutes from the original 13 minutes. This research aims to optimize the power capacity of the traction substation in the LAA 1.10 Cikarang area. The method is load flow analysis using ETAP 19.0.1 software. Results of the design for adding the Tambun Insertion substation and the Telaga Murni Insertion substation. On a 3-minute headway, the average voltage drop increased by 22.5% on the East Bekasi - Cibitung route from 1,222 VDC to 1,497 VDC. Meanwhile, the Cibitung-Cikarang route, originally 1,282 VDC, became 1,494 VDC, or an increase of 16.5%.

Keywords: EMU, headway, overhead power line, voltage drop

1 Introduction

An electric multiple unit or EMU is a public transportation means used by people in the Jakarta, Bogor, Depok, Tangerang and Bekasi areas [1–5]. EMU is chosen for its easy access, affordable prices, speed and precision, and ability to avoid traffic jams [6]. It is a railway facility that uses electrical energy to source its working voltage supply. When operating, the EMU requires electrical power, which will later be supplied from a traction substation using a conductor wire that extends along the upper part of the EMU route called the

Catenary system or the Upper Current Electricity (LAA) [6]. Electric rail trains use a voltage source of 1,500 VDC (direct current) as their working voltage. However, to obtain this working voltage, several processes are required, including a 20 kV alternating current (AC) power supply from the PLN substation [7, 8]. The transformer then lowers the 20 kV AC voltage to 1,200 VAC. The 1,200 VAC voltage is rectified using a silicon rectifier (SR) to a voltage of 1,500 VDC and then supplied to the electrical installation through a feeder, namely the overhead power network [9]. To maintain the reliability of the electric power supply, it is necessary to optimize the placement between the traction substations to be more efficient with the aim of obtaining the optimal distance between the Ceper and Gawok traction substations to avoid disruptions during train operations by using the voltage drop calculation method on the route that occurs on the EMU. The results of the study showed that the optimal placement of the Ceper-Gawok traction substation is ± 8 KM, and the maximum voltage drop is 9.62% [8–12].

The motivation of the research is the addition of a headway or EMU travel schedule on the East Bekasi-Cikarang route up to a 3-minute headway, which resulted in problems with the traction substation, namely frequent trips due to the increased EMU load [13]. In addition to trips at the traction substation, there was also a voltage drop due to the less-than-optimal placement of the traction substation. Where the LAA network and the traction substations experience a voltage drop (drop voltage) when the EMU passes from the Bekasi Timur station to the Cikarang station, causing the traction substation to trip [14, 15].

If the power capacity of the traction substation is not increased, trips will continue to occur. The more EMU facilities there are, the greater the need for electrical power to be supplied, and if possible, there must be an additional traction substation [1]. In previous studies, the Cikarang route was not comprehensively studied. There are other studies with similar locations that use different approaches. Other researchers are investigating the integration of photovoltaic energy for power sources [16, 17]. Other studies discuss harmonics and power quality [18–20]. Some researchers are conducting research on traction systems for high-speed trains [17–21].

The contribution of this study is to overcome the occurrence of voltage drops that cause trips to the EMU electrical system on the Cikarang Timur-Cikarang route. The method used is a simulation assisted by ETAP software. The simulation carried out is in the form of a load flow analysis of the overhead power network [22]. The expected result is no voltage drops and trips, especially during peak hours.

2 Research Method

An electric rail train is a rail facility that has its driver (Motor Car) using an electric power source from a traction substation and overhead electricity used to transport passengers [23]. The electricity source for the EMU comes from a traction substation, which is then distributed through the overhead electrical network (LAA). Electric rail trains use a 1.5 kV DC voltage source as their working voltage with a PLN supply of 20 kV AC, which then undergoes a conversion process of electrical energy from AC electricity to DC electricity [24].

