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Transformer Load Calculator & Simulator for 70kV Seduduk Putih Substation: Statistical Analysis and Prediction

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Abstract

This study aimed to analyze the load patterns of two power transformers at the 70kV Seduduk Putih Substation using descriptive statistical approaches, load analysis, and Multiple Linear Regression based on hourly data throughout 2024. The analysis focused on two main transformers with a capacity of 30 MVA each, employing descriptive statistics and regression methods to identify distribution, trends, and relationships between variables. The results indicate that the average load of the two transformers at the 70kV Seduduk Putih Substation is as follows: Transformer 1 operates at 60% of its maximum load, while Transformer 2 operates at 45% of its maximum load. This suggests that the average loads of both transformers remain below 80%, which is considered normal/safe. However, the peak load analysis shows that Transformer 1 reaches a maximum load of 92.08%, and Transformer 2 reaches 87.03%, indicating that their peak loads exceed 80%. Load data was collected periodically for specific periods, including hourly, monthly, and peak load measurements. Multiple Linear Regression was used to evaluate the relationship between time and transformer load. The findings reveal that the transformers exhibit distinct load patterns for each month, with a moderate correlation to time as indicated by the R-Square value. The peak load analysis identifies critical times with potential overloading risks. This study is expected to serve as a reference for PLN, the operator of the substation, in making operational decisions.

Keywords: Descriptive Statistics; Multiple Linear Regression; Peak Load; Average Load.

1. Introduction

Electrical power substations are fundamental nodes in power transmission and distribution systems, ensuring that electricity is delivered efficiently from generation sources to end consumers [1]. Within these substations, power transformers are among the most critical and capital-intensive assets [2]. The reliability and operational longevity of these transformers are paramount for maintaining grid stability and ensuring an uninterrupted power supply [3]. The performance of a power transformer is significantly influenced by its loading patterns, as fluctuations in load directly impact on its thermal condition, operational efficiency, and overall lifespan [4], [5].

Continuous operation under high load conditions, particularly exceeding 80% of the nominal capacity, can lead to accelerated aging of the transformer's insulation system due to excessive thermal stress [6], [7]. This degradation increases the probability of premature failure, which can result in costly outages and significant service disruptions [8]. Consequently, the diligent monitoring and analysis of transformer loads are not merely procedural tasks but essential components of a proactive asset management strategy [9], [10]. By understanding load characteristics, operators can identify potential overloading risks, optimize load distribution, and schedule maintenance more effectively [11].

In recent years, statistical analysis and predictive modeling have emerged as powerful tools for an in-depth understanding of transformer behavior [12]. Methodologies such as descriptive statistics provide a clear overview of central tendencies and variations in load, while regression analysis can model the relationships between load and other variables, such as time [13], [14]. These data-driven insights enable utilities to transition from reactive maintenance to a more predictive and condition-based approach [15].

This study focuses on the 70kV Seduduk Putih Substation, a key facility in the regional power distribution network. The substation operates two primary 30 MVA power transformers, whose performance is crucial for local energy security [16]. This research presents a comprehensive statistical analysis of the hourly load data from these two transformers throughout 2024. By employing descriptive statistics, peak load analysis, and Multiple Linear Regression, this study aims to identify distinct load patterns, pinpoint periods of critical stress, and model the underlying trends. The findings are intended to provide PLN, the substation operator, with actionable, data-driven insights to enhance operational decision-making, improve load management strategies, and ultimately safeguard the long-term reliability of the power distribution system [17].

2. Material and methods

The research on the statistical analysis of transformer load at the 70kV Seduduk Putih Substation employed a methodical approach, encompassing data collection, descriptive statistics, peak load and time distribution analysis, and Multiple Linear Regression.

2.1 Data Collection

Data for this study was directly obtained from monitoring activities at the 70kV Seduduk Putih Substation throughout 2024. The data collected included:

- Hourly transformer load for both 30 MVA transformers (Transformer 1 and Transformer 2).
- Daily and monthly maximum and minimum load data from January to November 2024.
- Supporting information such as transformer capacity, recording times, and daily fluctuations.

Data collection was performed by the Substation Operator who recorded the transformer load hourly.

2.2 Descriptive Statistics

Descriptive analysis was conducted to understand the general patterns of load distribution [18]. This involved:

- Calculating statistical values such as mean, median, mode, standard deviation, range, and maximum and minimum loads.
- Comparing load patterns between Transformer 1 and Transformer 2 across various time intervals (daily, weekly, and monthly).
- Identifying critical patterns such as peak load hours and low load periods.

