RELIABILITY EVALUATION OF TRACTION POWER SUPPLY SYSTEM FOR MASS RAPID TRANSIT

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Suranaree University of Technology has approved this thesis submitted in partial fulfillment of the requirements for a Master's Degree.

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คำสำคัญ : ความเชื่อถือได้/ความพร้อมใช้งาน/การซ่อมบำรุงรักษา/การวิเคราะห์ RAM/สถานีย่อยไฟฟ้ากระแสตรงขับเคลื่อน/ระบบขนส่งมวลชน/ดัชนีระบบไฟฟ้าขัดข้อง(LOLE)/การซ่อมบำรุงรักษาเชิงป้องกัน

วิทยานิพนธ์นี้ขอนำเสนอรูปแบบวิธีการประเมินความน่าเชื่อถือของระบบจ่ายกำลังฉุดลากสำหรับการขนส่งมวลชนด้วยกรณีศึกษารถไฟฟ้าใต้ดินสายสีม่วงเพื่อนำเสนอรูปแบบในการประเมินความเชื่อถือได้โดยแบ่งออกเป็นสามขั้นตอนตามรูปแบบความเชื่อถือได้ ความพร้อมใช้งาน และการซ่อมบำรุงรักษา (RAM) การประเมินความเชื่อถือได้โดยใช้ดัชนีอัตราความล้มเหลวเปรียบเทียบกับมาตรฐาน EN:50126 เพื่อคาดคะเนอัตราความล้มเหลวที่เพิ่มขึ้นตามเวลา การประเมินความพร้อมใช้งานโดยใช้ดัชนี LOLE เพื่อตรวจสอบความพร้อมใช้งานของสถานีย่อยไฟฟ้าขับเคลื่อนว่าสามารถรองรับกำลังงานไฟฟ้าโดยเปรียบเทียบกับมาตรฐาน BAL-502-RF-03 การพิจารณาการบำรุงรักษาเชิงป้องกันสามารถยืดอายุการใช้งานได้โดยการระบุช่วงเวลาการบำรุงรักษาเชิงป้องกันที่เหมาะสมที่สุดซึ่งสัมพันธ์กับงบประมาณการบำรุงรักษาที่เหมาะสม โดยผลลัพธ์ที่ได้แสดงให้เห็นถึงวิธีการประเมินด้วยระบบ RAM ที่สามารถนำมาใช้งานได้ตั้งแต่ช่วงการวางแผนโครงการจนถึงการวางแผนการปรับปรุงโครงการในอนาคตโดยมีนำเสนอกรณีศึกษาในการปรับปรุงความเชื่อถือได้และความพร้อมใช้งานของระบบ

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ลายมือชื่ออาจารย์ที่ปรึกษา ....

AEKKASIT KINGMANEERAT : RELIABILITY EVALUATION OF TRACTION POWER SUPPLY SYSTEMS FOR MASS RAPID TRANSIT. THESIS ADVISOR : PROF. THANATCHAI KULWORAWANICHPONG, Ph.D., 145 PP.

Keyword : Reliability/Availability/Maintenance/RAM Analysis/DC Traction Power Supply System/Mass Rapid Transit/Loss of Load Expectation (LOLE)/Preventive Maintenance

This thesis presents a methodology for assessing the reliability of traction power supply systems for mass rapid transit in a case study of the MRT Purple Line. The RAM model, which stands for reliability, availability, and maintenance, is used to create a three-step model to evaluate reliability. For the purpose of predicting a rise in the failure rate over time, reliability is assessed using the failure rate index in relation to the EN:50126 standard. A comparison of the LOLE index and the BAL-502-RF-03 standard is used in the availability assessment to determine the availability of traction substations that are able to supply electrical power. By determining the optimal preventive maintenance intervals in relation to the required maintenance budget, preventive maintenance has the potential to lengthen the service life of an asset. The results present a methodology for evaluating RAM that is suitable for use in project planning and the development of improvements for the future. The methodology includes scenarios that illustrate how to make the system more reliable and available.

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Academic Year 2022 — Advisor's Signature ....

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Aekkasit Kingmaneerat

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LIST OF ABBREVIATIONS

CB	=	circuit breaker
TR	=	power transformer
DS	=	disconnected switch
BUS	=	busbar
UGC	=	underground cable
DR	=	diode rectifier
MTTF	=	mean time to failure
MTTR	=	mean time to repair
COPT	=	capacity outage probability table
LOLP	=	loss of load probability
LOLE	=	loss of load expectation
RBD	=	reliability block diagram
RAM	=	reliability availability maintenance

CHAPTER 1

INTRODUCTION

1.1 General Introduction

The rail system is a large system with a long history. This system has become one of the most popular public transportation systems throughout the past century. Passenger and freight demand for both short-term and long-term rail travel is growing annually. It involves driving performance, velocity, and reliability compared to the traffic on the city ground routes to prevent traffic congestion. A dependable traction power supply system is vital for efficient and safe train transportation.

To evaluate the traction power supply systems' reliability for mass rapid transit systems. In order to assist in planning before the project begins, the researcher would want to provide a method for evaluating the traction power supply system's reliability. It offers an easy way to evaluate complex systems without the need to spend time collecting data for evaluation. Using the reliability data for electrical components is from the literature and proposed ways to improve the distribution circuit structure for better reliability.

1.2 Research Objectives

The main objective of this research is to assess the reliability of traction power systems for expressway mass transit systems by using a case study of the Purple Line mass transit system in Bangkok, Thailand. The reliability index to be used in the assessment is in the form of Reliability, Availability, and Maintenance (RAM), the research objectives are divided into topics as follows.

1.2.1 To evaluate the reliability of traction power supply systems for mass rapid transit.

1.2.2 To formulate the COPT, LOLP, and LOLE of traction power supply systems.

1.2.3 To apply the reliability-centered maintenance technique for traction power supply systems.

1.2.4 To improve the reliability index of the traction power supply systems by distribution circuit re-arrangement.

1.3 Scope and Limitation

The reliability evaluation of the traction power supply system for mass rapid transit conception inside the limits is shown as follows,

1.3.1 Use the MRT Purple Line in Bangkok as a case study.

1.3.2 The multi-train movement acquired is simulated.

1.3.3 To assess reliability, the EN 501261 standard is used.

1.3.4 To assess availability, the BAL-502-RF-03 standard is used for LOLE.

1.3.5 The reliability data for electrical components are from the literature.

1.3.6 Reliability evaluations are assessed from the distribution substations to the DC traction substations, excluding service substations.

1.4 Research Benefit

This thesis is expected to be useful in providing guidance in describing the design features of the distribution substation, traction power substation, and arrangement of the substation components to improve reliability.

1.5 Thesis Outline

The organization of this research is as follows. Chapter 2 the theory background and literature review to explain the theories involved in this research. Section 2.2 describes the reliability principle. Section 2.3 presents the reliability assessment method and reliability standard for the railway electrification system. Section 2.4 presents the reliability assessment of the power supply system by using the LOLE index. Section 2.5 presents the preventive maintenance model. Section 2.6 presents the DC railway traction power supply system for DC power flow. Section 2.7 describes the medium voltage power distribution circuit configuration for improving reliability in the traction substation. In Chapter 3, the reliability assessment of the DC railway traction power supply system is discussed. Section 3.2 presents a multi-train simulation for obtaining load curves. Sections 3.3, 3.4, and 3.5 present the results of the reliability assessment of the MRT Purple Line traction substation. Chapter 4 presents two case studies, first is a case study for improving reliability by rearrangement of the distribution circuit. The second case study presents the availability of traction substations with shorter headway effect for future plans. Finally, In Chapter 5 provides a conclusion and future work.

1.6 Chapter Summary

This chapter presents a general introduction to the importance of reliability assessments in mass rapid transit systems. Furthermore, the research objective, scope and limitation, and research benefit are presented in this chapter.

CHAPTER 2
THEORY BACKGROUND AND LITERATURE REVIEW

2.1 Chapter Overview

Chapter 2 the theory background and literature review to explain the theories involved in this research. Section 2.2 describes the reliability principle. Section 2.3 presents the reliability assessment method and reliability standard for the railway electrification system. Section 2.4 presents the reliability assessment of the power supply system by using the LOLE index. Section 2.5 presents the preventive maintenance model. Section 2.6 presents the DC railway traction power supply system for DC power flow. Section 2.7 describes the medium voltage power distribution circuit configuration for improving reliability in the traction substation.

2.2 Reliability Principle

In general, reliability is described by the rate at which failures occur over a certain amount of time. In recent years, there has been a rise in awareness regarding the significance of the idea of reliability, and it has emerged as a fundamental concern for engineered installations of technically advanced apparatus. Reliability analysis in engineering design can be used to determine whether it is more cost-effective to rely on redundant systems or to upgrade the reliability of a primary unit in order to achieve the required level of operational capability. This can be done so that the organization can achieve the desired level of operational capability (Frederick, 2009). The following is a list of definitions of associated variables that are connected to the concept of reliability.

2.2.1 Failure Rate

The number of expected failures for each unit throughout the course of each time interval is the definition of the failure rate. It is merely the value that would be expected. This estimate may not reflect the real number of failures that occur within any particular time span. When determining the failure rate of a collection of units, the cumulative amount of time that the units have been in operation should be utilized rather than the chronological amount of time (Chowdhury and Koval, 2009).

$$\text{Failure rate, } \lambda = \frac{\text{number of failures}}{\text{total operating time of units}} \tag{2.1}$$

2.2.2 Reliability Model

There are relatively simple formulas that may be constructed to describe the relationship between the failure rate and the reliability of components. Assume that the population was N_o when we started the experiment. Some of the units will stop working after time t, while others will go on operating. Assign them the names Nf and Ns, respectively. While N_f grows larger with time, N_s gets smaller as time passes. The time rate of increase of N_f is the number of expected failures per unit of time for the existing population at that moment. This number is equal to the failure rate multiplied by the number of units in the existing population, which is the formula failure rate multiplied by the number of units in the existing population equals N_f.

$$\frac{dN_f}{dt} = \lambda N_s \tag{2.2}$$

N_f and N_s change over time, but they always add up to the total population N_o, that is,

$$N_f + N_s = N_o \tag{2.3}$$

As stated in the (2.3), reliability is equal to the number of surviving units divided by the total population, that is,

$$R(t) = \frac{N_s}{N_o} \quad (2.4)$$

Combining these (2.2), (2.3) and (2.4) together, that is,

$$R(t) = \frac{N_s}{N_o} = 1 - \frac{N_f}{N_o}$$

$$\frac{dR(t)}{dt} = \frac{-1}{N_o}\frac{dN_f}{dt} = -\lambda\frac{N_s}{N_o} = -\lambda R(t)$$

$$\int \frac{1}{R}dR = -\int \lambda dt$$

$$\ln R(t) = -\lambda t$$

Therefore, the reliability function is,

$$R(t) = e^{-\lambda t} \quad (2.5)$$

R(t) is the probability of surviving after a certain amount of time. The process of deriving a probability density function is the same as the one used for continuously distributed probabilities; the area under the curve is used to represent the probability. The probability density function *f(t)* is derived for its complement *Q(t)*, which is the probability of failure in time *t*. This is depicted in Figure 2.1. Because *R(t)* declines with time, the probability density function *f(t)* is derived for it. Things that have a failure rate that is constant are certain to follow this exponential failure probability (Chowdhury and Koval, 2009).

$$Q(t) = 1 - R(t) = 1 - e^{-\lambda t} \tag{2.6}$$

$$f(t) = dQ(t) = \lambda e^{-\lambda t} dt \tag{2.7}$$

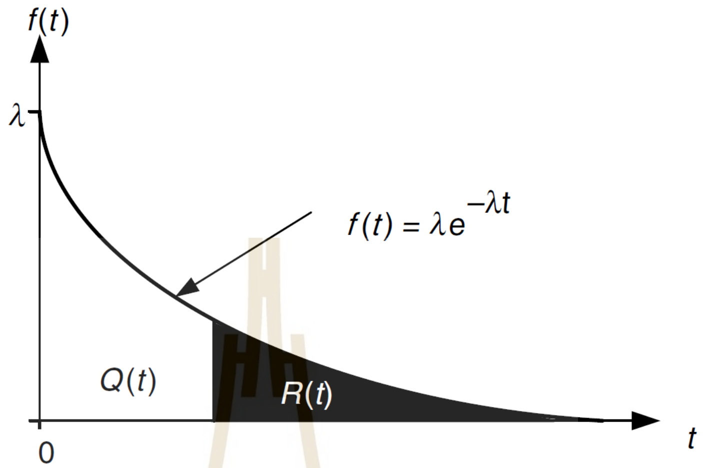

Figure 2. 1 Exponential density function and R(t) and Q(t)

2.2.3 Mean Time to Failure

The exponential reliability function is a continuous probability density function with respect to time, it has an expected value that can be thought of as the function average time value. This is because the expected value is proportional to the exponential probability density. Due to the fact that the reliability function is a failure density function, the mean time to failures, abbreviated as MTTF, is the typical amount of time that must pass before a failure takes place. It has been demonstrated that the MTTF can also be acquired by integrating the dependability function across the entire range (Chowdhury and Koval, 2009).

$$\text{MTTF} = \int_0^\infty R(t)dt \tag{2.8}$$

Combining these (2.5) and (2.8) together, that is,

$$\text{MTTF} = \int_0^\infty e^{-\lambda t} dt = \frac{1}{\lambda} \tag{2.9}$$

2.2.4 Mean Time to Repair

When a piece of equipment or a system fails to function properly, it is no longer of any use. The user will not be able to access its service until it is either fixed or replaced by another device. Even if we have access to spare units, the replacement process will still take some time. A repair shifts a unit from downstate to upstate. The amount of time required to restore service, whether it be by repair or replacement, is referred to as the mean time to repair (MTTR). Similar to how a failure rate is mutual for mean time to failures, a repair rate (μ) can be defined as being equal to the reciprocal of the mean time to repair (Chowdhury and Koval, 2009).

$$\mathrm{MTTR} = \frac{1}{\mu} \tag{2.10}$$

2.2.5 Availability Model

When a system fails, it will be out of operation for a period of time while it is being evaluated for possible repair or replacement. Even with systems that have spare units, the system will enter a downstate if a failure occurs and there are no more spares available to replace the failed unit(s). The percentage of time that a system is available to users and able to perform its intended functions is referred to as its availability (Chowdhury and Koval, 2009). In most instances, it is written in (2.11) and (2.12).

$$\text{Availability} = A = \frac{\text{total hours of operation in 1 year}}{8760} \tag{2.11}$$

$$\text{Unavailability} = U = \frac{\text{total hours of down time in 1 year}}{8760} \tag{2.12}$$

Since it takes an amount of time equal to the MTTF for the system to fail on average, and it takes an amount of time equal to the MTTR for the system to become operational once again, availability, which is defined as the uptime divided by the sum of uptime and downtime, can be represented as (2.13) and (2.14).

$$A = \frac{\text{MTTF}}{\text{MTTF} + \text{MTTR}} \tag{2.13}$$

$$U = \frac{\text{MTTR}}{\text{MTTF} + \text{MTTR}} \tag{2.14}$$

For systems that can be treated as a single component with a constant failure rate λ and repair rate μ, the availability and unavailability.

$$A = \frac{\text{MTTF}}{\text{MTTF} + \text{MTTR}} = \frac{1/\lambda}{1/\lambda + 1/\mu} = \frac{\mu}{\lambda + \mu} \tag{2.15}$$

$$U = \frac{\lambda}{\lambda + \mu} \tag{2.16}$$

2.3 Reliability Assessment Method

In the 1960s, research on the reliability of power distribution systems began gradually as qualitative analysis. As the investigation progresses, purely qualitative analysis can no longer match the requirements. Quantitative indicators were utilized by researchers to evaluate reliability. Experts in connected sectors have long been concerned with the research progress to date. In industrialized nations such as the United States, Japan, and France, relevant agencies have been established to study, investigate, and plan power distribution networks, and the system for evaluating network dependability has been largely established. The fundamental concept of an analytical reliability technique is to construct a corresponding model based on the original reliability data of the components, and then use mathematical analysis to derive power grid reliability indicators. A clear physical notion, excellent model precision, and a clear logical concept characterize the analytical technique (Lui et al., 2018). This research presented a reliability assessment method that is suitable for the traction power supply system.