In EMU operations, there are several types of train with different star formations (SF) [25]. SF is the number of trains/carriage arrangements connected in one set of electric

Figure 1: Z-type pantograph or single-arm.

trains. Some commonly used SFs are SF-8, SF-10, and SF-12 [13,20]. The main components that differentiate between the EMUs of the AC and DC system are the transformers and rectifiers owned by the EMUs of the AC system, where there are also differences in the protection system between the AC system and the DC system. In AC EMU, there is a transformer that functions as a voltage reducer obtained from the LAA substation of 15 kV with a frequency of 16.7 Hz and 25 kV with a frequency of 50 Hz [24]. Similarly to the AC EMU system, the DC EMU system also gets a voltage source from an electrical substation commonly called a traction substation of 750 V, 1,500 V and 3,000 V [23]. Before the voltage is supplied to the EMU, the traction substation changes the AC voltage from 20kV/1.2kV to a DC voltage of 1.5kV using a rectifier. (1) is a Z-type pantograph or single-arm.

In this study, the traction power of the motor on the train, the power of the train generator, and the power of the train air compressor driver motor are known, and then all these powers are added together so that the total power of the train can be calculated using (1).

$$P_T = P_M + P_G + P_{AC} \tag{1}$$

where P_T is total power required by EMU (kW), P_M is traction power of the motor (kW), P_G is EMU generator power (kW), and P_{AC} is Motor – Air compressor power (kW).

The maximum current can be determined after calculating the total power consumption on the EMU. Calculation of the maximum current on the EMU can be done using (2).

$$I = \frac{S}{V} \tag{2}$$

where I is maximum current on EMU (A), S is total power consumption of EMU (kW), and V is nominal voltage (1,500 VDC).

Before calculating the power capacity of the traction substation needed by each traction substation, the charging distance of each traction substation must first be known. The charging distance of the traction substation (D) is the distance between the midpoint of the interval between one traction substation and another. The distance between traction substations and the charging distance between traction substations must always be different; this can affect the power consumption needed by the EMU. Figure 2 is a picture of

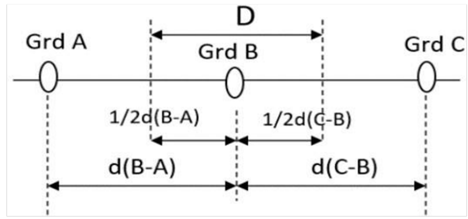

Figure 2: Traction substation charging distance.

the calculation of the charging distance at the traction substation. This can be determined using (3).

$$D = \frac{1}{2}d(B-A) + \frac{1}{2}d(C-B) \tag{3}$$

where D is traction substation charging distance (km), $d(B-A)$ is distance from substation B to substation A (km), and $d(C-B)$ is distance from substation C to substation B (km).

The resistance on the LAA conductor and rail resistance are calculated to calculate the resistance value of the conductor wire used to flow electric voltage to the EMU. This conductor wire is installed along 1,200-1,500 m with a certain distance interval, connected to the overhead contact wire through the feeding branch component. To calculate the LAA resistance, you can use (4) to (9) as follows [25].

a. Feeder wire resistance

$$R_f = \frac{\rho_f \times l}{A_f} \tag{4}$$

b. Messenger wire resistance

$$R_m = \frac{\rho_m \times l}{A_m} \tag{5}$$

c. Trolley wire resistance

$$R_T = \frac{\rho_t \times l}{A_t} \tag{6}$$

d. Rail resistance R 54 (rail type 54)

$$R_r = \frac{\rho_r \times l}{A_r} \tag{7}$$

e. Messenger feeder trolley resistance

$$R_{tmf} = \frac{R_T \times R_m \times R_f}{R_T + R_m + R_f} \tag{8}$$

f. Total conductor wire resistance

$$R_{TOT} = \frac{R_{tmf} \times R_r}{R_{tmf} + R_r} \tag{9}$$

where R_f is feeder resistance (Ohm), R_m is messenger resistance (Ohm), R_T is trolley resistance, R_r is rail resistance type R.54 (Ohm), R_{tmf} is total resistance of trolley, messenger and feeder (Ohm), R_{tot} is total resistance of electric power transmission (Ohm), A is cross-sectional area of conductor wire (m), and l is length of conductor wire (m).

