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Performance Analysis of Adaptive Defense Schemes (ADS) in Protection and Reliability Systems of Electric Power Transmission Systems

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The reliability of the electric power transmission system is a crucial factor in ensuring the continuity of electrical energy distribution to customers. Disturbances in the transmission system can cause significant technical and economic losses. Therefore, the application of Adaptive Defense Schemes (ADS) was developed as an effort to improve the performance of the protection system and the reliability of the electric power transmission system. This study aims to analyze the performance of ADS on the Barikin-Tanjung bay line electric power transmission system and evaluate its technical and economic effectiveness. The disturbance data used include the number of disturbances, the duration of disturbances, and Energy Not Supplied (ENS) during the period 2015–2022, which is divided into the pre-implementation period of ADS (2015–2018) and post-implementation period of ADS (2019–2022). The Autoregressive Integrated Moving Average (ARIMA) method is used to analyze the characteristics of time series data and forecast disturbances in the period 2023–2026. The results of the analysis show that the implementation of ADS is able to reduce the number of disturbances, the duration of disturbances, and the ENS value significantly in the post-implementation period. The selected ARIMA models, namely ARIMA (2,1,1) for the number of disturbances, ARIMA (3,1,1) for the duration of disturbances, and ARIMA (2,1,1) for ENS, produced stable predictions with residuals without significant autocorrelation. In addition, the results of the economic analysis showed that the implementation of ADS was able to reduce the company's potential losses by more than 50% compared to the scenario without ADS. Thus, ADS has proven effective in improving the reliability of the electric power transmission system and is worthy of being recommended for implementation in other transmission lines with high levels of vulnerability.
Keywords: Adaptive Defense Schemes, transmission system reliability, ARIMA, transmission disturbances, Energy Not Supplied.

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1. Introduction

The global development of the digital era demands an increasingly high level of reliability in electric power transmission systems. A reliable transmission system is the main foundation for the continuity of community activities, industrial operations, health services, and other critical infrastructure. Disruptions to the electric power transmission system not only cause significant economic losses, but can also reduce the quality of life and potentially endanger public safety. These disruptions can occur on a limited scale, such as blackouts in several areas within a city, but it is not uncommon to occur on a large scale, impacting several cities simultaneously [1]. Therefore, efforts to minimize the duration of disruptions (downtime) and accelerate system recovery after disruptions are a top priority in the management of electric power transmission systems.PT PLN (Persero) Main Distribution and Load Regulator Unit (UIP3B) North Sumatra is a unit responsible for the distribution and regulation of the electric power transmission system in the Medan area and its surroundings. This system serves the electricity needs of economic, industrial, and residential activity centers that have a relatively high load growth rate. The electricity generation sources in this system come from Hydroelectric Power Plants (PLTA), Steam Power Plants (PLTU), Gas Power Plants (PLTG), and Diesel

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Power Plants (PLTD). Electric power distribution is carried out through High Voltage Air Lines (SUTT) and Extra High Voltage Air Lines (SUTET) with voltage levels of 70 kV, 150 kV, and 275 kV that connect the power centers with substations and distribution networks in the Medan area and its surroundings.

In the interconnection system of North Sumatra, particularly the Medan system, there are several critical points that have the potential to disrupt the balance and reliability of the transmission system. Disruptions to main transmission lines or strategic substations can cause voltage drops, load shedding, and even widespread blackouts. These conditions require a protection system that is not only fast and selective but also able to adapt to changing system conditions dynamically.

In an effort to improve the reliability and resilience of the electric power transmission system in the Medan region, Adaptive Defense Schemes (ADS) technology has been developed and implemented. ADS is an automatic protection and control system designed to quickly detect disturbances, perform adaptive responses according to actual system conditions, and minimize the impact of disturbances on the continuity of electric power distribution. The ADS system integrates Industry 4.0-based technology, which combines Supervisory Control and Data Acquisition (SCADA) systems, protection systems, and information technology (IT) as a means of sensing, measuring, and controlling automatically and in real-time. Although ADS offers various advantages, a comprehensive performance evaluation is needed to ensure its effectiveness in improving the reliability of the electric power transmission system in the Medan region.

One method that can be used to analyze the performance and effectiveness of ADS is a forecasting method based on historical disturbance data. The forecasting method aims to predict future system conditions by utilizing data patterns in previous periods. In this study, the Autoregressive Integrated Moving Average (ARIMA) method is used as a time series analysis model. The ARIMA model, developed by Box and Jenkins [3], is capable of analyzing data that has autocorrelation patterns, trends, and non-stationary properties.