2.3.1 Reliability Block Diagram (RBD)

This section reviews the modeling of reliability and the failure rate by using a block diagram to represent reliability. This method of representing a system analyzes the possibility of the system failing by utilizing a graphical representation of the system. The operation of the system can be thought of in a variety of ways; however, the primary focus of this discussion will be on the flow of electrical energy or power from a traction power supply system in order to accommodate a particular load (Kingmaneerat et al., 2021). The connections between the blocks in the block diagram are made according to the effects the blocks have on the system (Čepin, 2011). Each block is a representation of the reliability, availability, unavailability, failure rate, and mean amount of time it takes to repair. The MTTR, MTTF, and failure rate of the series and parallel connected block are presented as follows for the purpose of calculating reliability.

2.3.1.1 Reliability Blocks in Series

Components of a system are said to have series reliability if the failure of one or more than one component of the system can result in the failure of the system as a whole (Brown, 2009). As shown in Figure 2.2, in order to complete the circuit from the input side to the output side, it is necessary to travel through each element.

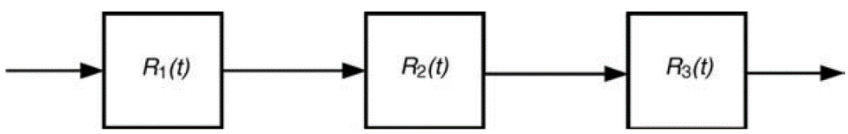

Figure 2. 2 Reliability block of the series system

Since reliability is defined as the probability of functioning within a given time interval, the reliability of a series system is defined as the possibility that all of the components will function simultaneously within that time interval. This is because reliability is defined as the probability of functioning. The product law of probability states that the probability of all components functioning properly is simply the product of the probabilities of each individual component functioning properly. This is the case if component failures are independent of one another. The mathematical expression for the series reliability of *n* identical and independent components is shown in Figure 2.3, where R_1, R_2, and R_3 denote the reliability of the component and R_{system} denotes the reliability of the entire system in its entirety.

$$R_{system}(t) = R_1(t) \times R_2(t) \times R_3(t) \ldots \times R_n(t) \quad (2.17)$$

If the components have exponential failure probabilities with corresponding failure rates, λ_1, λ_2, λ_3 to λ_n so on, then the system reliability,

$$R_{system}(t) = e^{-\lambda_1 t} \times e^{-\lambda_2 t} \times e^{-\lambda_3 t} \times \ldots \times e^{-\lambda_n t} \quad (2.18)$$

Therefore, from (2.18) the system failure rate can be explained,

$$\lambda_{system} = \lambda_1 + \lambda_2 + \lambda_3 + \ldots + \lambda_n \quad (2.19)$$

$$R_{system}(t) = e^{-\lambda_{systems} t} \quad (2.20)$$

Then MTTR of the series system,

$$\text{MTTR}_{system} = \frac{\sum_{i=1}^{n} (\lambda_i r_i)}{\lambda_{system}} \quad (2.21)$$

2.4.1.2 Reliability Block in Parallel

In terms of system reliability, a parallel system means that only one of the components in the parallel connections needs to function properly for the system as a whole to operate properly. As can be seen in Figure 2.3, there are a number of distinct paths that can be taken to get from the input side of the system to the output side (Čepin, 2011).

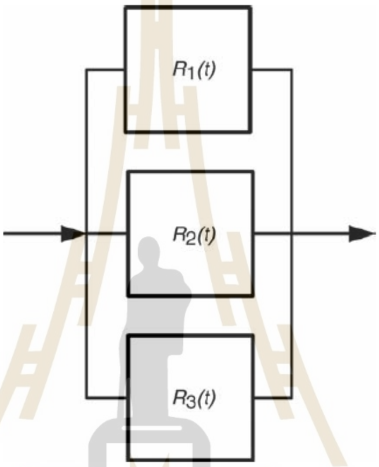

Figure 2. 3 Reliability block of the parallel system

Because every component in the parallel connection has to fail for the system as a whole to become unusable, redundancy contributes to the highly reliable nature of the system as a whole. If the failures are not related to one another in any way, then the probability that they will all fail is equal to the sum of the probabilities of failure for each of the individual components. If *Q(t)* denotes the probability of failure in each period or unreliability then,

$$R(t) = 1 - Q(t) \tag{2.22}$$

$$Q(t)_{system} = Q_1(t) \times Q_2(t) \times Q_3(t) \times \ldots \times Q_n(t) \tag{2.23}$$

$$R(t)_{system} = 1 - Q(t)_{system} \tag{2.24}$$

If each of the system components has a failure probability that is exponentially increasing along with a rate that is proportional to it, then the system failure rate can be expressed as an example of the following, in the case of a parallel system with two independent components (Trivedi and Bobbio, 2017).

$$R(t)_{system} = 1 - (Q(t)_1 Q(t)_2) = 1 - ((1 - R(t)_1)(1 - R(t)_2)) \tag{2.25}$$

$$R(t)_{system} = R(t)_1 + R(t)_2 - (R(t)_1 R(t)_2) \tag{2.26}$$

from (2.5),

$$R(t)_{system} = e^{-\lambda_1 t} + e^{-\lambda_2 t} - (e^{-\lambda_1 t} e^{-\lambda_2 t})$$

$$R(t)_{system} = e^{-\lambda_1 t} + e^{-\lambda_2 t} - e^{-(\lambda_1 t + \lambda_2 t)} \tag{2.27}$$

Form (2.9) MTTF can be found the system failure rate then,

$$\text{MTTF} = \int_0^\infty (e^{-\lambda_1 t} + e^{-\lambda_2 t} - e^{-(\lambda_1 t + \lambda_2 t)}) dt \tag{2.28}$$

$$\text{MTTF} = \frac{1}{\lambda_1} + \frac{1}{\lambda_1} - \frac{1}{\lambda_1 + \lambda_2} \tag{2.29}$$

Therefore, the system failure rate is,

$$\lambda_{system} = \frac{1}{\text{MTTF}} \tag{2.30}$$

Then MTTR of the parallel system is (Roy and Ronald, 1996)

$$\mathrm{MTTR}_{system} = \frac{\prod_{i=1}^{n} r_i}{\sum_{i=1}^{n} r_i} \tag{2.31}$$

2.3.2 Time-Varying Failure Rate Model

It is possible to calculate system reliability with the assistance of predictive reliability models, which take into account the system layout, operational planning, and component reliability data. This makes it possible to calculate system reliability. With the help of the predictive reliability model, which takes into consideration the system layout, operating strategy, and component reliability data, it is possible to calculate the system level of reliability. A method that can be implemented to effectively assign a relative condition grade to various pieces of equipment based on the findings of an inspection. After that, the failure rate function is transformed into these ratings through the application of low, typical, and high units (Chun-Yuan and Hsing-Hsiang, 2010). It was in this context that the particular formula for the failure rate function was selected (2.32).

$$\lambda(t) = Ae^{Bt} + C \tag{2.32}$$

Solving the parameters A, B, and C requires the use of three different data sets. Table 2.1 offers sequencing of these data sets by definition using low, general, and high units. These findings are based on research that was found in the relevant literature (Brown (2009), VMN Group LLC (2001), and Hayashiya et al. (2017)). As a result, there are three sets of data that correlate to (0) as low units, (1/2) as typical units, and (1) as high units. If we have these three values, then we may derive the function parameters (A, B, and C) as follows,

$$A = \frac{(\lambda(1/2) - \lambda(0))^2}{\lambda(1/2) - 2\lambda(1/2) + \lambda(0)} \qquad 2.33)$$

$$B = 2\ln\left(\frac{\lambda(1/2) + A - \lambda(0)}{A}\right) \tag{2.34}$$

$$C = \lambda(0) - A \tag{2.35}$$

Table 2. 1 Reliability parameter of components

Equipment	Failure rate (per year)		
	Low	Typical	High
TR	0.01	0.03	0.06
DS	0.004	0.01	0.16
CB	0.001	0.01	0.03
DR	0.00447	0.0131	0.0298
BUS	0.001	0.01	0.038
UGC	0.003*	0.07*	0.587*

Note: The failure rate for underground cable is per circuit mile

2.3.3 Reliability Standard

The EN 50126-1:2017 standard was developed by the CLC/TC 9X - Electrical and Electronic Applications for Railways Group to address the reliability of rail traction substations and to provide a risk assessment and reliable continuous system. Through the application of this standard and the experiences gained over the past few years, the need for revision and reorganization became apparent, along with the need to provide a systematic and consistent approach to reliability, availability, maintainability, and safety (RAMs) applicable to the entire railway.

Table 2.2 presents the frequency of occurrence of failure events for quantification time base. Table 2.3 presents the severity categories of the train service system. Table 2.4 presents the risk acceptance categories assigned to identified risks permit classification for decision-making purposes. The selection of risk acceptance categories should be contingent on the selection of risk acceptance criteria and the decision made. Table 2.5 presents the risk matrix calibration that should be performed based on the risk acceptance criteria, the frequency of occurrence categories, and the severity categories.

Table 2. 2 Frequency of occurrence of failure events for quantification time base

Frequency level	**Description**	**Equivalent occurrence in a 30-year lifetime of substation operating more than 5000 h/year**
Frequent	Probably occurring frequently. The occurrence will occur frequently.	more than about 150 times
Probable	Will recur multiple times. The occurrence is likely to occur frequently.	about 15 to 150 times
Occasional	Likely to occur frequently. Multiple occurrences of the event are anticipated.	about 2 to 15 times
Rare	Probably occurring at some point during the system life cycle. The occurrence can be reasonably anticipated.	perhaps once at most
Improbable	Unlikely, but not impossible. It is reasonable to assume that the event may occur on rare occasions.	not expected to happen within the lifetime
Highly improbable	Highly improbable to occur. That is reasonable to assume the event will not occur.	extremely unlikely to happen within the lifetime

Table 2. 3 Severity categories when the failure train service system

Severity category	Consequences on service
Catastrophic	Any of the below consequences in presence of consequences to persons or environment
Critical	Breakdown of a major system, stop train service
Marginal	Breakdown of partial system, stop train service
Insignificant	Minor system damage

Table 2. 4 Risk acceptance categories

Risk acceptance categories	Actions to be applied
Intolerable	The risk shall be eliminated
Undesirable	The risk shall be accepted only if its reduction is impractical and with the consent of the railway duty holders or the responsible Safety Regulatory Authority.
Tolerable	Risk can be tolerated and accepted with adequate control (e.g., maintenance procedures or rules) and the consent of the responsible railroad duty holders.
Negligible	The risk is acceptable without the agreement of the railway duty holders.

To assess system availability, there is a reference standard BAL-502-RF-03 created by The North American Electric Reliability Corporation (NERC). The objective of NERC, a non-profit international regulatory authority, is to ensure the effective and efficient reduction of risks to the grid reliability and security. NERC creates and enforces Reliability Standards; annually evaluates seasonal and long-term reliability; monitors the bulk power system via system awareness; and educates, trains, and certifies industry personnel. To establish common criteria, based on “one day in ten years” or

"0.1 days per year" loss of load expectation principles, for the analysis, assessment, and documentation.

Table 2. 5 Risk matrix calibration

Frequency of occurrence of failure events	Risk matrix calibration			
Frequent	Undesirable	Intolerable	Intolerable	Intolerable
Probable	Tolerable	Undesirable	Intolerable	Intolerable
Occasional	Tolerable	Undesirable	Undesirable	Intolerable
Rare	Negligible	Tolerable	Undesirable	Undesirable
Improbable	Negligible	Negligible	Tolerable	Undesirable
Highly improbable	Negligible	Negligible	Negligible	Tolerable
	Insignificant	Marginal	Critical	Catastrophic
	Severity categories			

2.4 Reliability Assessment of Electric Power Supply Systems

When assessing the capacity of a power supply, the definition of failure that is most commonly used and accepted is loss of load. A failure is defined as an outage that is brought on by insufficient capacity (Chowdhury and Koval, 2009). Loss of load expectation, also known as LOLE, is a reliability index that indicates how long an incident will cause the system available power supply to be less than the demand (Diewvilai et al., 2012). Instead of using the power supply system, the Capacity outage probability tables (COPT), Loss of load probability (LOLP), and daily load duration curves are utilized in the calculation of the LOLE reliability index.

2.4.1 Capacity Outage Probability Table

COPT is an abbreviation that describes the power supply model that is essential for the loss of load strategy. It is nothing more than a list of capacity requirements and the likelihood of those requirements happening (Billinton and Allan, 1996). Çağlar (2015) presented the COPT can be generated with the help of a straightforward algorithm for a multi-state unit, which is defined as a unit that can be in one or more derated or partial outage states in addition to fully up and fully down states. The formula for the COPT is as follows,

$$P_n(X) = (1 - U_n)P_{n-1}(X) + U_n P_{n-1}(X - C_n) \tag{2.36}$$

$$U = \frac{MTTR}{MTTF + MTTR} \tag{2.37}$$

$$A = 1 - U \tag{2.38}$$

where,

n	is number of unit states
$P(X)$	is the probability of a specific capacity outage state
X	is capacity outage state of X MW
C	is capacity outage
U	is unavailability
A	is availability

For (2.39) is set to the initial state before starting to formulate the capacity outage probability tables.

$$P_{n-1}(X) = \begin{cases} 1.0 & \text{for} \quad X \leq 0 \\ 0.0 & \text{for} \quad X > 0 \end{cases} \tag{2.39}$$

For example, if there are two 25 MW units and one 50 MW unit with unavailability of 0.02 were combined to form the power supply model as shown in Table 2.6. The system capacity outage probability is created, step-by-step, as follows,

Step 1: Add the first unit of U = 0.02 and C = 25 MW

$$P(0) = (1-0.02)(1.0)+(0.02)(1.0) = 1.00$$
$$P(25) = (1-0.02)(0)+(0.02)(1.0) = 0.02$$

Step 2: Add the second unit of U = 0.02 and C = 25 MW

$$P(0) = (1-0.02)(1.0)+(0.02)(1.0) = 1.00$$
$$P(25) = (1-0.02)(0.02)+(0.02)(1.0) = 0.0396$$
$$P(50) = (1-0.02)(0)+(0.02)(0.02) = 0.0004$$

Step 3: Add the last unit of U = 0.02 and C = 50 MW

$$P(0) = (1-0.02)(1.0)+(0.02)(1.0) = 1.00$$
$$P(25) = (1-0.02)(0.0396)+(0.02)(1.0) = 0.058808$$
$$P(50) = (1-0.02)(0.0004)+(0.02)(1.0) = 0.020392$$
$$P(75) = (1-0.02)(0)+(0.02)(0.0396) = 0.000792$$
$$P(100) = (1-0.02)(0)+(0.02)(0.0004) = 0.000008$$

After calculating the cumulative probabilities, the capacity outage probability table can be arranged as Table 2.7.