This study calculates the electrical power capacity at the EMU traction substation using an empirical study equation. Calculate the electrical power capacity at the EMU traction substation with a maximum load of one hour, and then (10) is used.

$$Y = C \times D \times \left(\frac{60}{H}\right) \times N \times P \times \left(\frac{W}{1,000}\right) \tag{10}$$

where Y is maximum load in one hour (kW), C is circuit arrangement (set), D is traction substation charging distance (km), H is train headway (minutes), N-type of track 2 (double track), 1 (single track), P – train consumption ratio (kWh/1,000 Ton km), W is total weight of EMU + total weight of passengers (capacity 200% assuming an average passenger weight of 60kg/person) (tons).

The peak load based on headway is the maximum load consumers use at a particular hour. The power capacity based on headway is symbolized by the letter (Z_1) to calculate the instantaneous peak load based on train headway, (11) can be used.

$$Z_1 = Y + C_m\sqrt{Y} \tag{11}$$

where Z_1 is instantaneous peak load based on headway (kW), C_m is DC electrification factor $1.7\sqrt{I_m}$. Instantaneous peak load based on maximum current is the load where two or more trains draw maximum current to drive the traction motor so that the train can move.

To find the instantaneous peak load based on the maximum current, (12) can be used.

$$Z_2 = 1.5 \times 2 \times I_m \times (1 - \alpha) \tag{12}$$

where Z_2 is instantaneous peak load based on maximum load (kW), I_m is maximum starting current of EMU (A), and α is current division ratio, used 0.08 (for DC).

The capacity of the traction substation required is the amount of electrical power the traction substation must provide to supply electrical power to the EMU adequately. The capacity of the traction substation power required is symbolized by the letter (Z_n) and can be calculated using (13).

$$Z_n = \frac{Z_1}{2.5}, \quad \text{if} \quad Z_1 > Z_2; \quad \text{or} \quad Z_n = \frac{Z_2}{2.5}, \quad \text{if} \quad Z_2 > Z_1 \tag{13}$$

Before calculating the LAA network voltage drop, the total current on the EMU must first be calculated. This can happen because the load on each EMU is constantly changing. To calculate the total current on the EMU, (2) is used. After calculating the total EMU current, the voltage drop on the LAA network can be calculated using (14) and (15) [**?**].

$$\Delta V_{\text{max}} = \frac{2 \times R_o + l \times R}{4} \times I \tag{14}$$

$$V_x = E - \left\{ \frac{2 \times R_o + l \times R}{4} - \frac{R^2\left[\frac{1}{2}l - x\right]^2}{2 \times R_o + l \times R} \right\} \times I \tag{15}$$

where ΔV_{max} is maximum voltage drops (Volt), R_0 is internal resistance of the substation (rectifier) (Ohm), R is resistance of the LAA and rail (Ohm/km), E is rectifier terminal

Table 1: Total weight specification data for EMU

Seri KRL	SF	Weight of EMU (Ton)
JR 205	12	569.4
JR 205	10	467.8
Tokyo Metro (TM) 6000/7000	10	495.7
Tokyo Metro (TM) 6000/7000	8	389.3

Table 2: Technical specification data of EMU

Type	SF	Power TM (kW)	Number of TM	Total Power TM (kW)
JR 205	12	120	32	3,840
JR 205	10	120	24	2,880
TM 6000/7000	10	160	24	3,840
TM 6000/7000	8	155	16	2,480

voltage (Volt), l is distance between traction substations (km), X is charging distance between traction substations (km), I is maximum current when the train passes (A), and V_x is remaining voltage in the middle between substations traction (Volt).

In the study, there are several technical specifications related to the objects that the author discusses in this study, including the technical specifications of electric rail trains operating in the LAA 1.10 Cikarang area. PT. KCI operates several types of EMU, such as the Tokyo Metro (TM) 6000 or Tokyo Metro (TM) 7000 series and the JR 205 series. Table 1 is the total weight specification data for EMU.

The calculation of power consumption on the EMU when operating is done by calculating the number of Traction Motors (TM) multiplied by the traction motor power, and the calculation of the current consumption of the EMU is calculated based on the comparison of the total power consumption with the nominal voltage on the LAA network as in Table 2.