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2.3 Peak Load and Time Distribution Analysis

This analysis aimed at determining the times of the highest load occurrences and evaluating the utilization level of the transformers [19]. This helps in understanding the dynamic stress placed on the equipment during periods of high demand.

2.4 Multiple Linear Regression

Multiple Linear Regression was utilized to analyze the relationship between one dependent variable (transformer load) and one or more independent variables (time) [20]. The objective was to model this relationship by forming an equation that describes the influence of independent variables on the dependent variable. Analysis parameters included regression coefficients, R-squared to measure the strength of the relationship, and residual analysis to check model accuracy [21].

3. Results and discussion

In The descriptive statistical analysis provides a detailed overview of the load characteristics for both Transformator 1 and Transformator 2 at the 70kV Seduduk Putih Substation.

Table 1. Descriptive Statistics for Power Transformers

Statistic	POWER TRANSFORMER 30 MVA 1 70/20 KV	POWER TRANSFORMER 30 MVA 2 70/20 KV
Mean	14,3398618	10,67982311
Standard Error	0,059588557	0,041530757
Median	14,4	10,3
Mode	11,5	9
Standard Deviation	5,667181919	3,949791138
Sample Variance	32,1169509	15,60085004
Kurtosis	376,0794294	216,2145083
Skewness	14,58917432	8,118923979
Range	197	135
Minimum	0	0
Maximum	197	135
Sum	129704,05	96599
Count	9045	9045
Confidence	0,116807058	0,081409683

Transformator 1: Exhibited an average load of 14.34 MW with a standard deviation of 5.67 MW. The maximum load recorded for Transformator 1 was an extreme 197 MW.

Transformator 2: Showed a lower average load of 10.68 MW with a standard deviation of 3.95 MW. Its maximum recorded load was 135 MW.

A two-sample t-test assuming equal variances was performed to compare the mean loads of the two transformers.

Transformator 1 (30 MVA, 70/20 KV): Mean load was 14.3398618 MW, with a variance of 32.1169509 and 9045 observations.

Transformator 2 (30 MVA, 70/20 KV): Mean load was 10.67982311 MW, with a variance of 15.60085004 and 9045 observations.

The pooled variance, calculated from combining both samples, was 23.85890047, which served as the basis for the t-statistic calculation. The hypothesized mean difference was 0, assuming no difference in means between the two transformers. The degrees of freedom (df) for the test were 18088.

Table 1. t-Test: Two-Sample Assuming Equal Variances

Statistic	POWER TRANSFORMER 30 MVA 1 70/20 KV	POWER TRANSFORMER 30 MVA 2 70/20 KV
Mean	14,3398618	10,67982311
Variance	32,1169509	15,60085004
Observations	9045	9045
Pooled Variance	23,85890047	
Hypothesized Mean	0	
df	18088	
t Stat	50,39062582	
P(T<=t) one-tail	0	
t Critical one-tail	1,644937873	
P(T<=t) two-tail	0	
t Critical two-tail	1,960095145	

The calculated t-statistic was 50.39062582, indicating a significant difference between the average loads of the two transformers. The p-value for both one-tail and two-tail tests was 0. This extremely small p-value (below the 0.05 significance level) strongly suggests that the observed difference is not due to chance, leading to the rejection of the null hypothesis that the means are equal. The t-critical values were 1.644937873 for one-tail and 1.960095145 for two-tail. Since the t-statistic (50.39) far exceeds these critical values, the null hypothesis is rejected.

Table 1. Descriptive Analysis of Peak Load from Two Transformers

Transformer	Month	Min Load Conc.	Max Load Conc.	Mean Load Conc.	Load Std Dev	Missing Data Count
Trafo 1	Januari	1	22,7	14,300	2,878	0
Trafo 2	Januari	0	14,2	8,746	2,144	8
Trafo 1	Februari	0	197,0	15,824	10,064	6
Trafo 2	Februari	0	17,7	10,768	2,543	6
Trafo 1	Maret	0	147,0	13,544	5,312	1
Trafo 2	Maret	0	20,0	13,868	2,495	4
Trafo 1	April	0	141,0	13,978	6,174	6
Trafo 2	April	0	18,8	13,494	2,604	6
Trafo 1	Mei	0	21,1	13,799	4,256	47
Trafo 2	Mei	0	135,0	13,844	5,833	47
Trafo 1	Juni	0	19,2	13,168	4,387	57
Trafo 2	Juni	0	14,1	8,911	2,970	60
Trafo 1	Juli	0	152,0	14,601	5,611	9
Trafo 2	Juli	0	100,0	8,779	4,341	16