Table 2. 6 Example capacity outage probability table

Capacity (MW)	Capacity outage (MW)	State probability	Cumulative probabilities
100	0	0.941192	1.000000
75	25	0.038416	0.058808
50	50	0.019600	0.020392
25	75	0.000784	0.000792
0	0	0.000008	0.000008

2.4.2 Loss of Load Probability

This method involves combining the applicable system COPT with the system load curve in order to determine the expected risk of load loss. Additionally, the load duration curve is utilized, and the time units can be either seconds or hours. The example shown in Figure 2.4 is the traction substation load curve and Figure 2.5 is the traction substation load duration curve.

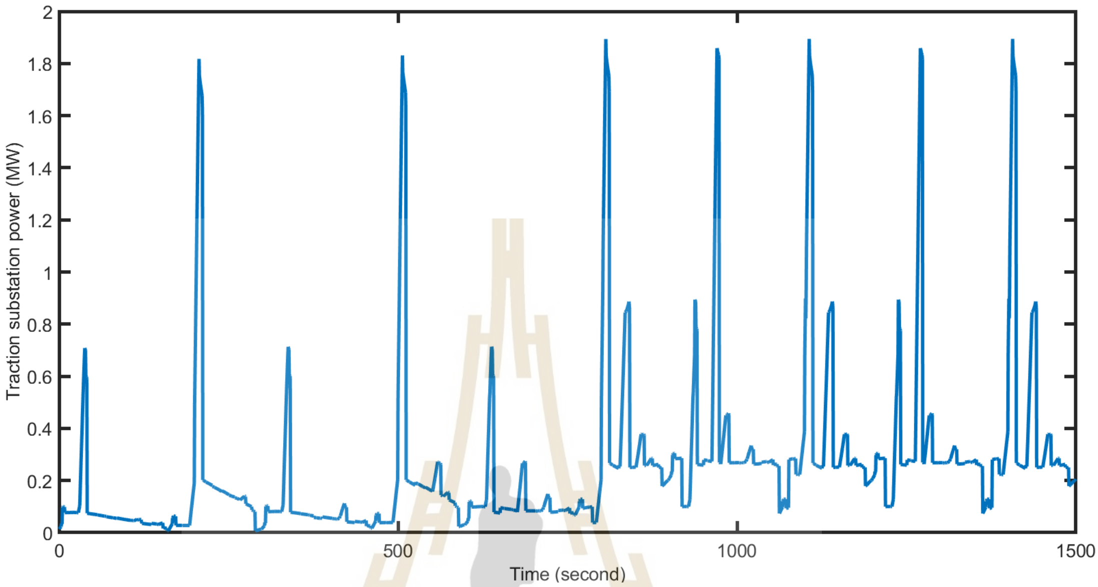

Figure 2. 4 The traction substation load curve

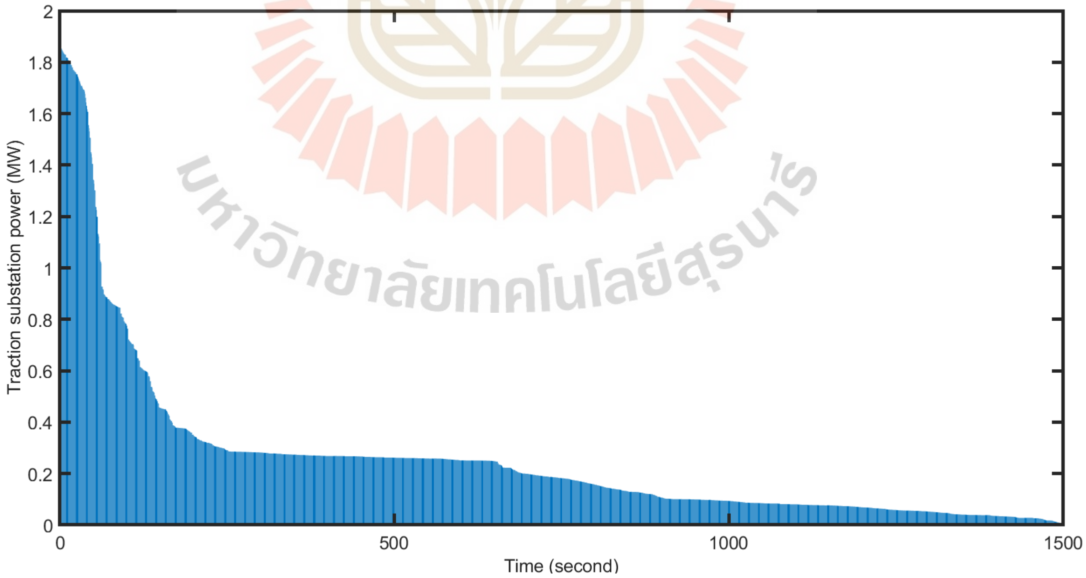

Figure 2. 5 The traction substation load duration curve

In the event of a loss of power supply, which is referred to as a capacity outage, there may or may not be a loss of load. The amount of load on the system as well as the capacity reserve margin of the power supply both influence this condition. A LOLP will not happen unless the load demand exceeds the system capacity of the remaining power supply capacity. (Billinton and Allan, 1996). The calculation of LOLP utilizes the following formula,

$$LOLP = \text{Cumulative probabilities of } [X > RS] \tag{2.40}$$

$$RS = \text{ Full capacity (MW) - Load reserve (MW)} \tag{2.41}$$

2.4.3 Loss of Load Expectation

The term loss of load expectation abbreviated LOLE refers to the possibility that traction substation capacity will be unable to meet the power requirements that were expected. LOLE is an index that indicates the ability to distribute power to the load, which may affect the operation, causing the system to stop working or not, the system may be overloaded but still able to continue working. There is a strong connection between the terms LOLE and LOLP. If the LOLP quantity is expressed in terms of time units rather than proportional values, then it is said to be expressed in terms of time units. When the capacity outage probability table and the load duration curve are combined, it is possible to determine the number of hours within each period during which the daily peak load will be greater than the available capacity. The index is referred to as the LOLE in this particular scenario. The LOLE can be expressed as given in (2.42), where $LOLP_i$ is the individual per period and T_i is the period of loss of power offered in a variety of time units second, minutes, or hours (Ferdinant et al., 2020).

$$LOLE = \sum_{i=1}^{n} LOLP_i \cdot T_i \tag{2.42}$$

2.5 Preventive Maintenance Model

The maintenance of the mass rapid transit system traction power system is becoming an increasingly important requirement for the system's effective operation. It is quickly becoming one of the most important aspects of the industrial sector in nations both developed and still in the process of industrialization. Maintenance issues are complex, time-consuming, and expensive. If you do not perform routine maintenance on machinery and equipment, the machine can run the risk of it breaking down much sooner than the age that the manufacturer recommends. This will result in a greater loss of investment as well as an increase in budgets, tools, and manpower. Therefore, maintenance is essential in order to improve the state of the system and guarantee that there will be no interruptions to the operations as a result of downtime (Thongchai et al., 2017). The practice of performing preventative maintenance on traction power supply systems is quite common. This executes maintenance procedures on a regular basis at intervals of varying lengths of time. There are several methods for determining the correct time by using reliability evaluations, and each one has its own set of advantages and disadvantages. (Ho T. et al., 2006).

2.5.1 Reliability-Centered Maintenance Technique

In the actual world, an item or system usable life is typically limited however, for degradable and repairable items, the rate of degradation and, as a result, the rate of failure can be decreased, and then the item can be restored to a younger state through preventative maintenance (Thongchai et al., 2017; Chun-Yuan and Hsing-Hsiang, 2010). The preventive maintenance model for lowering the percentage of equipment failures over a finite period of time is shown in Figure 4. Where L is the finitely usable lifetime of the component, T is the time interval between each preventive maintenance procedure and δ is the restoration factor that determines how much of the component failure rate is reduced. Preventive maintenance typically reduces failure rates by 90%.

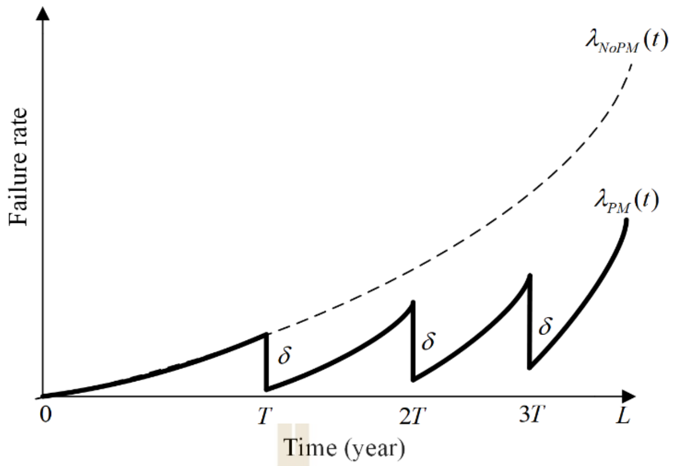

Figure 2. 6 Preventive maintenance model for failure rate.

$$\lambda_{PM,n}(t) = \lambda_{NoPM,n}(t) - (\lambda_{NoPM,n-1}(t) \times \delta) \qquad (2.43)$$

where,

λ_{PM} is failure rate with preventive maintenance.

λ_{NoPM} is failure rate without preventive maintenance.

t is time in unit years.

n is number of preventive maintenance sessions n = 1,2,3,..

δ is the restoration factor to reduced a failure rate.

2.5.2 Preventive Maintenance Cost

Attributed to the reason that each phase of preventative maintenance lasts a different amount of time, there will be varying costs associated with each cycle of maintenance. Consequently, the cost is yet another consideration that ought to be taken into account when determining the suitable time period. The costs that are associated with preventive maintenance can be divided into two distinct buckets according to their nature. The first type of cost is a fixed one, and it takes into account things like the cost of routine maintenance, equipment, spare material, and so on. The second category of costs is known as a variable cost, and it refers to an expense that differs from one instance of maintenance to another (Sudket and Chaitusaney, 2014). It is possible to characterize it based on the amount of preventative maintenance that was carried out. The following is a breakdown of the expenses that can be associated with preventative maintenance.

$$C_{PM} = x + y \cdot \eta \tag{2.44}$$

$$\eta = \frac{\delta_{PM}}{\delta_{first,PM}} \tag{2.45}$$

where,

C_{PM} is preventive maintenance cost

x is fixed cost

y is variable cost

η is ratio of preventive maintenance level

Variable cost is the cost of equipment that must be replaced, modified, or adjusted. The fixed cost is the cost of maintenance services and employee wages.

Each preventive maintenance level is then divided by the initial preventive maintenance level to arrive at the ratio of preventive maintenance levels. In the context of this case study, it was not possible to determine an accurate estimate of the amount of money needed for maintenance. As a result, it is necessary for them to be characterized by using multiplier variables. to conduct a comparison and analysis of the costs associated with the upkeep of each model over a variety of different time spans. Table 2.7 contains typical cost-level model data of preventive maintenance costs.

Table 2. 7 The common preventive maintenance cost multiplier variables.

Preventive maintenances duration	Cost of preventive maintenances
every 1 year	0.2A
every 2 years	0.4A
every 3 years	0.6A
every 5 years	1.0A
every 10 years	2.0A

Note: A is the maintenance cost

2.6 DC Railway Traction Power Supply System

Electric power can be sent from the traction substation to the electric train using the DC railway traction power supply system via the feeder line and the contact rail. After that, the electric train is guided by the track return line back to the traction substation where it first started. A typical traction network will consist of contact rails, feeder rails, running rails, and return lines. These are the components that make up the network. The traction network and the traction substation are both essential components of the DC traction power supply system. The traction substation is an essential part of the system. The contact rail is predominantly a conductive rail that supplies electric power directly to an electric train power receiver. The feeder line is the conductor that carries traction power from the substation to the contact rail. It is the duty of the return line to return the traction power to the traction substation (Ma, 2021).

The voltages 600 V, 750 V, and 1.5 kV are the ones that are applied the most frequently for DC railroads in urban, interurban, and regional systems, respectively [4]. Light rail systems typically use catenary with voltages ranging from 600 to 800 V, whereas regular interurban or regional lines use catenary with voltages ranging from 1.5 to 3 kV. In several ways, the general layout of a DC power supply system for a railway is much different from that of an industrial DC power supply system. This is one of those ways. Overhead catenaries or conductor rails, feeder transformers, converters, circuit breakers, disconnectors, and insulators are some of the major components that are frequently included in a railway power supply system. Earthing and bonding is another feature that may be incorporated into the DC railway power supply system. The electricity that is necessary for the electrified railway can be supplied in the form of direct current (DC) or alternating current (AC), and it can be sent to the feeder substations at either high or medium voltage level. Configurations of a DC feeding circuit are demonstrated in the diagram depicted in Figure 2.7.

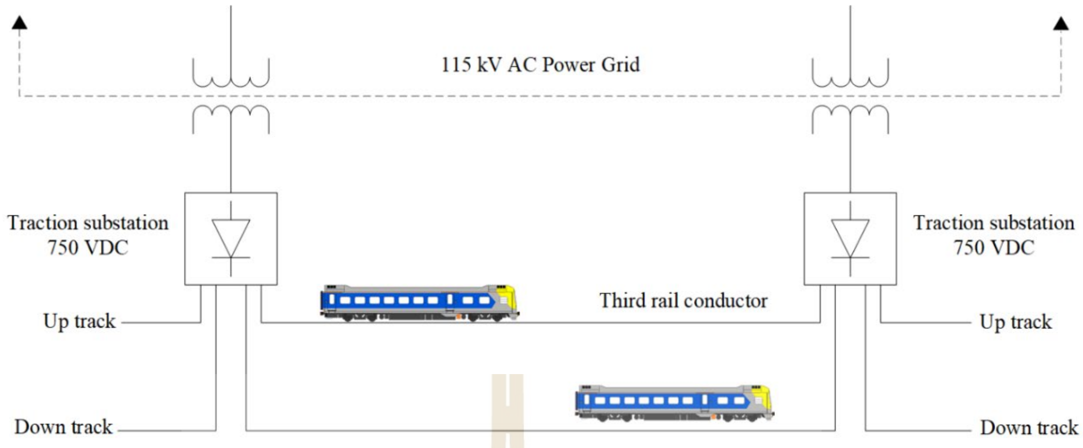

Figure 2. 7 Circuit diagram of a typical DC railway power system

2.6.1 Multi-train Modeling and Simulation

Information on the side of the power supply system from which the traction power station is required for the reliability assessment of the power supply system can be found in section 2.4. Because of this, there needs to be a simulation of the electric train operating so that data can be collected for analysis regarding the dependability of the power supply system. As a result, Multi-train modeling and simulation are utilized in this thesis in order to acquire load curve data.