Calculations must be carried out to determine the electrical power capacity at the traction substation, including calculating the charging distance between traction substations, as in Table 3. There are 3 LAA traction substations in the 1.10 Cikarang area, namely the East Bekasi substation, the Cibitung substation and the Cikarang substation, where each traction substation has a different equipment capacity according to the needs of the area as in Table 4.

The conductor wire or LAA is installed 1,300 to 1,500 meters long at certain intervals and is branched with a contact wire (Trolley wire) through a feeding branch. There are three types of resistance on each LAA conductor wire, as in Table 5.

Table 3: Distance between traction substations in the LAA 1.10 Cikarang area

Traction Substation	Initial	Final	Range (KM)
Bekasi Timur	28.800	36.800	8
Cibitung	36.800	43.289	6.489
Cikarang	43.289	44.880	0.7955

Table 4: Traction substation capacity data

Traction Substation	Main Power (kVA)	Transformer Capacity (kVA)	Power SR (kW)	Voltage (V)
Bekasi Timur	4,730	4,530	4,000	1,500
Cibitung	4,730	4,530	4,000	1,500
Cikarang	7,000	3,400	3,000	1,500

Table 5: Traction substation capacity data

Type	Material	Wide (mm^2)	Diameters (mm^2)	Weight (kg/m)	Resistance (Ω/m)
Feeder Wire	Bare Copper	300	22.5 ± 2%	2.6 – 2.75	0.06 - 11
Messenger Wire	Galva. Steel Wire	90	12 ± 2%	205 – 305	1.65 - 3
Trolley Wire	CuMg 0.2 Groov	110	12.34	0.978	0.20 - 2
Rail Type R-54	Cast Steel	693.4	72.2	54.43	0.01 - 111

3 Results

After performing a power flow simulation by adding traction substations between existing traction substations, there is an increase in voltage after adding a new traction substation on the ETAP, as in Figure 3 and Figure 4.

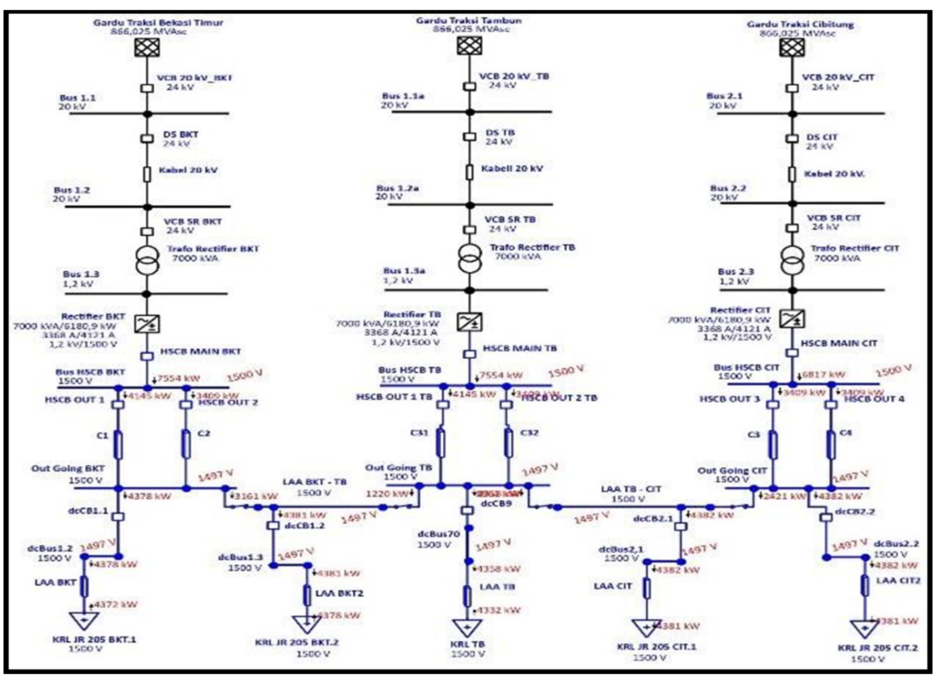

Figure 3: ETAP simulation for the East Bekasi - Cibitung route.