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Trafo 1	Agustus	0	177,0	14,972	7,686	12
Trafo 2	Agustus	0	12,0	9,100	1,805	12
Trafo 1	September	0	21,8	15,322	2,687	1
Trafo 2	September	0	14,3	9,516	1,629	1
Trafo 1	Oktober	0	102,0	14,938	4,737	16
Trafo 2	Oktober	0	108,0	10,116	5,495	18
Trafo 1	November	0	20,9	13,339	3,989	26
Trafo 2	November	4,7	20,0	10,326	2,360	0
Trafo 1	Beban Puncak	0	22,1	17,710	2,177	1
Trafo 2	Beban Puncak	5,4	20,9	12,684	3,034	0

In summary, Transformator 1 consistently exhibited a higher average load (14.34 MW) compared to Transformator 2 (10.68 MW). A rekapitulation of the descriptive analysis for peak loads across different months reveals additional insights:

- **Transformator 1:** Recorded its highest maximum load in February at 197.0 MW, with an average load of 15.824 MW for that month, indicating a significant load surge. The highest standard deviation for Transformator 1 was in August (7.686), suggesting substantial load fluctuations.
- **Transformator 2:** Had a lower maximum load compared to Transformator 1, with its highest value also in February (17.7 MW).
- **Missing Data:** A notable amount of missing data was observed, particularly for Transformator 1 in May (47 data points) and June (57 data points), and for Transformator 2 in May (47 data points) and June (60 data points). This could potentially affect the analysis for these specific months.
- **Overall Peak Loads:** The overall peak load recapitulation shows Transformator 1 reaching 22.1 MW and Transformator 2 reaching 20.9 MW.

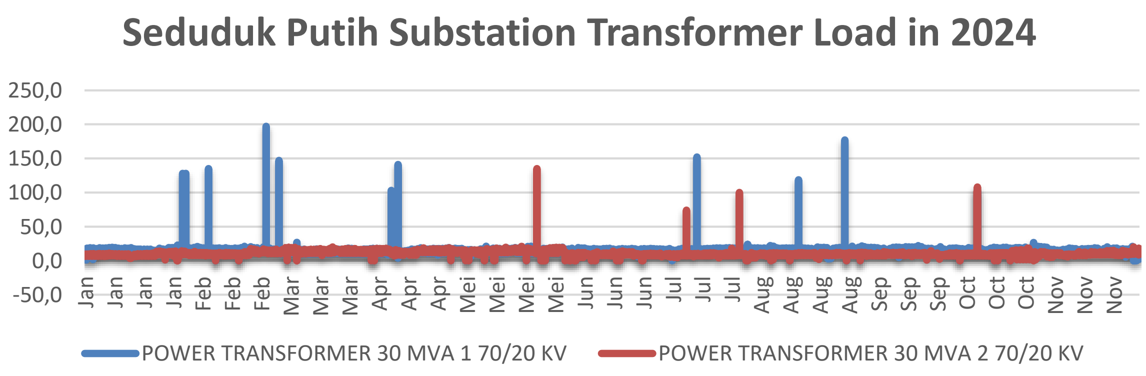

Figure 1. Average Load Graph of Seduduk Putih Substation Transformers in 2024

The maximum permissible load for a 30 MVA transformer with a power factor (cos phi) of 0.8 is calculated as follows:

$P(MW)=S(MVA)\times\cos(\phi)$

$P(MW)=30\times0.8=24MW$

The loading percentages for the 70kV Seduduk Putih Substation transformers are:

- **Average Load Percentage:**

Transformator 1: 2414.34×100%=60%

Transformator 2 : 2410.68×100%=45%

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Both transformers' average loads are still below 80%, indicating a normal and safe operational range.