Position, speed, and acceleration rate are the three most crucial dynamic variables to consider whenever a train is in motion. During single-train motion, the only thing that governs the relationships between these variables is the straightforward kinematic equation that is based on Newton second law of motion (Kulworawanichpong, 2015). In Figure 2.8, a train climbs a rail surface that is inclined upwards. As can be seen, this motion can be mathematically expressed by using a free body diagram, which is a diagram that depicts all of the forces that are acting on the train (2.46).

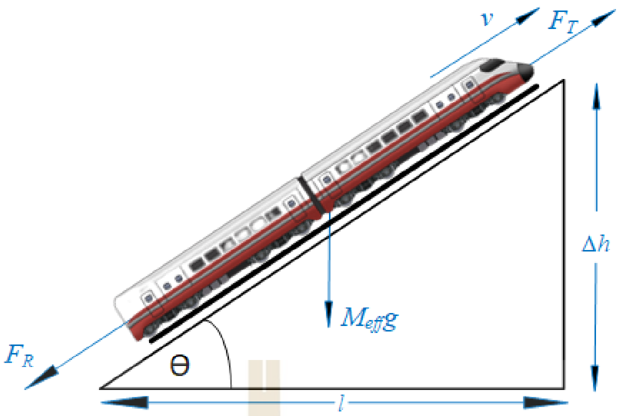

Figure 2. 8 Free body diagram of the train movement

$$F_T - F_R - F_{grad} = M_{eff}\,a \tag{4.46}$$

where,

F_T	is the tractive effort of the train (N)
F_R	is the resistance force of the train (N)
M_{eff}	is the total effective mass of the train (ton)
F_{grad}	is the gradient force of the train (N)
a	is the train acceleration (m/s^2)

The towing motor, which is the component of an electric train that is responsible for turning the vehicle wheels, contributes to the tractive effort of the train. Traction is determined by several factors, the most important of which are the electric train weight and speed. The manufacturer conducted tests and presented the findings in the form of electric train traction in comparison to the speed of the electric train, as shown in Figure 2.9. The traction force is diminished whenever the speed of the electric train is higher than the predetermined base speed.

The movement of an electric train is met with some level of resistance due to the combination of air resistance and the friction that occurs between the wheels and the rail. The value of friction resistance combined with air resistance is the most common metric that manufacturers choose to specify. which is considered to be a feature of the electric train that does not depend on the route and is collectively referred to as the resistance force of an electric train and which can be calculated using the Davies equation in (2.47).

$$F_R = A + Bv + Cv^2 \tag{2.47}$$

where,

A, B, and C	is coefficients (kN), (kN·h/km), (kN·h^2/km^2)
v	is the train speed

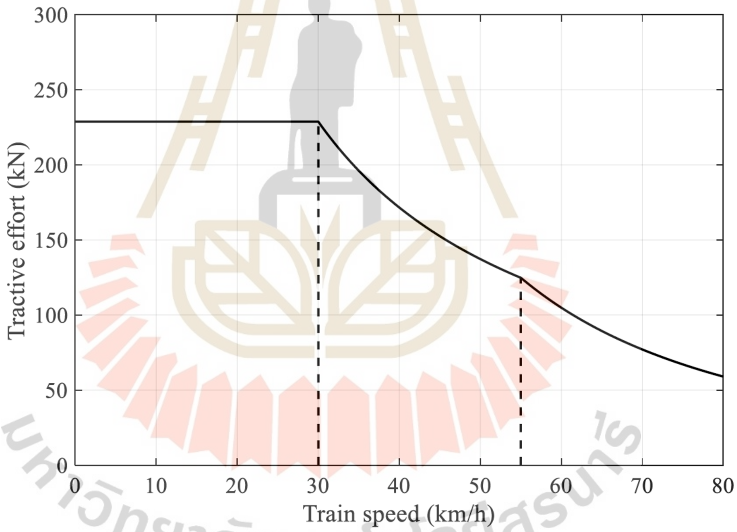

Figure 2. 9 The tractive effort of the MRT Purple Line

The resistance to motion can now be calculated with the help of the Davies equation, which was developed specifically to suit the service of that country. The Davies equation is given in accordance with the Japanese industry standards JIS E 6002 can be found in (2.48).

$$F_R = (1.65 + 0.0247v)W_m + (0.78 + 0.0028v)W_t + (0.78 + 0.0078(n-1))v^2 \tag{2.48}$$

where,

W_m is the total weight of the electric motor in the train (ton)

W_t is the total weight of the train car (ton)

n is the number of cars in the train

In general, the path taken by the electric train has a modest amount of incline, also known as a gradient, and the gradient itself is subject to frequent changes. The gradation force is determined by the inclination of the motion given in (2.49).

$$F_{grad} = M_{eff}\, g \sin\theta = \frac{M_{eff}\, g \Delta h}{l} \tag{2.49}$$

where,

g is the earth gravitational acceleration (9.81 m/s^2)

Δh is the difference of the vertical distance (m)

l is the horizontal distance (m).

There are three modes of movement: Acceleration mode, Cruising mode, and Deceleration mode. The movement of electric trains to transport passengers between passenger stations. As can be seen in Figure 2.10, the research only looked at three different operational modes. The acceleration mode begins to speed up from the station at the acceleration that is specified and continues to do so until it reaches the speed that is specified. After that, it shifts into cruising mode, which keeps the vehicle moving at the predetermined speed until the driver puts their foot on the brake to bring it to a stop at the passenger terminal. Calculations for the electric train speed and position can be made using equations (2.50) and (2.51) in the appropriate manner (Chatwongtong et al., 2021).

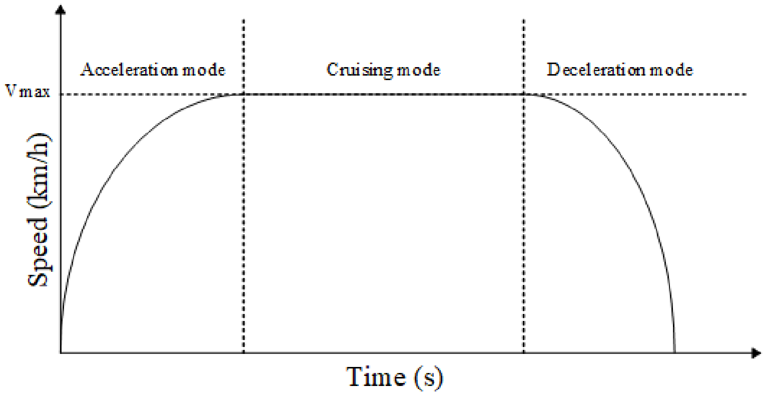

Figure 2. 10 Train operating mode

$$v_{t+1} = v_t + a\Delta t \tag{2.50}$$

$$s_{t+1} = s_t + v_{t+1}\Delta t + \frac{a\Delta t^2}{2} \tag{2.51}$$

where,

v_t is the train speed before the updating (m/s)

v_{t+1} is the train speed after updating (m/s)

s_t is the location of the train before updating (m)

s_{t+1} is the location of the train after updating (m)

Δt is time step (s)

The calculation of the amount of electric power that is used by the electric train while it is in motion includes auxiliary power from things like lighting and air conditioning, among other things, while the amount of power that is used to move depends on the traction of the electric train. Train speed and the efficiency with which mechanical energy can be converted into electrical energy, given by,

$$P_{tr} = \frac{F_T v_{t+1}}{\eta} + P_{aux} \tag{2.52}$$

where,

P_{tr} is the train electric power (W)

η is the efficiency of converting mechanical energy into electrical energy

P_{aux} is the auxiliary power (W)

2.6.2 Current Injection Method for DC Railway Power Flow Solution

Due to two nonlinearities, the DC railway power supply system is not a straightforward DC linear circuit. These nonlinearities are caused by the calculation of the electricity supplied from the traction power substation. The first one is the rectifier substation, which is responsible for ensuring that current never flows in the opposite direction. The traction power of the train is the second factor to consider (Kulworawanichpong, 2015). The equivalent circuit of DC railway power supply systems is broken down and presented in Figure 2.11. Even though the total number of trains operating during service hours and the number of rectifier substations in DC mass transit systems can reach a hundred nodes, multi-train system simulation is still a computational burden. Therefore, there is a need for efficient DC railway power flow calculation. The current injection method was utilized in this study to determine the flow of power through a multi-conductor system, and the results were given as,

$$I_{ss,i} - \frac{P_{tr,j}}{V_j} = \sum_{i=1}^{n} G_{k,ij} V_i \tag{2.53}$$

$$[I] = [G][V] \tag{2.54}$$

where,

V_i, V_j is voltage at bus *i* and *j* respectively (V)

$I_{ss,i}$ is short-circuit capacity of the substation at bus *i* (A)

$P_{tr,j}$ is the power load of the train connected at bus *j* (W)

$G_{k,ij}$ is an element *i to j* of the bus conductance matrix (S)

$[I]$ is the current matrix

$[G]$ is the conductance matrix

$[V]$ is the voltage matrix

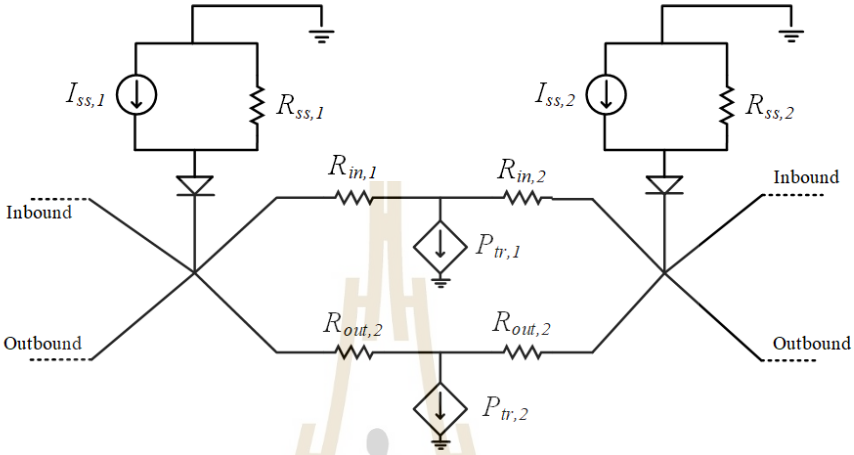

Figure 2. 11 The equivalent circuit of DC railway power supply systems

2.7 Medium Voltage Power Distribution Circuit Configuration

The connection configuration of medium voltage power distribution circuits has an impact on reliability. Brown (2009) explained distribution circuits come in many configurations. The model of distributed circuits that will be used in the research will be presented as follows.

2.7.1 Radial System

The most fundamental primary distribution system consists of independent feeders with corresponding consumers. Because there are no feeder interconnections, a fault will result in the disconnection of all downstream services until the problem is resolved. Radial systems have a number of advantages over networked circuits, such as simpler fault current protection, simpler voltage control, simpler prediction and control of power flows, and lower cost, but they have the lowest reliability.

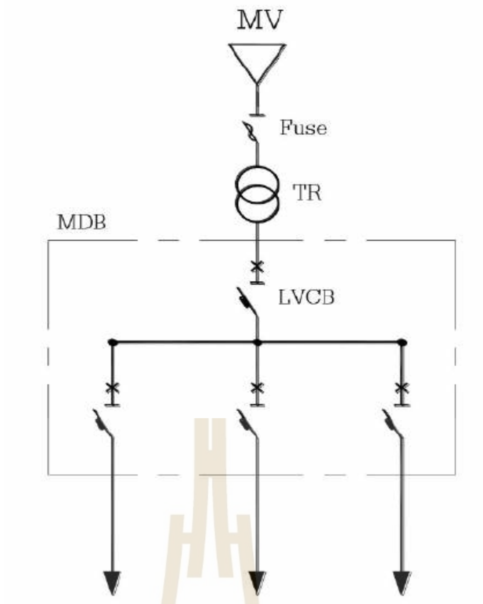

Figure 2. 12 Radial system circuit

2.7.2 Primary Selective System

Each customer is assigned a preferred and backup feeder. In the event that the preferred feeder loses power, a transfer switch disconnects the preferred feeder and connects the alternate feeder. The primary selective circuit is more reliable than the radial circuit, but it is also more expensive.

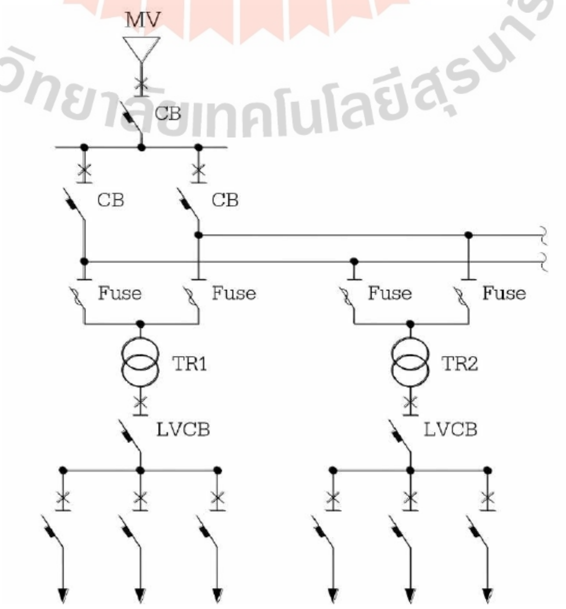

Figure 2. 13 Primary selective system circuit

2.7.3 Secondary Selective System

Utilizing secondary voltage switches in place of primary voltage switches yields comparable results in a secondary selective system. For secondary selective service to provide the greatest reliability benefits, each distribution transformer must be able to supply the entire load.

