Analysis harmonic distortion of side outgoing transformer 20 kv/ 1.2 kv in traction substation of Tanjung Barat KRL Station

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Abstract. Operational Electrical Railway of PT. KAI Commuter Jabodetabek is supplied by overhead contact system 1500 VDC. Traction substation of Tanjung Barat station uses 6 pulse rectifiers to change alternating current (AC) become direct current (DC) with silicon rectifier type. The effect of the rectification process is harmonic current that causes overheating even fire in transformer. This paper aims to resolve the problem on the rectification process by a simulation using an ETAP 12.6.o application by introducing a single tuned passive filter of the 5th order which is customized to the converter circuit load system. The simulation results showed that filter installation caused reduction of average total harmonic distortion (THD) value where 20% load reduced from 20.19% to 1.02%, 40% load reduced from 20.19% to 3.93%, in 60% load reduced from 20.19% to 1.70% and 80% load reduced from 20.20% to 4.91%. It was highlighted that the obtained total harmonic distortion (THD) reduction below 5 % that meet the standards of IEEE 519-1992.

1. Introduction

Transportation in the modern world today is a component that cannot be separated from daily human activities. Despite various types of transportation available, electric train (KRL) is an alternative transportation that has advantages such as reducing congestion and more time efficiency [1], KRL is a type of transportation driven by DC electric motors supplied from a converter in a traction substation. The KRL traction substation requires an electricity supply to meet the operational needs of the KRL. A quality electricity supply system is needed to expedite the operation of transportation [2]. The supply of electrical energy in its distribution is inseparable from various disturbances that can disrupt KRL operations. Disorders that often occur in the supply of electrical energy, one of which is harmonic distortion. The power supply of the KRL traction substation uses AC voltage on the incoming side of the transformer with 6 silicon rectifier system resulting in harmonics. The KRL traction substation consists of transformers as a distribution of AC PLN sources, from transformers distributed to silicon rectifiers (SR). The SR is the producer of DC sources needed by top-flow electricity (LAA) as a supply of DC motors and utilities in the KRL system. In the KRL traction substation system, a 20 kV PLN AC voltage is lowered on the incoming transformer side 1.2 kV on the outgoing transformer side. A 1.2 kV AC source as a supply of DC 1500 V source generating converter for LAA requirements. This paper aims to resolve the problem on the rectification process by a simulation using an ETAP 12.6.o
application by introducing a single tuned passive filter of the 5th order which is customized to the converter circuit load system [3-5].

2. System presentations

The West Tanjung KRL traction substation has an installed power of 4,330 kVA PLN and an output power of 3919 KW. There are 6 pulses on SR (Silicon Rectifier) that it affects harmonic distortion. The more KRL load, the more current needed, caused an increase in the harmonic distortion value. The following figure 1 explained the substation capacity of the Tanjung Barat station.

![Figure 1. The capacity of the West Tanjung electrical substation.](image1.png)

KRL crossing from Depok Station crosses Tanjung Barat Station which goes to Pasar Minggu Station until Manggarai Station is called Hilir, while the KRL from Manggarai Station to Duren Kalibata Station crosses Tanjung Barat Station to Depok Station called Hulu. The following table 1 displays KRL cross-trips on the KRL system Tanjung Barat Station.

| Direction                  | Feeder (mm²) | Messenger (mm²) | Trolley (mm²) |
|----------------------------|--------------|-----------------|--------------|
| TNT - PSM (SP. HILIR)      | BC2 x 300 mm²| St 1 x 90 mm²   | Cu 1 x 110 mm²|
| PSM - TNT (SP. HULU)       | BC 2 x 300 mm²| St 1 x 90 mm²   | Cu 1 x 110 mm²|
| LNA - TNT (SP. HILIR)      | BC 2 x 300 mm²| St 1 x 90 mm²   | Cu 1 x 110 mm²|
| TNT - LNA (SP. HULU)       | BC 2 x 300 mm²| St 1 x 90 mm²   | Cu 1 x 110 mm²|

![Figure 2. The illustration of fundamental harmonics, harmonic waves, and harmonic order charts.](image2.png)
Generally, voltage and current waves are transmitted and distributed from source to load in the form of pure sinusoidal waves. However, in the process of transmission and distribution, there are various kinds of interference so that the waveform is no longer sinusoidal pure. One of the deviation phenomena of sinusoidal waveforms is harmonic distortion. If a superposition occurs between the fundamental frequency waves and the harmonic frequency waves, a distorted wave will be formed so that the waveform is no longer sinusoidal. Harmonics caused by infected non-linear loads in the power system. Harmonics usually occur in odd order with increasing harmonic order, and the magnitude tends to decrease.