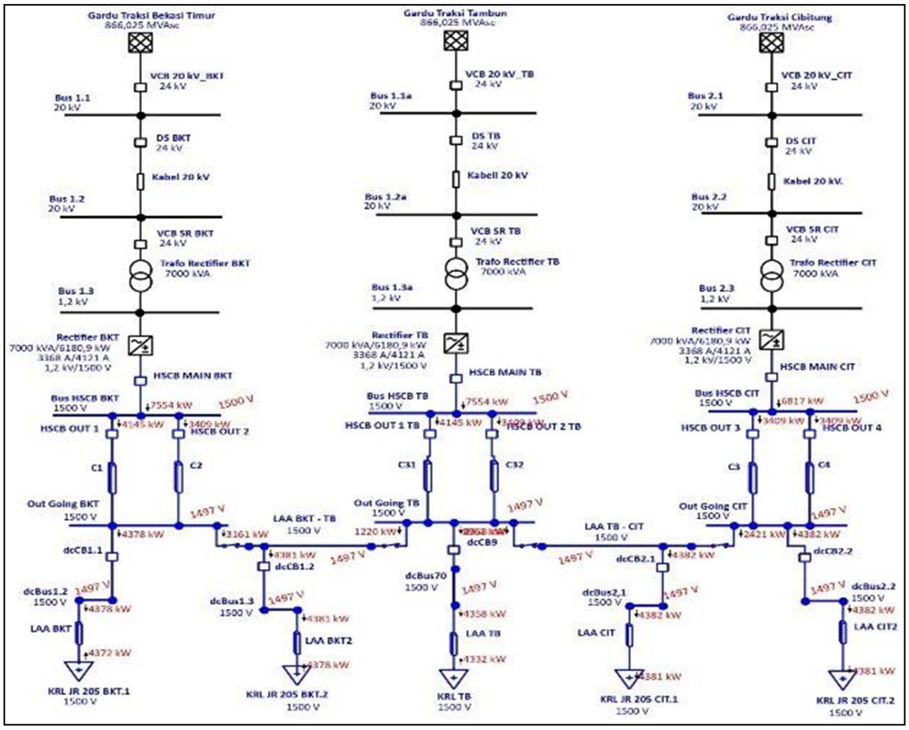

Figure 4: ETAP simulation of the Cibitung-Cikarang route.

After conducting a power flow simulation for overhead electricity for the East Bekasi-Cibitung route by adding the Tambun traction substation, the nominal voltage on the LAA, which should be 1,500 VDC, has decreased in voltage to ± 1,497 VDC from the previous ± 1,223 VDC and the HSCB Bus of the traction substation has increased in voltage to 1,500 VDC from the previous ± 1,315 VDC. This occurs because the distance between the substations previously ± 8 KM has become ± 4 KM.

After conducting a power flow simulation for the upper flow electricity on the East Bekasi-Cibitung route by adding the Telaga Murni traction substation, the nominal voltage on the LAA, which should be 1,500 VDC, has increased in voltage to ± 1,494 VDC from the previous ± 1,282 VDC and the HSCB Bus traction substation has increased in voltage to 1,500 VDC from the previous ± 1,380 VDC. This occurs because the distance between the substations, which was previously ± 6.4 KM, has now become ± 3.25 KM with the parameter of a load of 5 EMU on one East Bekasi-Cibitung route, from the previous one only having a load of 4 EMU.

4 Discussion

In progress with a time of 10, 5, and 3 minutes, the capacity of the existing substation is not sufficient to bear the EMU load, as proved by comparing the results of the calculated

Table 6: Traction substation capacity analysis results in data

Substation	Capacity (kVA)	H	Power measurement (kVA)	Description
Bekasi Timur	4,530	10	4,634.8	Not enough
Cibitung	4,530	10	5,079.6	Not enough
Cikarang	3,400	10	3,599	Not enough
Bekasi Timur	4,530	5	8,596.62	Not enough
Cibitung	4,530	5	8,472.4	Not enough
Cikarang	3,400	5	5,494.5	Not enough
Bekasi Timur	4,530	3	12,728.2	Not enough
Cibitung	4,530	3	12,590.9	Not enough
Cikarang	3,400	3	8,015.2	Not enough