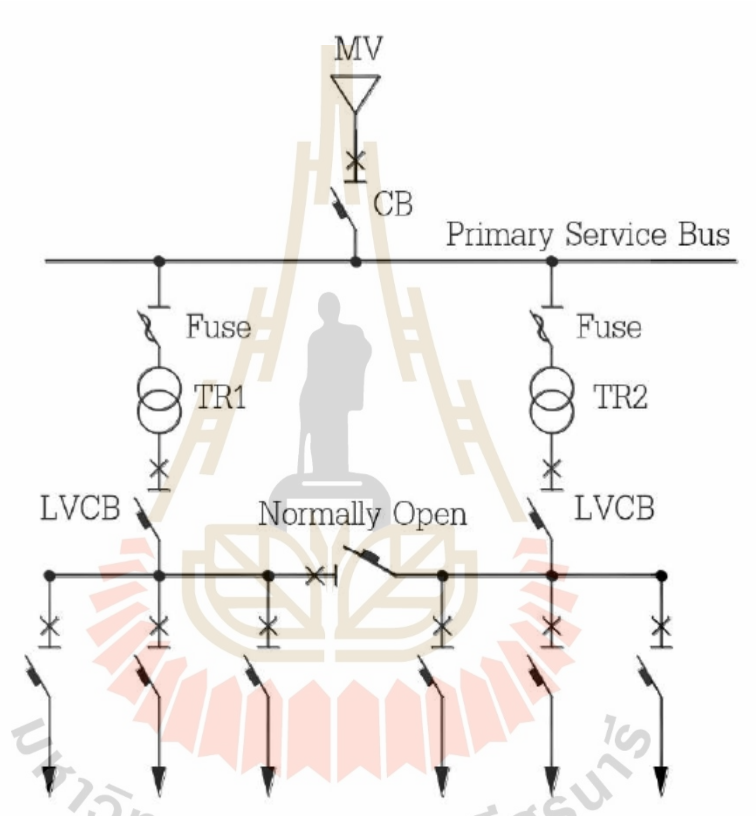

Figure 2. 14 Secondary selective system circuit

2.7.4 Closed-Loop Distribution System

According to J. C. Gu et al. (2007), a normally closed-loop distribution system can be created by connecting the ends of two radial feeders. The advantage of the loop system over radial arrangements is that the failure of a single transformer or feeder cable will not result in a loss of service in a single portion of the facility, and a single feeder cable can be maintained without interruption of service.

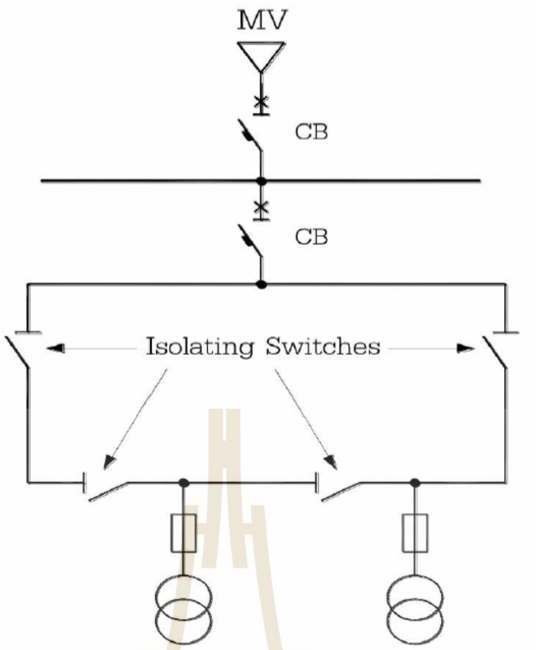

Figure 2. 15 Closed-loop distribution systems circuit

2.7.5 Open-Loop Distribution System

Open-loop systems are frequently used in high-density areas where large loads must be served, and a high level of dependability is required. Multiple utility services are paralleled at the medium voltage in this configuration, resulting in a highly reliable system. The primary benefit of the open-loop system is service continuity. None of the system loads will be interrupted by a single fault anywhere on the primary system. System protection devices are specially designed circuit breakers or disconnect switches used to disconnect the traction substation from another power supply system in the event of a fault. Many faults will be secured without affecting the performance of any load.

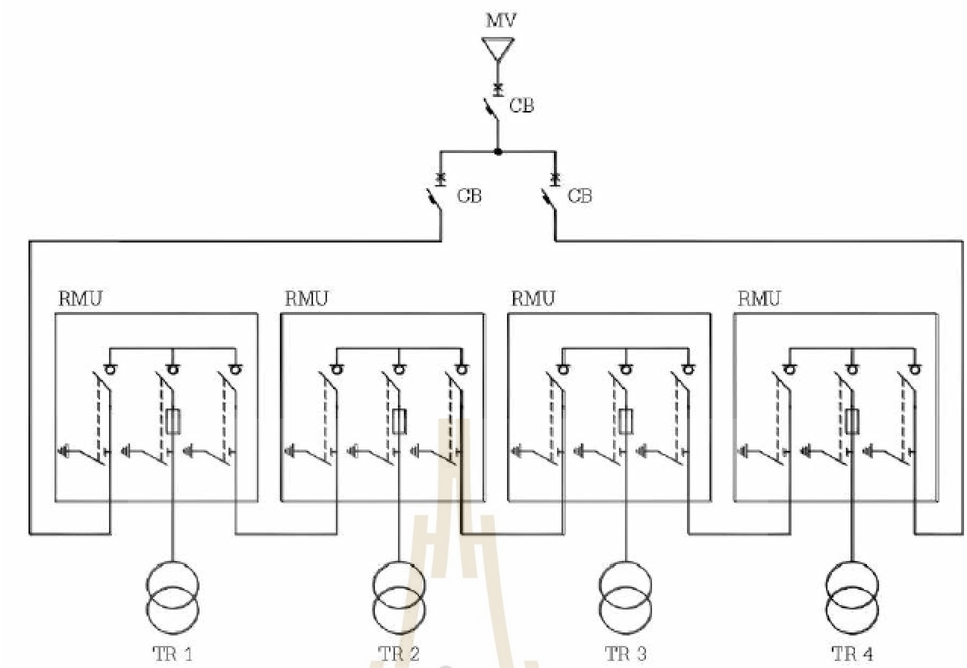

Figure 2. 16 Open-loop distribution system

2.8 Review of Literature and Related Research

Presentation of literature reviews and related research capable of summarizing various research operations used to evaluate the dependability of electrical power systems. Table 2.8 provides a summary of research from the past to the present.

Table 2. 8 Review of literature and related research

Year	Author	Research implementation
2002	Marko C.	This research demonstrates that testing and maintenance of safety equipment in nuclear power plants represent a significant risk and cost reduction opportunity. The approach determines the appropriate testing and maintenance schedule for safety equipment based on the minimization of selected risk measures.
2006	Ho T. K. et al.	A stochastic lifetime model has been implemented as a software tool to evaluate the relative risk and cost of different maintenance intervals for the components of a traction power system.

Table 2. 9 Review of literature and related research (Continued)

Year	Author	Research implementation
2008	Cheng C. Y. et al.	The objective of this study is to develop an optimal preventive maintenance (PM) policy that reduces the failure rate within a finite time period while minimizing the expected total maintenance cost. It is assumed that the PM cost is a linear function of each PM effect.
2010	Boonpan P. and Sirisumrannukul S.	This paper presents a reliability assessment of the distribution system dependability with optimal restoration time. The methodology is evaluated on a distribution system in MEA, THAILAND, taking into account constraints of available manpower, distance to the faulty component, and customer interruption cost.
2014	Pobporn W. et al.	This paper presents a Reliability Centered Maintenance (RCM) implementation on PEA power distribution systems, THAILAND. RCM prioritizes failure types by effect and selects effective maintenance operations.
2014	Sudket N., and Chaitusaney S.	This study assesses the optimal substation equipment maintenance in terms of cost and reliability. As a result of age-related deterioration and consistent use, the failure rate of a piece of equipment tends to rise gradually over its lifetime. Therefore, it is proposed that the failure rate of equipment be modeled using the appropriate Weibull distribution.
2018	Liu, J. et al.	This paper presents the improved Monte Carlo method with average and distributed sampling, which increases the speed and accuracy of reliability evaluation, reduces computing time, and offers a good path for the future reliability assessment of power distribution networks.

Table 2. 9 Review of literature and related research (Continued)

Year	Author	Research implementation
2018	Okakwu, I. et al.	This paper presents a probabilistic and analytic perspective on COPT. As the number of unavailability units increases, the capacity outage (MW) similarly increases, while the capacity available (MW), individual state probability, and cumulative probability decrease.
2019	Husain Saleh, M. J. A. et al.	This paper presents that LOLP and LOLE are simulated to evaluate the system reliability effects of the system parameters such as forced outage rate is tested on the LOLP index and LOLE index.
2019	Qamber I. S.	This paper presents the reliability index (LOLE) for the electric network that combines the four power plants under consideration. The investigated system could reduce LOLE if the four power stations are combined.
2022	Dat H.T. et al.	This paper presents a variety of characteristics and directions for applying the ETAP reliability function to the distribution network, as well as some usual reliability indices.

CHAPTER 3
RELIABILITY ASSESSEMENT OF
DC RAILWAY TRACTION POWER SUPPLY SYSTEMS

3.1 Chapter Overview

In this chapter, the reliability assessment of the DC railway traction power supply system is discussed. Section 3.2 presents a multi-train simulation for obtaining load curves. Sections 3.3 present result of MRT Purple Line reliability assessment. 3.4 present result of MRT Purple Line power supply system. 3.5 present result of MRT Purple Line preventive maintenance.

3.2 Train Movement Simulation

As a case study for multi-train simulation, the MRT purple line, which serves trains in Bangkok, Thailand, was selected. The simulation was based on a system model for collecting data on energy consumption at each substation for use in the assessment of reliability. There are 16 passenger stations and 10 traction substations in total. Table 3.1 displays the locations of passenger stations and traction substations. The simulation simulated 16 trains operating in the system at varying travel time and speed for each segment of the passenger terminal. It calculates the train speed at each station based on the service frequency table shown in Table 3.2. This study utilized railway data and systems of the MRT Purple Line. The train is electrically powered by the drive station via the third rail with a rated voltage of 750 VDC. It has a power rating of 1 x 2.5 MW. The simulation parameters for the MRT Purple Line train and the traction substation are displayed in Tables 3.3 and 3.4, respectively. Figure 3.2 depicts the procedure for calculating multi-train movement simulation and performance. For a typical train service hours of MRT Purple line are between 5.30 a.m. and 12.00 a.m. (18.5 hours), in normal hour average headway is 9 minutes per train and peak hour (06.30 a.m. to 08.30 a.m. and 05.00 p.m. to 07.30 p.m.) average headway is 6 minutes per train.

Table 3. 1 Position of passenger stations and traction substations

Station	Position of passenger stations (km)	Position of traction substation (km)
(PP01) Klong Bangphai	0.00	0.00
(PP02) Talad Bangyai	1.27	1.27
(PP03) Bangyai	2.83	2.83
(PP04) Bangphu	4.40	-
(PP05) Bang Rakyai	5.60	5.60
(PP06) Bang Raknoi	6.85	-
(PP07) Saima	8.10	8.10
(PP08) Pha Nungklao	9.57	-
(PP09) Yak Nonthaburi	11.20	11.20
(PP10) Bang Kasor	12.46	-
(PP11) Nonthaburi Center	13.36	13.36
(PP12) Ministry Public Health	15.15	-
(PP13) Yak Tiwanon	16.35	16.354
(PP14) Wongsawang	18.07	18.07
(PP15) Bangson	19.36	19.36
(PP16) Taopoon	20.94	-

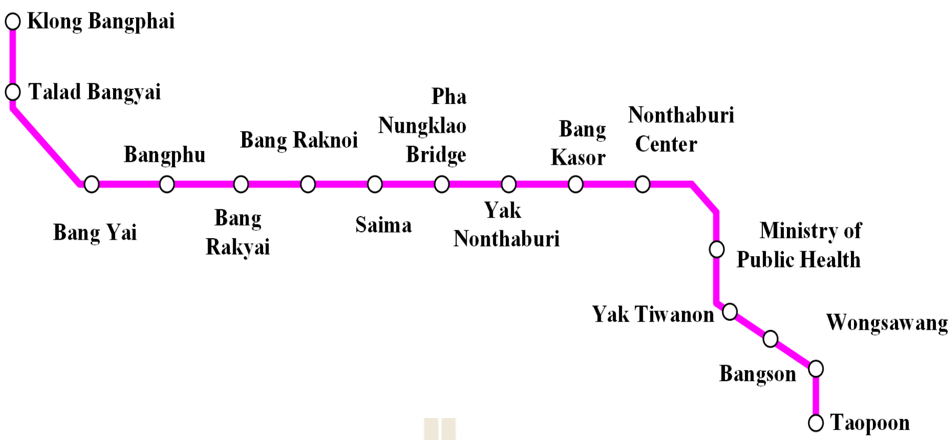

Figure 3. 1 MRT Purple Line route

Table 3. 2 Travel time and speed of each passenger stations

Station	From Klong Bangphai to Taopoon		From Taopoon to Klong Bangphai	
	Travel time (s)	Speed (km/h)	Travel time (s)	Speed (km/h)
Klong Bangphai	120	50	-	-
Talad Bangyai	120	45	120	45
Bangyai	180	60	180	60
Bangphu	120	45	120	50
Bang Rakyai	120	45	120	50
Bang Raknoi	180	40	60	45
Saima	120	50	180	40
Pha Nungklao	120	50	120	45
Yak Nonthaburi	180	50	120	50
Bang Kasor	120	40	120	40
Nonthaburi Center	120	40	180	40
Ministry Public Health	240	40	120	55
Yak Tiwanon	120	40	120	55
Wongsawang	180	40	120	60
Bangson	180	50	120	55
Taopoon	-	-	120	

Table 3. 3 MRT Purple Line train parameters

Parameter	Value	Unit
Maximum acceleration	1.2	m/s^2
Maximum deceleration	0.9	m/s^2
Maximum velocity	80	km/h
Train mass	153	ton
Passenger mass	75	ton
Maximum tractive effort	228.8	kN
Maximum braking effort	168.8	kN
Power auxiliary	270	kW
Efficiency motor and inverter	0.86	-

Table 3. 4 MRT Purple Line traction substation parameter

Parameter	Value	Unit
Short-circuit capacity	50	MW
No-load voltage	750	V
3^{rd} Rail resistance	0.0070	Ω/km
Running Rail resistance	0.0175	Ω/km
Rail to Earth conductance	0.1	S*km