- **Peak Load Percentage:**
  Transformator 1 : 2422.1×100%=92%
  Transformator 2 : 2420.9×100%=87%

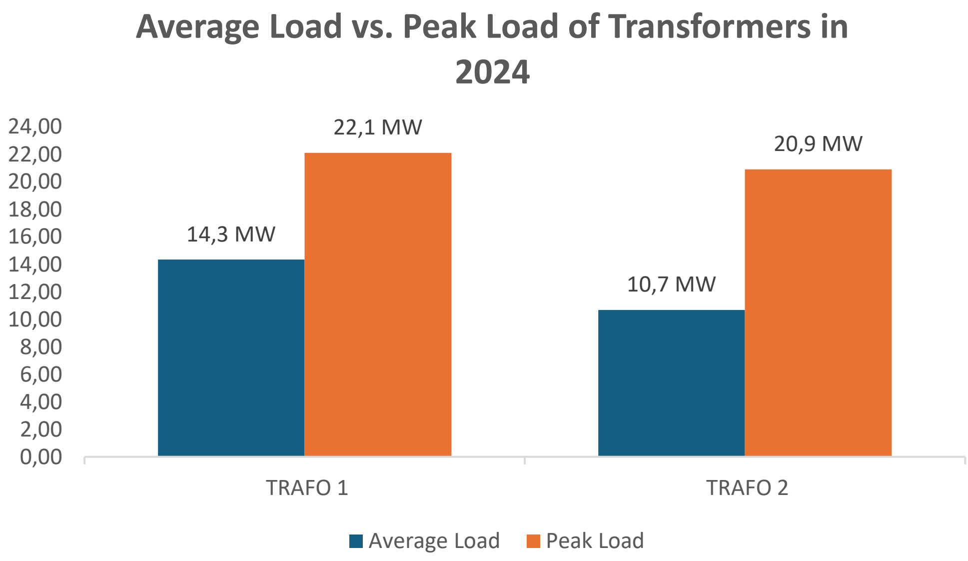

Figure 2. Comparison Chart of Average Load and Peak Load in 2024

While the real-time peak loads are still below the maximum transformer capacity, they both exceed 80%. While the real-time peak loads are still below the maximum transformer capacity, they both exceed the 80% guideline. This condition warrants attention, as consistent operation above this level increases thermal stress, accelerates insulation aging, and reduces the transformer's effective lifespan [22]. The daily peak loads for both transformers typically occur around 19:00 WIB. This aligns with established patterns where residential electricity consumption increases sharply in the evening due to lighting, cooking, and entertainment activities [23]. This condition warrants attention as operating transformers consistently above 80% load can lead to several concerns:

- **Increased Temperature and Overheating:** Higher current loads lead to increased winding temperatures, which can damage insulation and shorten the lifespan of the transformer.
- **Increased Power Losses:** High loading increases copper losses (I2R), impacting transformer efficiency and operational costs.
- **Higher Current and Overload Risk:** Continuous operation above 80% increases the risk of overload, potentially triggering protection trips or system disturbances.
- **Decreased Insulation Quality:** High loading accelerates the degradation of insulation oil and materials due to increased temperature and oxidation, leading to a decline in insulation properties.
- **Reduced Transformer Lifespan:** Continuous operations above 80% can reduce the effective lifespan of the transformer, as its life is highly dependent on operating temperature and insulation levels.
- **Voltage Sag and System Instability:** Transformers nearing full load can cause voltage drops on the secondary side, affecting the quality of the power supplied.

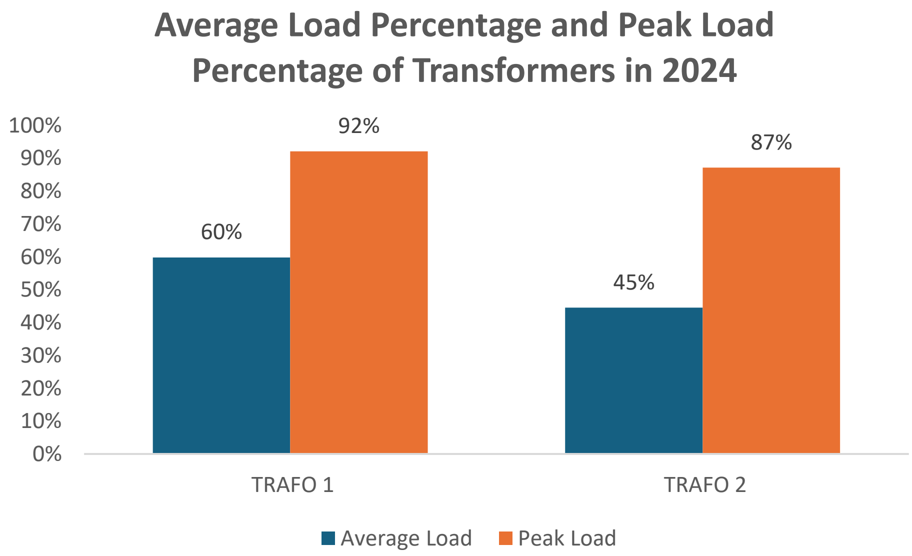

Figure 3. Comparison Chart of Average Load Percentage and Peak Load Percentage in 2024