The frequency and duration of disturbances in the electric power transmission system in the Medan region tend to be non-stationary due to increased loads, changes in network configuration, and continuous updates to the network protection and defense systems. Therefore, the use of the ARIMA method is considered appropriate for analyzing disturbance trends before and after the implementation of ADS. The results of this analysis are expected to provide a quantitative overview of the contribution of ADS in improving the reliability of the electric power transmission system in the Medan region. The ARIMA method itself has been widely applied in various fields, such as the financial and business sectors [4][5], disturbance detection systems [6][7], and the health sector [8][9].

2. Literature Review

Electric Power Transmission System

The electric power transmission system is a crucial component of the electric power system, delivering electrical energy from generating plants to distribution systems with a high level of reliability and power quality. Transmission systems generally operate at high and extra-high voltage levels to minimize power losses during the transmission process. Transmission system reliability is heavily influenced by network configuration, equipment condition, and the effectiveness of the protection system in detecting and isolating faults quickly and selectively. Disruptions to the transmission system can be caused by various factors, such as natural disturbances (lightning, extreme weather), equipment failure, operational errors, and external disturbances. Electrical power protection systems function to protect equipment and maintain continuity of electrical power supply by detecting disturbances and isolating affected parts of the system. Conventional protection systems generally operate based on fixed settings determined from system studies. While these systems are quite reliable under normal conditions, they have limitations in responding to dynamic changes in system conditions, such as changes in load, network configuration, and the integration of new power plants.

Adaptive Defense Schemes (ADS)

Adaptive Defense Schemes (ADS) are automated protection and control systems designed to improve the resilience and reliability of electric power systems against disturbances. ADSs utilize real-time data from various sources, such as SCADA systems, Intelligent Electronic Devices (IEDs), and communication systems, to analyze system conditions quickly and accurately. Unlike conventional protection systems, ADSs can adjust protection and control strategies based on actual system conditions. Responses that ADSs can implement include adaptive load shedding, network reconfiguration, and dynamic protection coordination.

Reliability of Electric Power System

Electric power system reliability is defined as the system's ability to continuously provide electrical energy with quality that meets standards. Commonly used reliability indices to evaluate power system performance include the System Average Interruption Duration Index (SAIDI), the System Average Interruption Frequency Index (SAIFI), and Energy Not Supplied (ENS). The implementation of effective protection and defense systems, including ADS, plays a crucial role in improving these reliability indices. Reducing the frequency and duration of interruptions is a key indicator of the success of a protection system in maintaining reliable power distribution.

3. Research Methods

This study uses data on transmission system disruptions on the Barikin–Tanjung bay line for the period 2015–2022. The data is divided into two periods: the pre-ADS implementation period (2015–2018) and the post-ADS implementation period (2019–2022). This division aims to compare system conditions before and after the implementation of Adaptive Defense Schemes (ADS). Exploratory data analysis was conducted to understand the initial characteristics of the disturbance data, including distribution, trends, and patterns. This analysis included calculating descriptive statistics such as mean, median, mode, and standard deviation, as well as data visualization using histograms and time series plots. This process was performed using Microsoft Excel software. Stationarity testing is performed to ensure that time series data meets the requirements for using the ARIMA model. Testing is performed using the Augmented Dickey-Fuller (ADF) Test or KPSS Test. If the data is not stationary, a differencing or logarithmic transformation is performed until the data becomes stationary. The entire stationarity testing process is performed using the Python programming language [10].

ARIMA modeling was performed to determine the best model to represent the disturbance data. Parameters p, d, and q were determined by analyzing the Autocorrelation Function (ACF) and Partial Autocorrelation Function (PACF) graphs, and using the Auto ARIMA feature for comparison. The best model was selected based on the smallest Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) values. The forecasting process was performed using the selected ARIMA model. Forecasting was conducted in two stages. The first stage used data from 2015–2018 to predict disruptions in 2019–2022, reflecting conditions without ADS. The second stage used data from 2019–2022 to predict disruptions in 2023–2027 to evaluate the system's condition after ADS implementation. The effectiveness of ADS was analyzed by comparing disruption data before and after ADS implementation, both based on actual data and ARIMA model forecasting results. The results of this analysis were used to assess the contribution of ADS in reducing disruption frequency and as a basis for recommendations for ADS implementation on other transmission lines with high vulnerability levels.