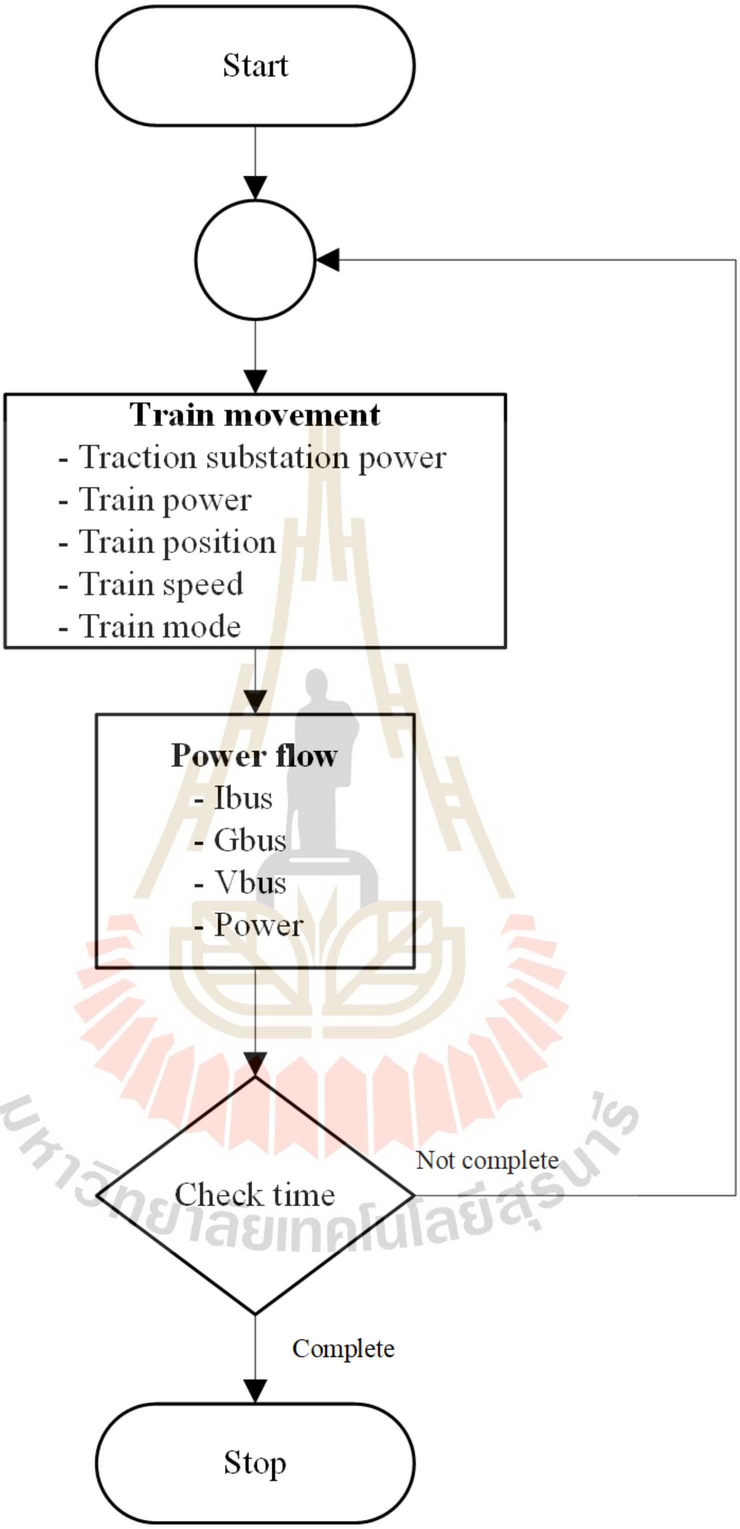

Figure 3. 2 The procedure for calculating multi-train simulation

The simulation results of the MRT Purple Line will present only the information necessary to assess reliability. By taking load of traction power substation after 1 day of service, for load curve of traction power substation after 1 day of service show in Appendix A. for load duration curve is derived from simulation sorted in descending order of load.