The standard limitation of harmonic distortion values for voltage and current must conform to international standards IEEE-519-1992 so that the equipment used remains in a safe and durable condition. Standard harmonic voltages and currents are shown in Table 2.

### Table 2. Standardization of Voltage Harmonics.

| No | Power Rail Voltage PCC | Individual Voltage Distortion (IHDv) | Total harmonics Voltage Distortion (THDv) |
|----|------------------------|-------------------------------------|------------------------------------------|
| 1  | ≤ 69 kV                | 3.0                                 | 5.0                                      |
| 2  | 69 < V ≤ 161 kV        | 1.5                                 | 1.5                                      |
| 3  | > 161 kV               | 1.0                                 | 1.5                                      |

To determine the current harmonic limit according to IEEE-519-1992 standard according to the value of the Short Circuit Ratio (SCR). Where SCR is the ratio between short circuit current and nominal load current as in Table 3:

### Table 3. Standardization of Current Harmonics.

| No | Order of Harmonics (in %) | Total Demen Distortion (TDD) |
|----|---------------------------|-------------------------------|
|    | Hsc/I_L                   | 11-17 | 17-23 | 23-35 | > 35 | 0.5 | 8.0 | 12.0 | 15.0 | 20.0 |
| 1  | < 20                      | 4.0   | 2.0   | 1.5   | 0.6  | 0.3 | 0.5 |       |       |       |
| 2  | 20 < 50                   | 7.0   | 3.5   | 2.5   | 1.0  | 0.5 | 0.5 | 12.0  | 15.0  | 20.0  |
| 3  | 50 < 100                  | 10.0  | 4.5   | 4.0   | 1.5  | 0.7 | 0.7 |       |       |       |
| 4  | 100 < 1000                | 12.0  | 5.5   | 5.0   | 2.0  | 1.0 | 1.0 |       |       |       |
| 5  | > 10000                   | 15.0  | 7.0   | 6.0   | 2.5  | 1.4 | 2.0 |       |       |       |

Silicon rectifiers are one of the main components of the traction substation which serves to rectify 1200 VAC voltage to 1500 VDC voltage. At the electrical substation of PT. KAI there are two types of silicon rectifiers, namely SR 6 pulses and SR 12 pulses. At present, the silicon rectifier technology used for the traction substation system is a 12 pulses rectifier. The semiconductor component used by the rectifier for rectifier is the press pack version diode. Silicon Rectifier (SR) 6 pulses are SR which rectify 6 AC wave pulses, the number of pulses rectified depends on the type of connection transformer [6-8].
Figure 3. A transformer circuit with SR 6, 12 pulses and AC wave rectifier becomes DC.

ETAP (Electric Transient and Analysis Program) PowerStation 12.6 is application software that is used to simulate an electric power system. ETAP caton work in offline conditions for simulating electric power. The features contained in ETAP vary, among others, features used to analyze power plants, transition systems and electric power distribution. The advantages of using ETAP software include. Figure 4 shows display of ETAB software. From the above settings, the ETAP software is obtained in accordance with the specified amount of load. This explanation can be seen in figure 5.