4. Results and Discussion

Disturbance Data 2015 - 2022.

The disturbance data used in this study includes the number of disturbances, duration of disturbances, and Energy Not Supplied (ENS) in the electric power transmission system during the period 2015–2022. This data is used as the basis for analysis to evaluate the performance of Adaptive Defense Schemes (ADS) in improving transmission system reliability. Figure 2 shows a summary of the number of monthly outages over an eight-year period. Meanwhile, the disturbance duration is shown in Figure 3 and the ENS value is shown in Figure 4.

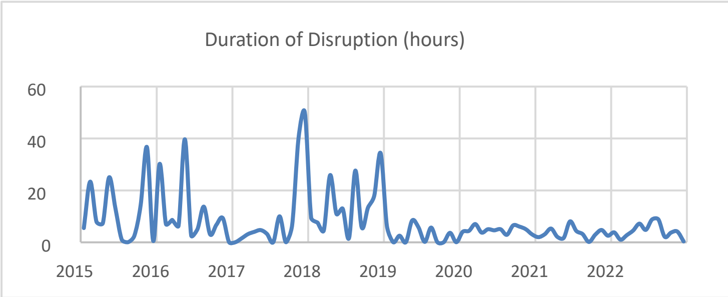

Figure 2. Recapitulation of Number of Disturbances 2015 - 2022

Figure 2 shows a significant change in the trend of disruptions after 2018, which coincided with the ADS implementation period. This trend change is also supported by the analysis results in Appendices 1 to 8, which show a difference in the mean value of disruptions between the pre-ADS implementation period (2015–2018) and post-ADS implementation period (2019–2022). Furthermore, the highest number of disruptions occurred in 2018, the initial year of ADS implementation. This high number of disruptions was due to the installation and testing of the ADS system on the Barikin–Tanjung transmission line, which, during the initial implementation phase, had the potential to cause temporary disruptions to the transmission system. After that period, the trend in the number of disruptions showed a downward trend, indicating an improvement in the protection system performance and transmission system reliability after the ADS was operating optimally.

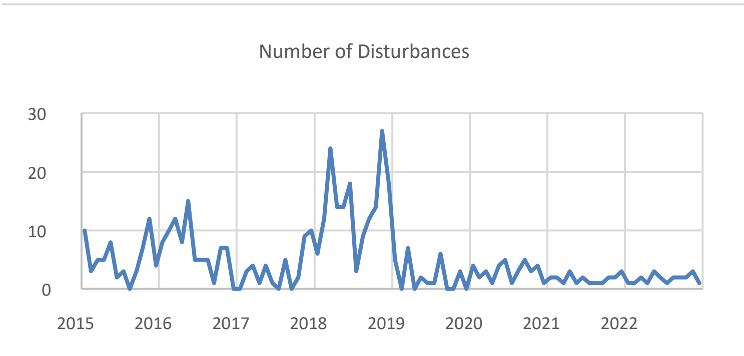

Figure 3. Recapitulation of Disruption Duration for the 2015–2022 Period

Based on Figure 3, the duration of power transmission system disruptions showed a significant downward trend after the implementation of Adaptive Defense Schemes (ADS). In the post-ADS implementation period, from 2019 to 2022, the duration of disruptions remained relatively stable, ranging from 0 to 8.77 hours.

The relatively high duration of outages in 2018 was due to the implementation and testing of the ADS system on the Barikin-Tanjung bay line. During the initial implementation phase, adjustments were made

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to the protection system and network configuration, potentially leading to temporary disruptions to power supply to customers. After the ADS was fully operational, outage durations decreased and tended to be more manageable, indicating improved protection system performance and power transmission system reliability.