Table 7: Traction substation capacity analysis results in data

GT	Power (kVA)	H	Power Measurement (kVA)	Description
Bekasi Timur	7,000	10	3,599	Sufficient
Cibitung	7,000	10	3,599	Sufficient
Cikarang	7,000	10	3,599	Sufficient
Bekasi Timur	7,000	5	4,695.5	Sufficient
Cibitung	7,000	5	5,079.5	Sufficient
Cikarang	7,000	5	3,590	Sufficient
Bekasi Timur	7,000	3	6,799	Sufficient
Cibitung	7,000	3	6,678	Sufficient
Cikarang	7,000	3	5,138.8	Sufficient

substation capacity calculation, whose value far exceeds the installed substation capacity as in Table 6, where KDH $>$ KDP.

Based on the calculation of the power capacity at the traction substation, the largest electric train load is at a headway with a time of 3 minutes, where the load at the East Bekasi traction substation is 6,799 kVA, the Cibitung traction substation is 6,678 kVA, and the Cikarang traction substation is 5,138.8 kVA. The capacity of the existing substation is only 4,530 kVA. The power for a 5-minute headway is calculated from the East Bekasi Substation 4,695.5 kVA, the Cibitung Substation 5,079.5 kVA, and the Cikarang Substation 3,590 kVA. For a 10-minute headway, the East Bekasi Substation 3,599 kVA, the Cibitung Substation 3,599 kVA, and the Cikarang Substation 3,599 kVA.

The power capacity detailed in Table 6 is insufficient; therefore, this research introduces additional substations. The system was recalculated and re-simulated by incorporating the Tambun Insert substation and the Telaga Murni Insert substation to address the capacity shortfall. Currently, the existing substations are the East Bekasi substation, Cibitung Substation, and Cikarang substation, plus an insert substation box. The simulation result data are given in Table 7, where KDH $<$ KDP.

The traction substation's power capacity is to accommodate the EMU load up to the narrowest headway with a time of 3 minutes by increasing the capacity of the existing substation by 7,000 kVA, which was initially only 4,530 kVA. New traction substations were installed between the available substations: the East Bekasi substation with the Cibitung substation, and the Cibitung substation with the Cikarang substation. Adding the Tambun traction substation and the Telaga Murni traction substation, with a power capacity of 7,000 kVA, can reduce the charging distance between substations so that they are not far apart. This can improve the variation in the voltage drop LAA on the East Bekasi station route to Cikarang station.

In conditions before adding new traction substations in the ETAP 19.0.1 software, the voltage in East Bekasi-Cibitung was ±1,222 VDC and Cibitung-Cikarang was ±1,282 VDC. In the condition after the addition of the Tambun Traction substation, the voltage in the JLAA increased by an average of 22.5%, while in the East Bekasi-Cibitung JLAA it was 1,497 VDC and Cibitung-Cikarang it was 1,494 VDC, or an increase of 16.5%. After calculating the voltage drop, the ideal and appropriate distance between substations to reduce or minimize voltage drops is ±3 km to ±4 km because this distance does not exceed the minimum voltage provisions permitted based on the Indonesian Minister of Transportation Regulation No. PM 50 of 2018.

5 Conclusion

The new traction substation between the East Bekasi substation and the Cibitung substation is named the Tambun Insert substation. Meanwhile, between the Cibitung substation and the Cikarang substation, the Telaga Murni insert substation was added. By adding the insert substation and increasing the capacity of the traction substation to 7,000 kVA, the LAA is still stable up to 3 seconds headway. Before the addition of the traction substation, the voltage in East Bekasi-Cibitung was ±1,222 VDC and improved to 1,497 VDC. This has improved by 22.5%. On the Cibitung-Cikarang LAA, the voltage of 1,282 VDC increased to 1,494 VDC, or increased by 16.5% . The results of this optimization have a difference of 0.2% from the ideal frequency of 1,500 VDC on the East Bekasi-Cibitung line and 0.4% on the Cibitung-Cikarang line.

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