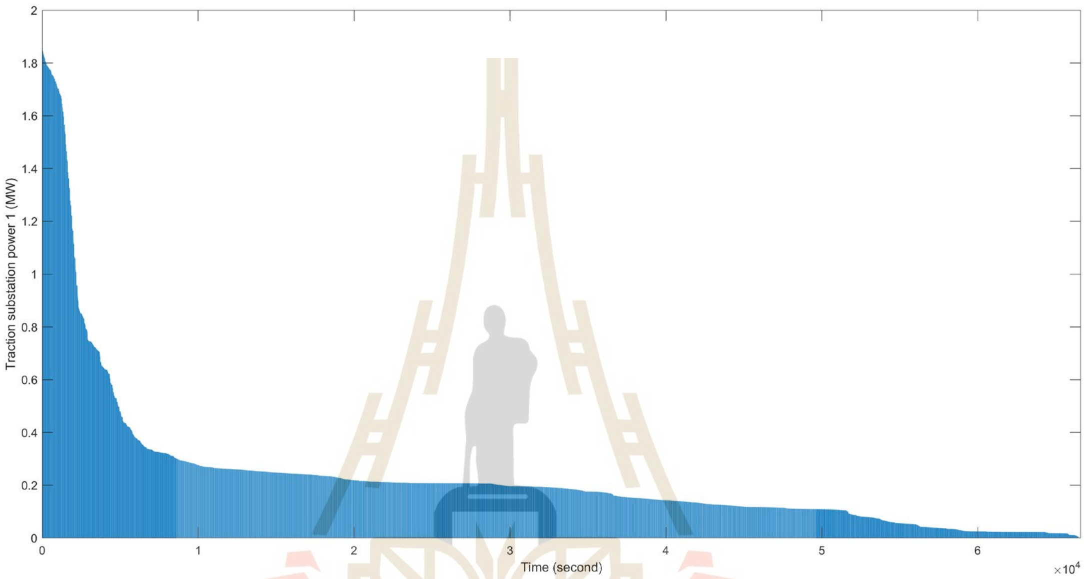

Figure 3. 3 Klong Bangphai traction substation load duration curve

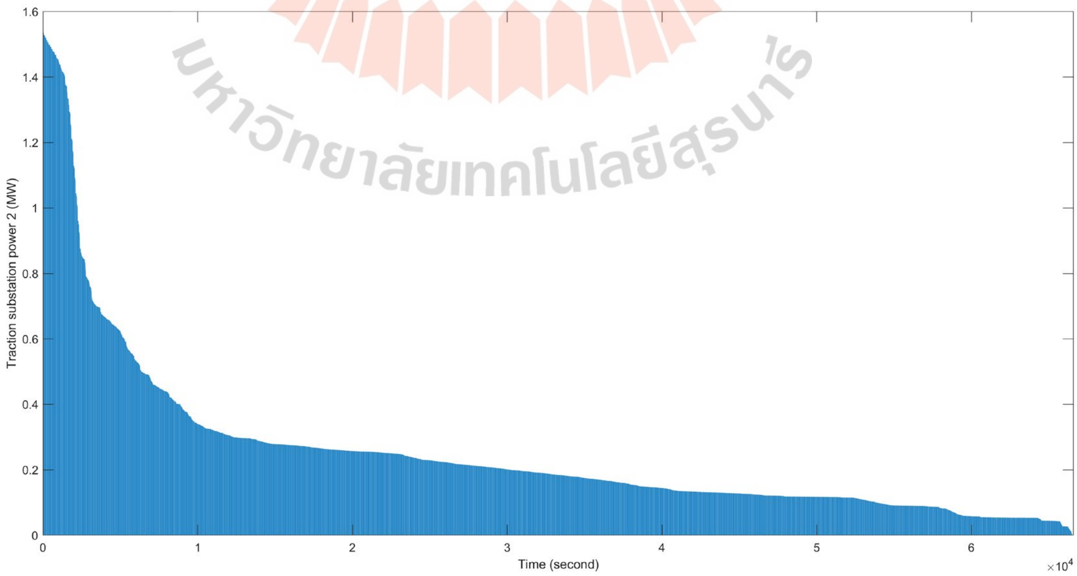

Figure 3. 4 Talad Bangyai traction substation load duration curve

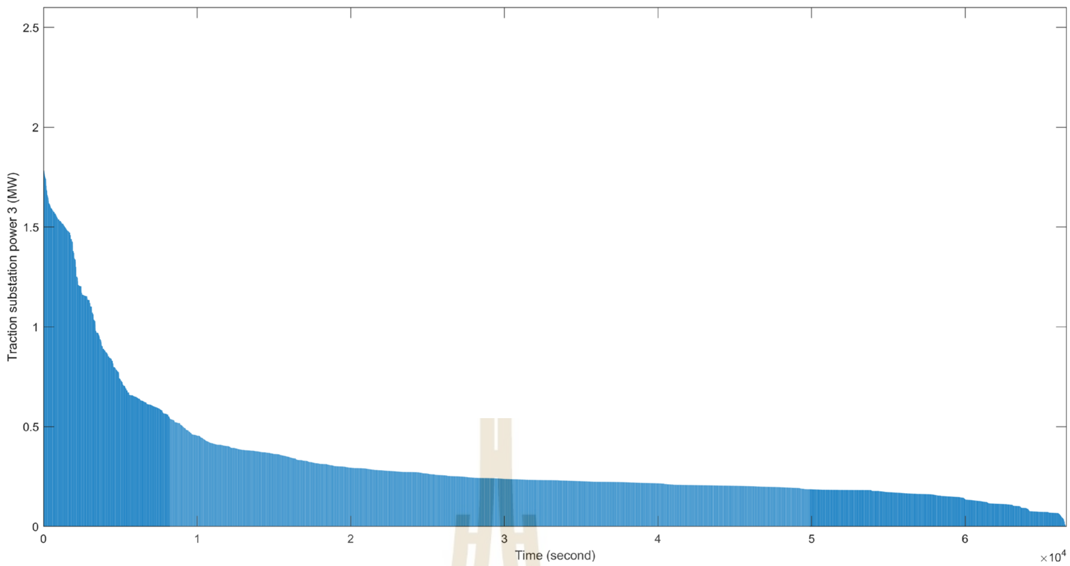

Figure 3. 5 Bangyai traction substation load duration curve

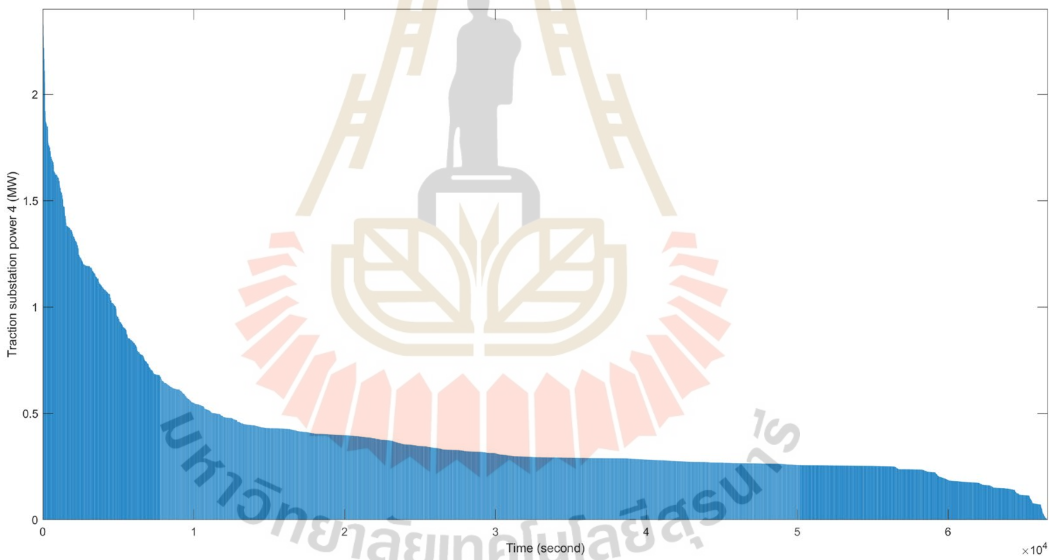

Figure 3. 6 Bang Rakyai traction substation load duration curve

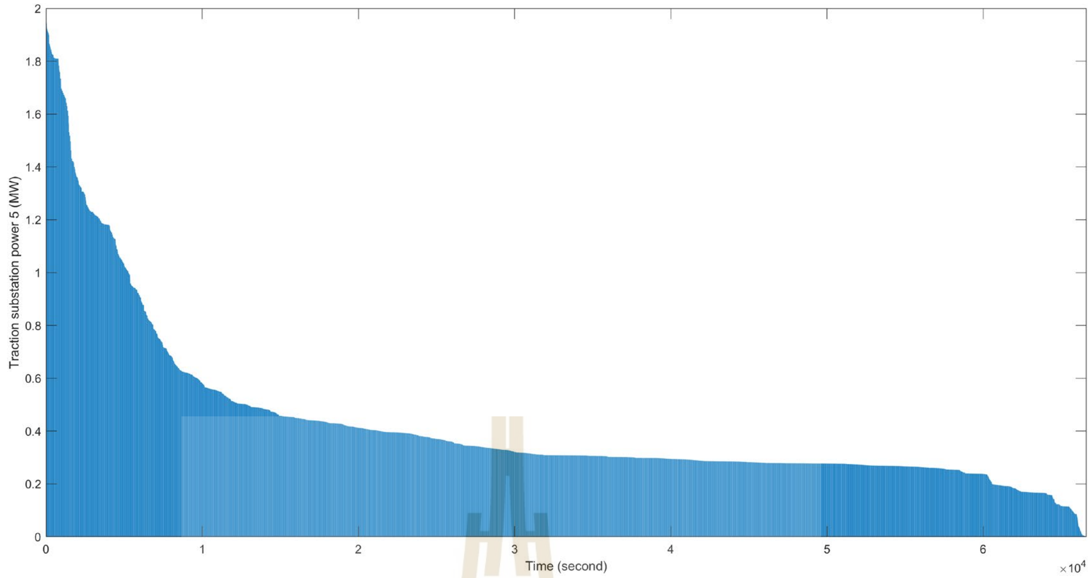

Figure 3. 7 Saima traction substation load duration curve

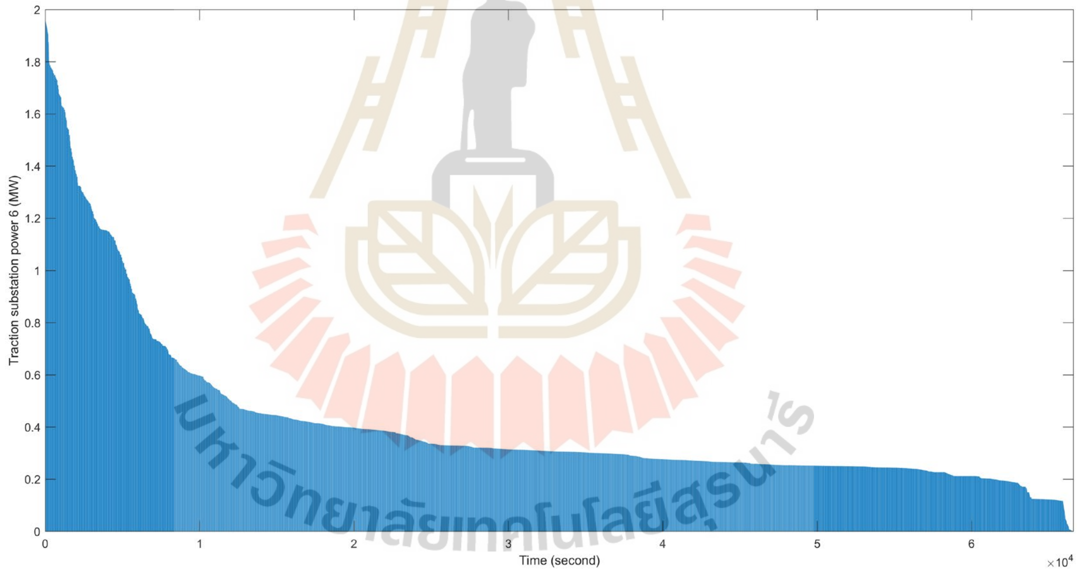

Figure 3. 8 Yak Nonthaburi traction substation load duration curve

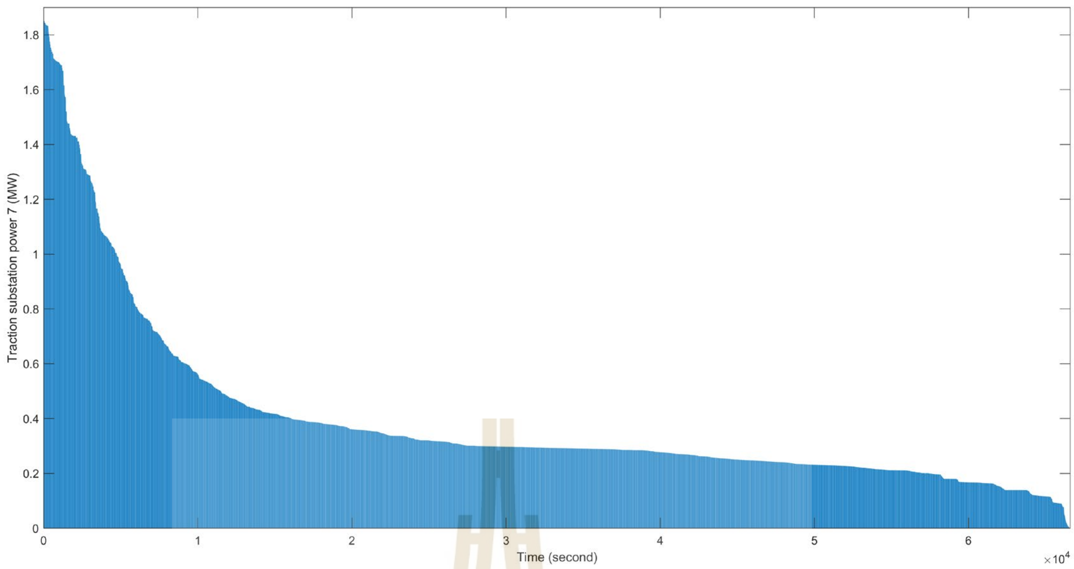

Figure 3. 9 Nonthaburi Center traction substation load duration curve

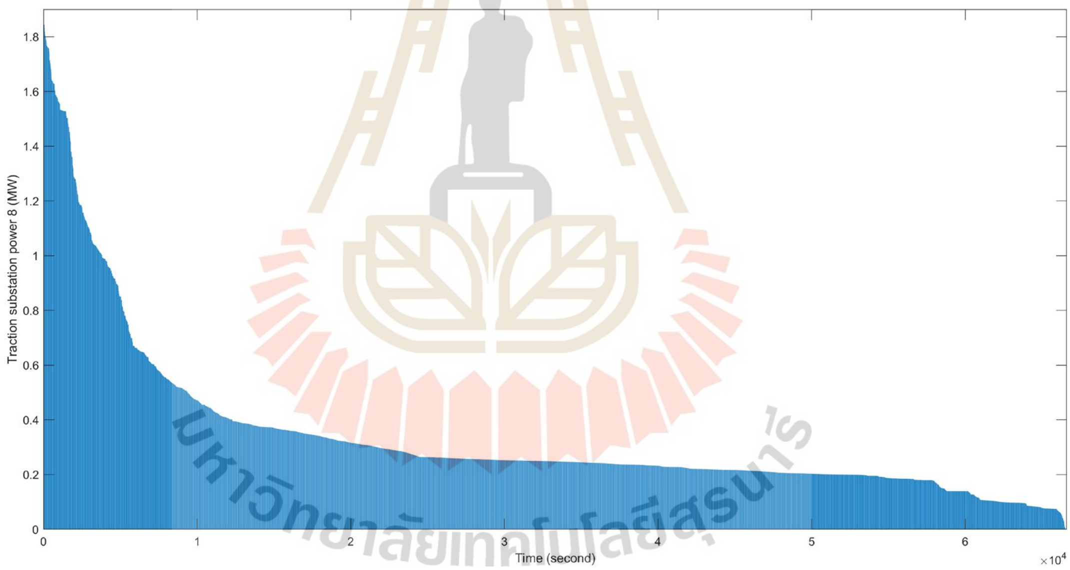

Figure 3. 10 Yak Tiwanon traction substation load duration curve

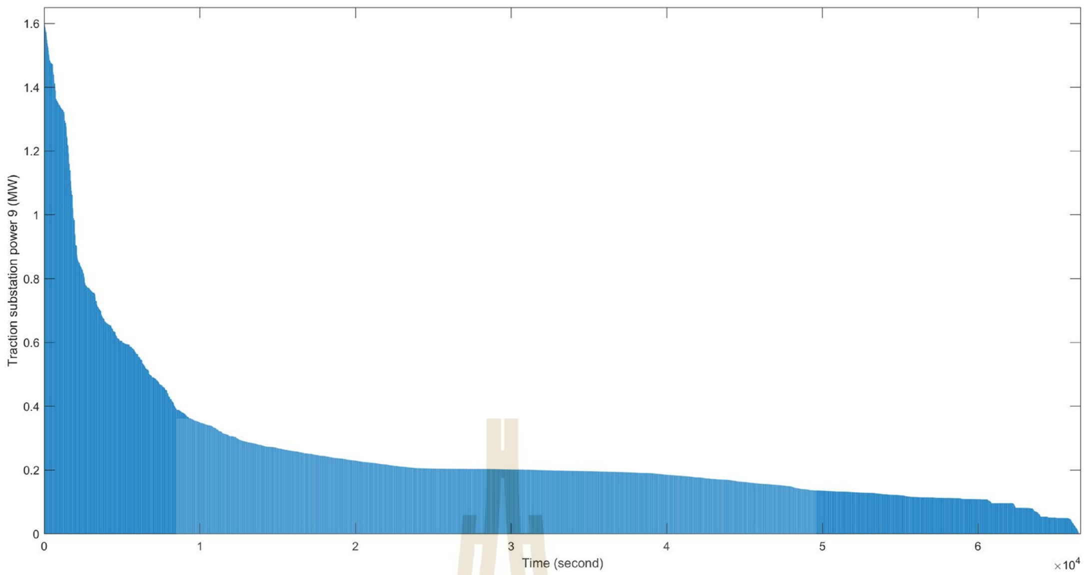

Figure 3. 11 Wongsawang traction substation load duration curve

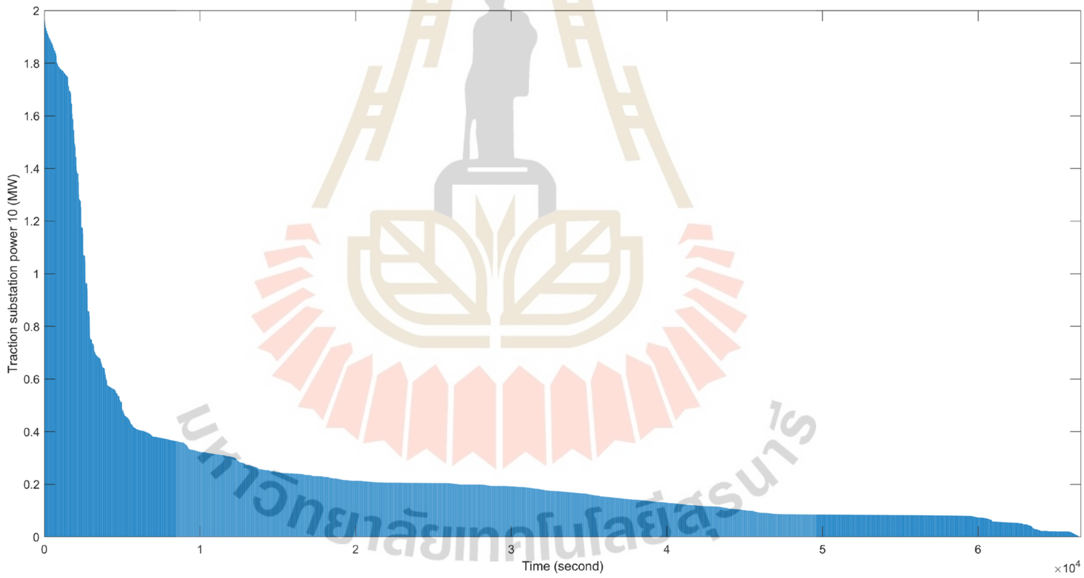

Figure 3. 12 Bangson traction substation load duration curve

3.3 Reliability Assessment of Bangkok MRT Purple Line

This section provides an analysis of the traction power supply system's reliability. Figure 3.13 represents the single-line diagram for the case study. From a single line diagram, a block diagram can be created for the RBD method to calculate the failure rate, MTTF, MTTR, availability, and unavailability. Figures 3.14, 3.15, and 3.16 show a distribution substation block diagram construction example.