The daily peak loads for both Transformator 1 and Transformator 2 typically occur around 19:00 WIB. This aligns with increased electricity usage across various sectors (household, commercial, and some industrial) simultaneously. Key factors contributing to this peak include:

- **Increased Household Activity:** People returning home from work/school (17:00–19:00 WIB) begin using appliances like lights, TVs, refrigerators, fans, ACs, rice cookers, and washing machines. As the sun sets, indoor and outdoor lighting is switched on, sharply increasing electricity consumption.
- **Entertainment and Leisure Activities:** Evening hours are a time for family gatherings and entertainment, involving the use of TVs, computers, electronic devices, and streaming services, all requiring electricity.
- **Air Conditioning Usage:** While ambient temperatures may cool down at night, indoor activity increases, leading many households and offices to turn on ACs or fans for comfort, with ACs being significant energy consumers.
- **Ongoing Industrial and Commercial Consumption:** Although industrial activity generally decreases at night, some industries operate night shifts (e.g., 24-hour factories, data centers), and commercial establishments like shopping centers and restaurants remain active into the evening.
- **Cooking and Dinner Preparation:** Many families cook or reheat meals in the evening using electric appliances, further contributing to the load.
- **Public Lighting:** Streetlights, offices, parks, and places of worship also turn on artificial lighting at night, adding to the overall electricity load.

Monthly peak loads tend to occur from the 15th onwards or towards the end of the month. This pattern can be attributed to several factors:

- **Industrial Production Activity:** Industries often maximize production during the middle to end of the month to meet production targets or shipping deadlines, requiring higher energy consumption.
- **Bill and Installment Payments:** Many bills (installments, business operational costs, monthly payments) are due at the end of the month or around the 15th,

leading to increased activity in offices, service centers, and greater use of electronic devices.

- **Household Consumption Patterns:** After receiving salaries, people tend to engage in more consumption activities (shopping, entertainment), which often require more electricity, leading to increased visitor numbers at shopping centers and restaurants.
- **Increased Use of Cooling or Electric Machinery:** The use of appliances like air conditioners, production machines, or other electrical equipment typically increases towards the end of the month due to work pressure or business needs.

For the year 2024 up to November, the peak load for Transformator 1 was observed in August at 22.1 MW, and for Transformator 2, it was in May at 20.9 MW.

Multiple Linear Regression

The initial Multiple Linear Regression model yielded the following equation:

$Y=4.4911+0.3010\times\text{Trafo 1}+0.3461\times\text{Trafo 2}$

- **Intercept (Constant):** 4.4911. This is the estimated value of the dependent variable (Y) when both Transformer 1 and Transformer 2 are zero.
- **Coefficient for Trafo 1:** 0.3010. For every 1-unit increase in Transformer 1 load, Y is estimated to increase by 0.3010 units, assuming Transformer 2 remains constant. The positive coefficient indicates a positive impact on Y. This coefficient is statistically significant with a P-value of 6.1789E-118.
- **Coefficient for Trafo 2:** 0.3461. For every 1-unit increase in Transformer 2 load, Y is estimated to increase by 0.3461 units, assuming Transformer 1 remains constant. This positive coefficient also indicates a positive impact on Y. This coefficient is statistically significant with a P-value of 3.08258E-77.

The

R-squared value for this model is 0.113545435. This indicates that only 11.35% of the variation in the dependent variable (Y) can be explained by the independent variables (Transformer 1 and Transformer 2). This is considered a low value, suggesting that the model is not very strong in explaining data variation, and other factors might have a greater influence.

The overall **p-value** for the model is 2.405E-237. This extremely small p-value (less than 0.05) indicates that the model is statistically significant, meaning there is a significant relationship between independent and dependent variables. Similarly, the individual p-values for the coefficients (6.1789E-118 and 3.08258E-77) are very small, reinforcing their statistical significance within the model.