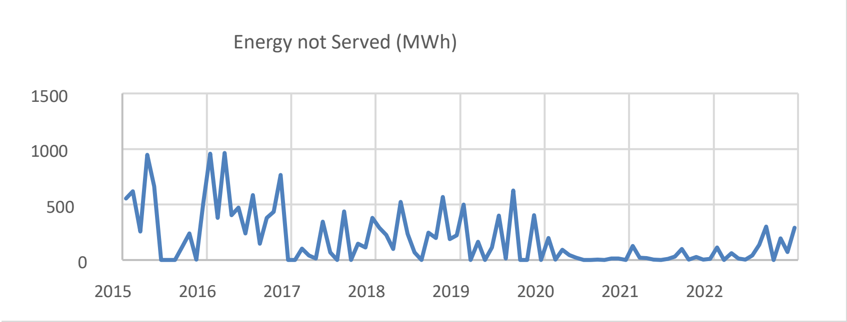

Figure 4. Recapitulation of Energy Not Supplied (ENS) for the 2015–2022 Period

Figure 4 shows a significant change in the Energy Not Supplied (ENS) value after the implementation of Adaptive Defense Schemes (ADS) in 2018. In contrast to the number and duration of disruptions that experienced a spike in 2018, the ENS value did not show a significant increase during that period. This is because ENS represents the amount of electrical energy that is not supplied due to disruptions, which is greatly influenced by the amount of power affected by each disruption event. Each disruption has different characteristics and levels of impacted power. Therefore, although in 2018 there was an increase in the number and duration of disruptions, the impact of unsupply energy can be reduced through more effective system management and control.

Exploratory Data Analysis

This section conducts an exploratory analysis of the disturbance data to identify key characteristics, including the mean, median, standard deviation, minimum, and maximum values. The results of this analysis serve as a basis for understanding data patterns, distribution, and variability, as well as determining the appropriate modeling approach for forecasting analysis.

Table 1. Summary of Disturbance Data for the Period 2015–2022

Parameter	Number of Disturbances	Duration (hours)	ENS (MWh)
Mean	4.77	7.76	191.09
Median	3.00	4.68	98.90
Standard Deviation	5.20	9.76	238.66
Minimum	0.00	0.00	0.00
Maximum	27.00	50.02	964.57

Source: Disturbance Data for the Period 2015–2022

Based on Table 1, the number of disruptions on the Barikin–Tanjung bay line during the 2015–2022 period had an average value of 4.77 disruptions per month with a median of 3 disruptions and a standard deviation of 5.20, indicating significant data variation. The minimum value of the number of disruptions recorded was 0, while the maximum value reached 27 disruptions in one month. For the disruption duration parameter, the average value was 7.76 hours, a median of 4.68 hours, and a standard deviation of 9.76 hours. The minimum disruption duration value was recorded at 0 hours, while the maximum value reached 50.02 hours, indicating the occurrence of disruptions with a relatively long duration during a certain period.

Meanwhile, the Energy Not Supplied (ENS) parameter has an average value of 191.09 MWh with a median of 98.90 MWh and a standard deviation of 238.66 MWh. The minimum ENS value is 0 MWh, while the maximum value reaches 964.57 MWh, indicating significant variation in the amount of energy not supplied due to disturbances. The high variability in these three parameters indicates that the disturbance data is non-stationary, so a time series analysis method capable of handling these characteristics is needed, such as the ARIMA model.

Stationarity Test

Stationarity test is performed before applying ARIMA model because this model assumes that the time series data used is stationary. In this study, stationarity test is performed using Augmented Dickey-Fuller (ADF) and Kwiatkowski–Phillips–Schmidt–Shin (KPSS) on three parameters, namely the number of disturbances, the duration of the disturbance, and Energy Not Supplied (ENS). The ADF test is used to detect the presence of a unit root, where a p-value > 0.05 indicates non-stationary data. Conversely, the KPSS test is used to test the stationarity of the trend, where a p-value < 0.05 indicates non-stationary data [4]. These two tests complement each other in determining the statistical properties of the data.

Table 2. ADF and KPSS Test Results

Parameter	p-value ADF	ADF Conclusion	KPSS p-value	KPSS Conclusion	Final Conclusion
Number of Disturbances	0.062	Non-stationary	0.068	Stationary	Non-stationary
Duration	0.119	Non-stationary	0.014	Non-stationary	Non-stationary
ENS	0.013	Stationary	<0.01	Non-stationary	Non-stationary

Based on Table 2, it can be concluded that the three parameters are non-stationary, because none of the parameters meet the stationary criteria in both tests simultaneously.

Fitting the ARIMA Model

The ARIMA model fitting process is carried out through several stages, namely differencing data, determining candidate parameters p, d, q using ACF/PACF, selecting the best model based on AIC/BIC criteria, and model diagnosis for validation. The differencing process is performed to transform non-stationary data into stationary data. The d parameter in the ARIMA model indicates the level of differencing used. Stationarity retesting is performed after differencing using Python on the Google Collaboratory.