Data sources in this study were obtained using calculations and assisted by using ETAP 12.6.0 software adapted to the specifications of the Tanjung Barat KRL traction substation. The calculation is done on the transformer bus at a voltage of 1.2 kV before being distributed to SR. In addition to using calculations also use ETAP simulations to determine the THDi value. Voltage and harmonic currents from these calculations, a comparison is made using harmonic standards. So that the results of voltage and current are close to harmonic standards so that the equipment in the traction substation system remains safe when operating. In ETAP simulations, we know the harmonic distortion values based on calculations with minimum and maximum loads. So that it can be planned to install passive filters using ETAP simulations to reduce harmonic distortion values. The calculation and simulation above aim to determine the value of harmonic distortion, plan the installation of filters and to reduce the value of harmonic distortion. By observing the harmonic distortion value and adjusting the harmonic distortion value according to harmonic standards, the equipment in the traction substation used remains in a safe condition and lasts longer [9].
Figure 4. Display transformer voltage and input settings in ETAP software.
3. Results and discussion

Data processing and data analysis in this study used two methods. The research method of harmonic distortion in the KRL traction substation is analyzing the data from the simulation using SR load. After the simulation is done, analyze the data to plan passive filters that aim to reduce the value of harmonic distortion. The data that has been obtained from the simulation is compared with the data obtained from calculations with the theory of harmony to adjust to harmonic standards.

3.1. Power flow simulation

This power flow simulation is needed to get apparent power (kVA), real power (kW), receptor power (kVAR) and power factor (PF) needed to do passive harmonic filter design to reduce harmonics that occur in the system. In this power flow analysis is carried out by varying loading from the maximum 80% transformer capacity of 3625 kW, so that a measurement variation can be achieved that can represent the actual traction substation loading system. The loading variations include:

1. When the load is 20% of the transformer capacity of (725 kW)
2. When the load is 40% of the transformer capacity of (1445 kW)
3. When the load is 60% of the transformer capacity of (2175 kW)
4. When the load is 80% of the transformer capacity of (2899 kW)

After loading variations are obtained, then can simulate the system power flow with two simulations, simulating the load of 20%, 80%, 40% and 60%:
Figure 6. Display power simulation images at loads of 20%, 40%, 80% and 60%.

From the simulation results the power flow in the load is obtained by variable real power (kW), reactive power (kVAR), apparent power (kVA), current (A), and power factor (PF).

Table 4. Results of simulation of system power flow.

| Simulation result   | Load variation |     |     |     |     |
|---------------------|----------------|-----|-----|-----|-----|
|                     | 20%            | 40% | 60% | 80% | Total|
| Real power (kW)     | 435            | 872 | 1309| 1748| 4364 |
| Reactive power (kVAR)| 326           | 653 | 980 | 1307| 3266 |
| Apparent power (kVA)| 544            | 1089| 1635| 2182| 5450 |
| Current (A)         | 269.4          | 539.2| 809.6| 1080.4| 2698.6|
| Voltage (V)         | 1200           | 1200| 1200| 1200| 1200 |
| Power factorDaya (%)| 80             | 80  | 80  | 81  | 80.25|

Before simulating harmonics, the parameters of the simulation program are filled out, so that the resulting order, waveform, and spectrum harmonics are produced. Based on equation (2.3), at the 1st order angle $\theta$ is fundamental at a frequency of 50 Hz, then the 5th order at a frequency of 250 Hz as a discussion in the highest value research.
Figure 7. Display library harmonic loading of 20%, 40%, 60% and 80%.

Then a harmonic simulation can be done with the aim to get the value of the SR load on the outgoing transformer side of the Tanjung Barat traction substation. The effect of KRL loading on SR and the form of harmonics prior to filter installation is shown in figure 8 below:
3.2. Filter design

To improve the power factor of the transformer unit, the following calculations can be done. The following is an example of 20% loading:

\[
I_1 = 269.4 \, A
\]
\[
S = 544 \, kVA
\]

Reactive power needed to improve the power factor can be calculated as follows:

\[
Q_1 = 326 \, kVAR
\]

If the power factor (power factor) is increased to 0.9, then the amount of reactive power:

\[
PF = \theta_2 = 0.9
\]

\[
Q_2 = 544 \times \sin[\cos^{-1}(0.9)] = 544 \times \sin[25.84] = 237 \, kVAR
\]
Therefore $C = 326 + 237 = 563 \text{kVAR}$ and the reactive required passive harmonic filter to compensate according:

$$Q_C = Q_1 - Q_2$$
$$Q_C = 326 - 237 = 89 \text{kVAR}$$

Then to determine the reactance of the filter ($X_{\text{filter}}$):

$$X_{\text{filter}} = \frac{(V_L)^2}{Q_C}$$
$$X_{\text{filter}} = \frac{(1.2 \text{kV})^2 \times (1000)}{89 \text{kVAR}} = 16.2 \Omega$$