Despite the model being statistically significant (very small p-value), the low R-squared value (0.11) implies that while a relationship exists, the independent variables only explain a small portion of the variation in the dependent variable. This suggests that the model has low predictive power but confirms that the independent variables do influence the dependent variable. Both Transformer 1 and Transformer 2 show a positive influence on the dependent variable Y. However, the low R-squared indicates that many other variables influencing Y are not included in the model. All coefficients in the model are statistically significant due to their very small P-values.

Exponential and Square Root Transformations

After applying exponential and square root transformations to the transformer load data, the following regression equation was obtained: Y=4.4433+7.7174X1+2.5169X2

- **Y** : Dependent variable.
- **Intercept** : 4.4433. This is the average value of Y when both independent variables (X1 and X2) are zero. The intercept's P-value of 4.58E-33 indicates it is statistically significant.
- **X1 (Transformer 1)** : The regression coefficient for Transformer 1 is 7.7174E-86. This value is extremely small, implying a practically insignificant effect on the dependent variable Y. Its P-value of 0.6907 (greater than 0.05) confirms that Transformer 1 is not statistically significant in influencing Y after this transformation.
- **X2 (Transformer 2)** : The regression coefficient for Transformer 2 is 2.5169. This means that for every one-unit increase in Transformer 2, the value of Y increases by 2.5169, assuming other variables remain constant. Its P-value of 6.04E-107 indicates that Transformer 2 significantly influences the dependent variable Y.

R-squared value for this transformed model is 0.052, which is even lower than the previous model's 0.11. This reduction in R-squared can occur if the linear relationship between independent and dependent variables is disturbed, if data variation decreases due to transformation leading to loss of important information, or because R-squared is optimal for linear relationships, not non-linear ones.

The **F-Statistic** value is 248.035 with a Significance F of 0, indicating that the overall regression model is statistically significant. This implies that at least one independent variable has a significant relationship with the dependent variable, even if the R-squared value is small.