Table 3. ADF and KPSS Test Results for d = 1

Parameter	p-value ADF	ADF Conclusion	KPSS p-value	KPSS Conclusion	Conclusion
Number of Disturbances	0,000	Stationary	0.10	Stationary	Stationary
Duration	0.0003	Stationary	0.10	Stationary	Stationary
ENS	0,000	Stationary	0.10	Stationary	Stationary

The test results show that d = 1 is sufficient to make all parameters stationary, so that no additional differencing is required. Autocorrelation Function (ACF) and Partial Autocorrelation Function (PACF) analysis are used to determine candidate autoregressive parameters (p) and moving average (q).

Table 4. Candidate ARIMA Parameters

Parameter	p	d	q
Number of Disturbances	2, 11	1	1, 11
Duration	3, 10	1	1, 4

Parameter	p	d	q
ENS	2, 13	1	1

Table 5. ARIMA Model Candidate Combinations

Variables	Combination (p,d,q)
Number of Disturbances	(2,1,1); (2,1,11); (11,1,1); (11,1,11)
Duration	(3,1,1); (3,1,4); (10,1,1); (10,1,4)
ENS	(2,1,1); (13,1,1)

The best model was selected using the Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC). The model with the lowest AIC and BIC values was selected, and if there was more than one best candidate, cross-validation was performed.
Model selection results:

1. Number of Interferences → ARIMA (2,1,1)
2. Duration → ARIMA (3,1,1)
3. ENS → ARIMA (2,1,1)

Model diagnostics were performed to ensure that the residuals were free of autocorrelation and that the model was suitable for forecasting. Residual analysis showed no specific pattern, and the Ljung–Box test yielded a p-value of 0.992, indicating no residual autocorrelation. Model accuracy was evaluated using MAE = 3.99 and RMSE = 4.57, indicating acceptable predictive performance. Cross-validation results also showed that the selected model configuration had the lowest MAE and RMSE values compared to other candidates.

Forecasting

Forecasting was conducted to project the number of disturbances, duration of disturbances, and ENS on the Barikin–Tanjung bay line for the period 2023–2026 using historical data from 2015–2022. The ARIMA model used is:

1. Number of Interferences: ARIMA (2,1,1)
2. Duration: ARIMA (3,1,1)
3. ENS: ARIMA (2,1,1)

The forecasting results show that all three parameters tend to remain constant at low values, indicating continued improvement in system reliability after ADS implementation.

ADS Effectiveness

The effectiveness of ADS is analyzed by comparing:

1. Actual pre-ADS data (2015–2018)
2. Actual post-ADS data (2019–2022)
3. Forecast data without ADS (2019–2022)
4. Data forecast with ADS (2023–2026)

The comparison results show that:

1. The number of disturbances decreased by 70%
2. The duration of the outage decreased significantly compared to the scenario without ADS.
3. ENS decreased drastically in the post-ADS period

Financially, with an ADS investment cost of IDR 585,517,230 and an equipment lifetime of 4–5 years, the implementation of ADS is capable of:

1. Reduce company losses by up to 65% (±Rp 7.13 billion) in the 2019–2022 period
2. Reduce potential losses by up to 59% (±Rp 6.40 billion) in the 2023–2026 period

These results indicate that ADS is technically and economically effective in improving the reliability of the electric power transmission system on the Barikin–Tanjung bay line.

5. Conclusion

Based on the analysis results, it can be concluded that the implementation of Adaptive Defense Schemes (ADS) on the Barikin–Tanjung bay line power transmission system has significantly improved system reliability. This is indicated by a decrease in the number of disruptions, the duration of disruptions, and the Energy Not Supplied (ENS) value in the post-ADS implementation period compared to the pre-implementation period. The use of the ARIMA model in time series analysis is able to represent the characteristics of non-stationary disruption data and produce stable and consistent forecasts for future periods. The forecasting results show that the disruption trend in the 2023–2026 period tends to be low and stable, indicating a continued improvement in the protection system performance after the ADS operates optimally. In addition, from an economic perspective, the implementation of ADS provides significant benefits by being able to reduce potential company losses due to disruptions by more than 50% when compared to the scenario without ADS. Thus, ADS can be declared effective both technically and financially and is worthy of being recommended for implementation on other transmission lines with high levels of vulnerability.

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