While each inductive reactance value and capacitive reactance, at a tuning frequency of 250 Hz (5th order harmonics):

$$X_C = \left[\frac{h^2}{h^2 - 1}\right] \times X_{\text{filter}}$$
$$X_C = \left[\frac{4.5^2}{4.5^2 - 1}\right] \times 16.2 = \left[\frac{20.25}{20.25 - 1}\right] \times 16.2 = 17 \Omega$$

Where the value $h$:

$$h = n - (n \times 10\%) = 5 - (5 \times 10\%) = 5 - (0.5) = 4.5$$

Determine the value of the capacitor:

$$C = \frac{1}{2\pi f X_C} = \frac{1}{2 \times 3.14 \times 50 \times 17} = 1.87 \times 10^{-4} \mu F$$

While the value for the inductor:

$$X_L = \frac{X_C}{h^2}$$
$$X_L = \frac{17}{4.5^2} = \frac{17}{20.25} = 0.84 \Omega$$

Determine the value of the inductor:

$$L = \frac{X_L}{2\pi f} = \frac{0.84}{2 \times 3.14 \times 50} = 0.0268 \text{H}$$

Passive harmonic filter circuit consists of R, L, and C which have values and obtained from the calculations above, then the determination of the R value, with Q is between 20-100, $Q = 50$ is adjusted according to the data in the ETAP simulation, then obtained:

$$Q = \frac{n \times X_L}{R}$$
$$50 = \frac{5 \times 0.84}{R}$$
$$R = \frac{5 \times 0.84}{50} = 0.084 \Omega$$

The effect of passive filter installation is that the sub-harmonic distortion value is permitted by the IEEE-519-1992 standard that harmonic distortion must be below 5%. Then the KRL system is in a safe condition to operate and the equipment is protected from damage caused by harmonic distortion.
Table 5. Comparison of harmonic simulation results.

| Load variation | Before applying filter (THD, %) | After applying filter (THD, %) |
|----------------|---------------------------------|-------------------------------|
| 20%            | 20.19                           | 1.02                          |
| 40%            | 20.19                           | 3.93                          |
| 60%            | 20.19                           | 1.70                          |
| 80%            | 20.20                           | 4.91                          |

Figure 10. Load comparison chart after and before using the filter.

4. Conclusion

From the results of the study obtained the total harmonic distortion current value of 20.19%. This shows the harmonic distortion value above 5% and exceeds the standard IEEE-519-1992 harmonics limit, it is necessary to improve the value of the harmonic distortion.

Power flow analysis simulations on the 1.2 kV outgoing transformer side using varying loads adjusted for to obtain apparent power values (kVA), real power (kW), receptor power (kVAR) and power factor (PF).

Passive filter design results obtained parameter values: for 20% load are: $C = 653$ kVAR, $X_L = 0$, $84\Omega$, and $R = 0.084\ \Omega$; for 40% load are: $C = 712$ kVAR, $X_L = 0.419\Omega$, and $R = 0.0419\ \Omega$; for 60% load are: $C = 950$ kVAR, $X_L = 0.08\Omega$ and $R = 0.008\ \Omega$; for 80% load are: $C = 1188$ kVAR, $X_L = 0.079\Omega$ and $R = 0.0079\ \Omega$;

The reduction of the total harmonic distortion current in the load (20%) dropped from 20.19% to 1.02%; expenses (40%) decreased from 20.19% to 3.93%; expenses (60%) decreased from 20.19% to 1.70%; and expenses (80%) decreased from 20.20% to 4.91%. So that the total harmonic distortion reduction results are below 5%. Based on IEE 519-1992 standards that the harmonic distortion value must not exceed or a maximum of 5%.
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