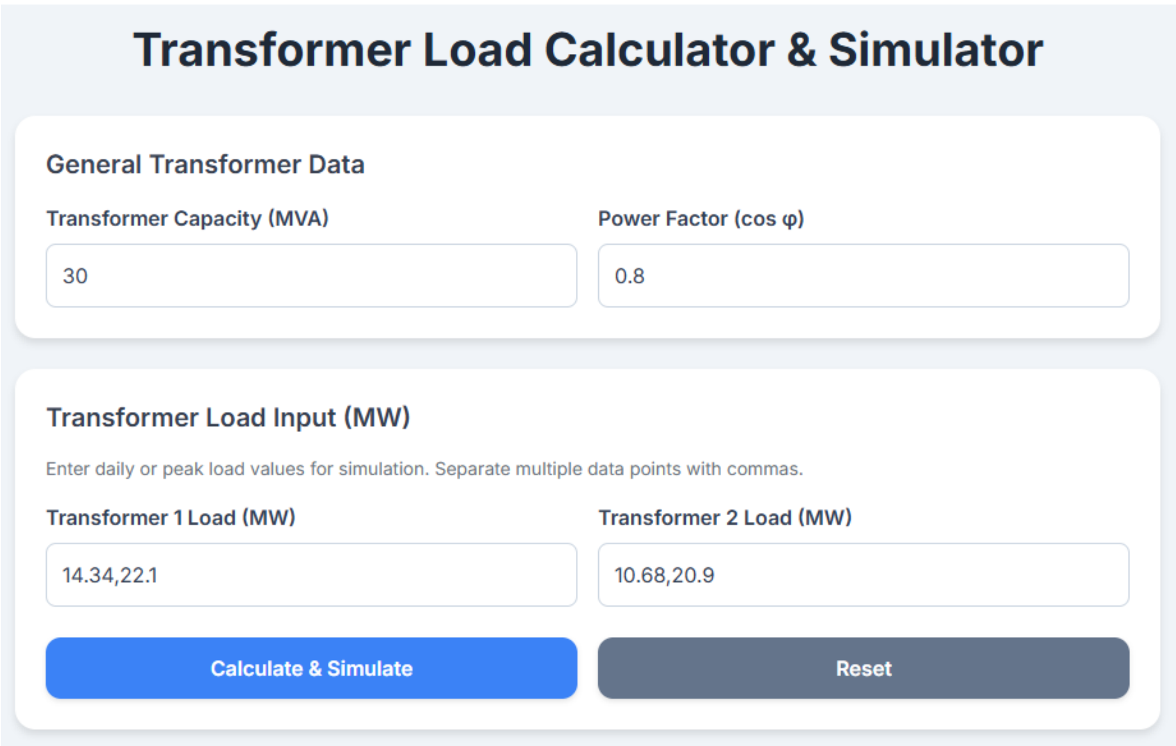

Figure 4. Transformer Load Calculator & Simulator Interface

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This figure 4 displays a "Transformer Load Calculator & Simulator" interface. It allows users to input general transformer data, specifically the "Transformer Capacity (MVA)" and "Power Factor (cos φ)". In the example shown, the transformer capacity is set to 30 MVA and the power factor to 0.8. Additionally, there's a section for "Transformer Load Input (MW)," where users can enter daily or peak load values for simulation. For "Transformer 1 Load (MW)," the input is "14.34, 22.1," and for "Transformer 2 Load (MW)," the input is "10.68, 20.9". The interface includes "Calculate & Simulate" and "Reset" buttons.

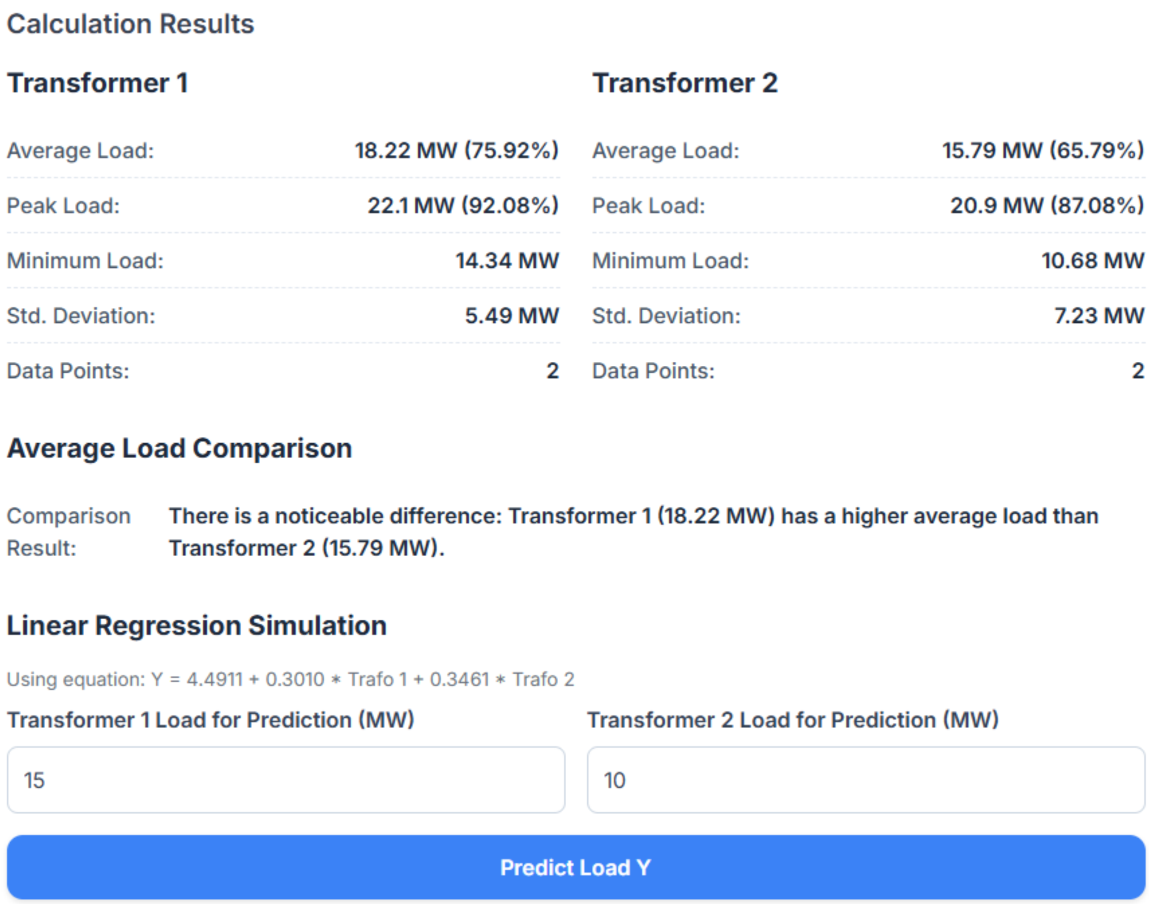

Figure 5. Transformer Load Calculation Results and Linear Regression Simulation Interface

This figure 5 displays the "Calculation Results" and "Linear Regression Simulation" sections of a transformer load analysis tool. For Transformer 1, the average load is 18.22 MW (75.92%), the peak load is 22.1 MW (92.08%), the minimum load is 14.34 MW, and the standard deviation is 5.49 MW, based on 2 data points. For Transformer 2, the average load is 15.79 MW (65.79%), the peak load is 20.9 MW (87.08%), the minimum load is 10.68 MW, and the standard deviation is 7.23 MW, also based on 2 data points.

An "Average Load Comparison" highlights a noticeable difference, with Transformer 1 having a higher average load (18.22 MW) than Transformer 2 (15.79 MW). The "Linear Regression Simulation" uses the equation Y = 4.4911 + 0.3010 * Trafo 1 + 0.3461 * Trafo 2. It provides input fields for "Transformer 1 Load for Prediction (MW)" (set to 15) and "Transformer 2 Load for Prediction (MW)" (set to 10), along with a "Predict Load Y" button.

Predicted Load Y: 12.47 MW

Recommendations Based on Load Analysis

- Regularly monitor **Transformer operating temperature** using thermometers or temperature sensors.
- Check the **Transformer cooling system** (cooling oil or fans) for optimal operation.
- Evaluate **load patterns** to ensure the Transformer does not experience prolonged overload durations.
- Distribute load to other Transformers if possible to **balance the load**.
- Monitor **current** via control panels or current transformer (CT) measurement devices.
- Ensure **protection systems** like overcurrent relays are functioning correctly.
- Perform regular **Transformer oil quality tests** (DGA - Dissolved Gas Analysis).
- Consider replacing or treating **insulating oil** if its quality deteriorates.
- Keep the load within reasonable limits, ideally **not exceeding 80% of maximum capacity**.
- Perform **regular preventive maintenance**.
- Check **voltage regulation** and tap changer adjustments.
- Ensure the **supply system** from the Transformer remains stable.
- Monitor Transformer conditions in **real-time** using SCADA or other monitoring systems.
- Perform **periodic maintenance** (preventive maintenance) such as: Checking temperature, oil levels, and cooling systems. Testing insulating oil quality and insulation condition.
- Consider **adding Transformer capacity** or installing additional Transformers if the load consistently increases significantly.
- Further steps could involve additional analysis of peak load distribution over time and causes of load differences for better operational planning.
- A more comprehensive study could consider other factors such as ambient temperature or customer consumption patterns.

Figure 6. Predicted Load Y and Recommendations Based on Load Analysis

This image presents "Recommendations Based on Load Analysis" for transformers, alongside a "Predicted Load Y" value of 12.47 MW.

4. Conclusion

This research provides significant insights into the load distribution patterns of the transformers at the 70kV Seduduk Putih Substation. The t-test results conclusively demonstrate a statistically significant difference between the average loads of Transformer 1 (14.34 MW) and Transformer 2 (10.68 MW). While the average loading percentages (60% and 45%, respectively) are within a safe operational range, the peak load analysis reveals a more critical situation. With peak loads reaching 92.08% for Transformer 1 and 87.03% for Transformer 2, both units operate above the recommended 80% threshold during high-demand periods. This poses a long-term risk to transform health and system reliability.

The multiple linear regression model, despite its statistical significance, showed a low R-squared value of 0.11, indicating that time alone is a weak predictor of load variation. This underscores the need for more complex models that incorporate additional variables like ambient temperature and customer class data for more accurate forecasting. The findings of this study provide a crucial data-driven foundation for PLN to implement proactive load management strategies, consider load balancing between the transformers, and schedule condition-based maintenance to mitigate the risks associated with frequent peak loading.

Author contribution

Nur Aldillah Julita led this research, handling its conceptualization, methodology, statistical analysis, data curation, and visualization. She also prepared the original manuscript and managed the project's administration under the supervision of Syamsir Abduh and Farid Wijaya.

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Competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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