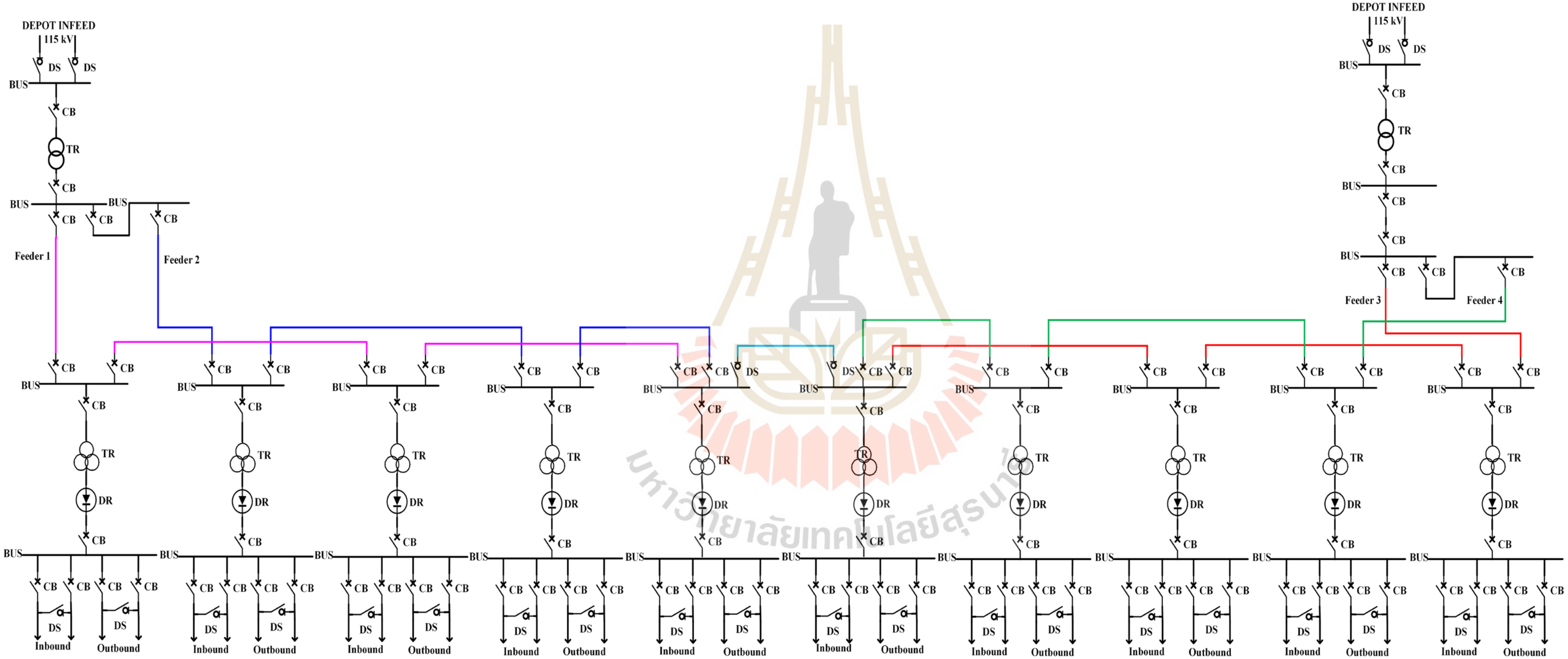

Figure 3. 13 Traction power circuit diagram of MRT Purple Line

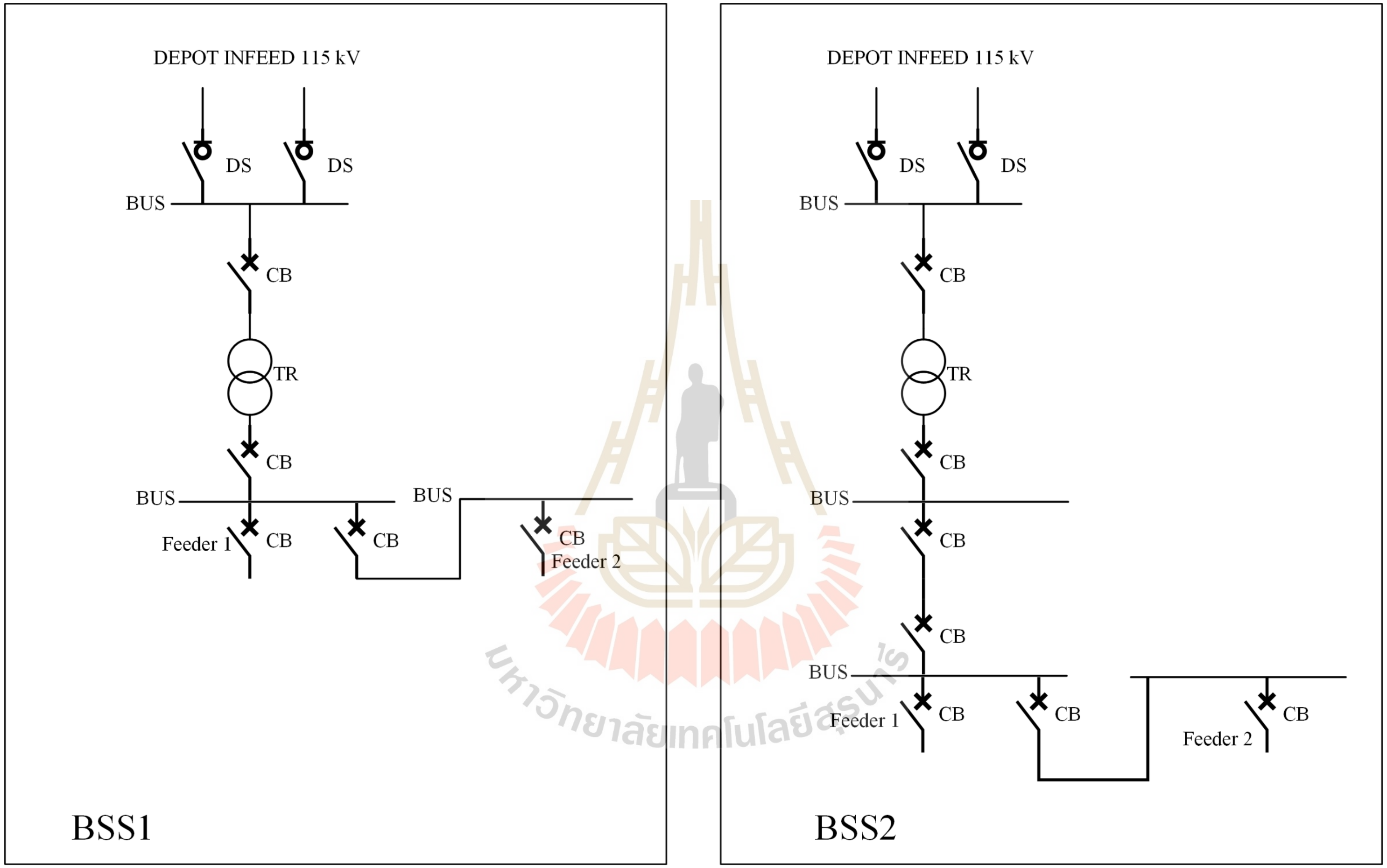

Figure 3. 14 Distribution substation BSS1 and BSS2

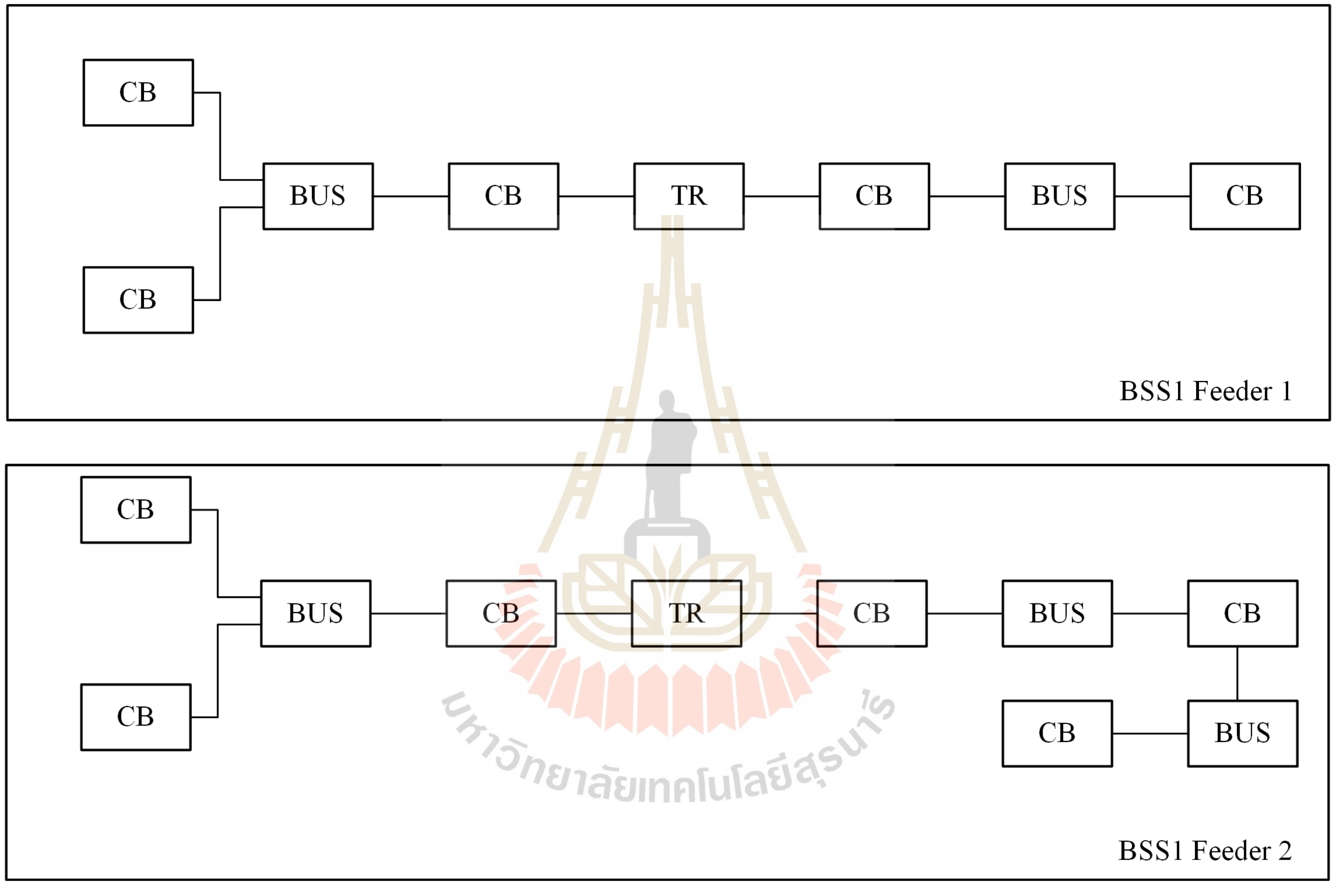

Figure 3. 15 Distribution substation BSS1 block diagram

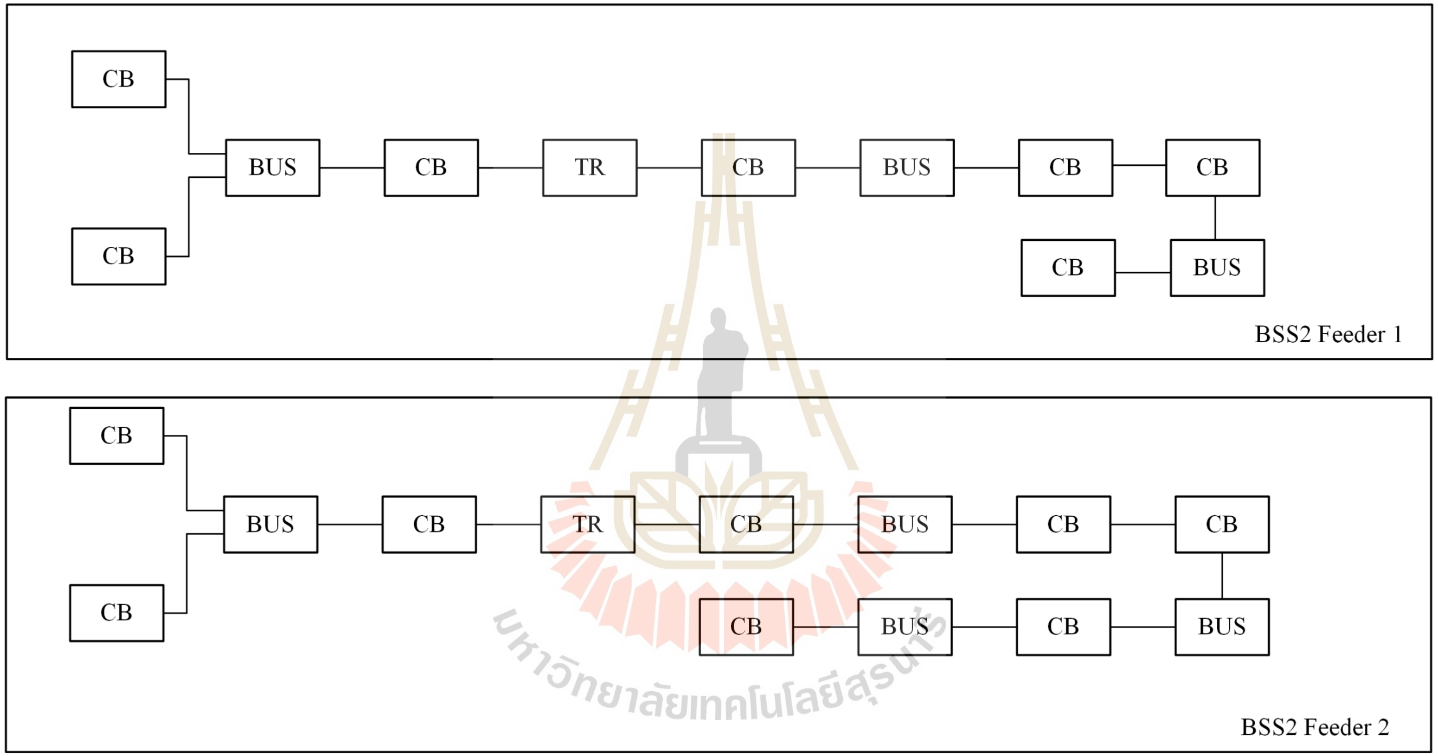

Figure 3. 16 Distribution substation BSS2 block diagram

Figures 3.17 and 3.18 present an example of a building block diagram of a traction power substation.

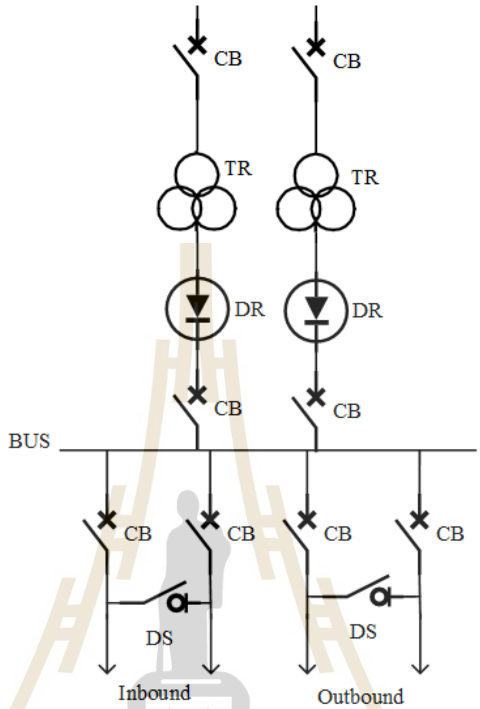

Figure 3. 17 Traction power substation diagram

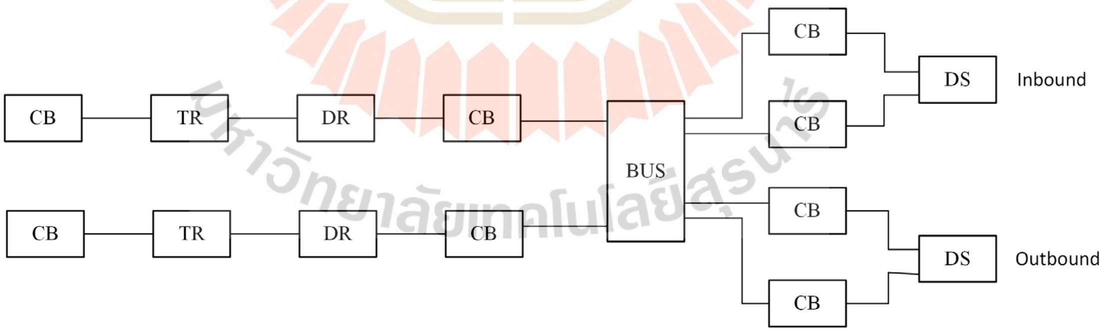

Figure 3. 18 Traction power substation block summary

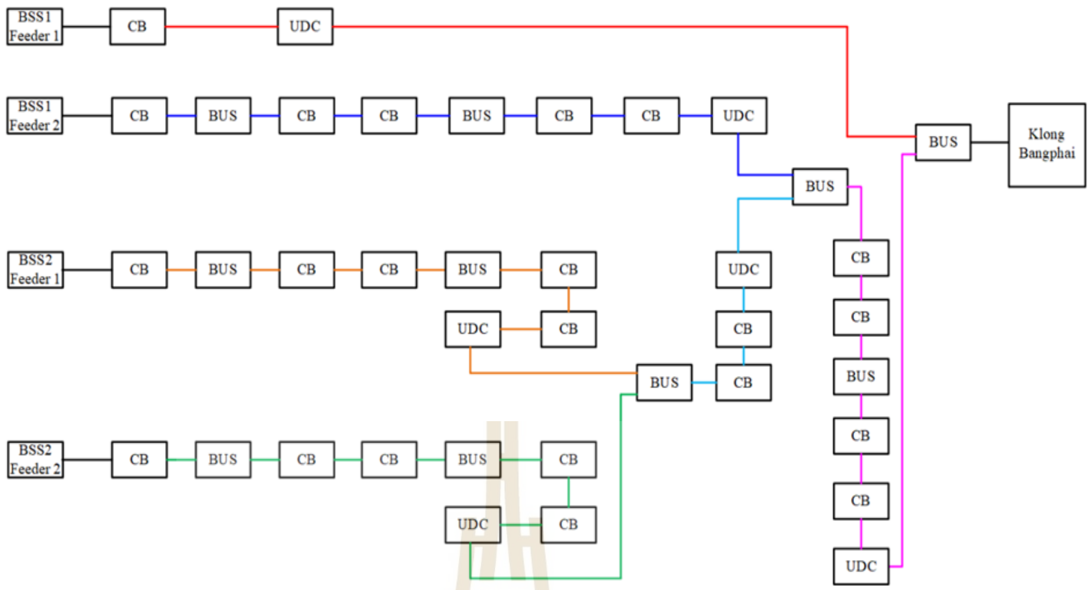

Figure 3. 19 Klong Bangphai substation block combination

The RBD method is used to compute the block diagram of all devices in the system from multiple blocks to a single block. In the calculations, separate calculations are made for each traction substation. For example, Figure 3.19 presents the connection block diagram of all equipment in the system connected to the Klong Bangphai traction power substation. After the block diagram has been created, the RBD method is used to calculate the reliability indexes that are connected in series or parallel to formulate the reliability of the Klong Bangphai block. The failure rate and reliability calculation results of all traction substations are shown in the following figure.

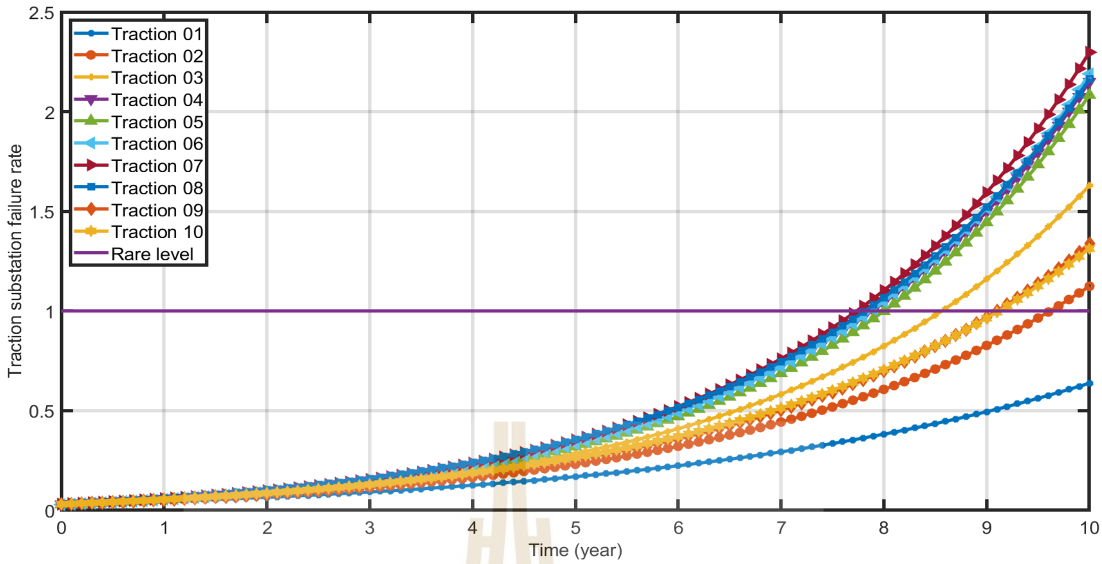

Figure 3. 20 Failure rate of all substations from 0 to 10 years of services

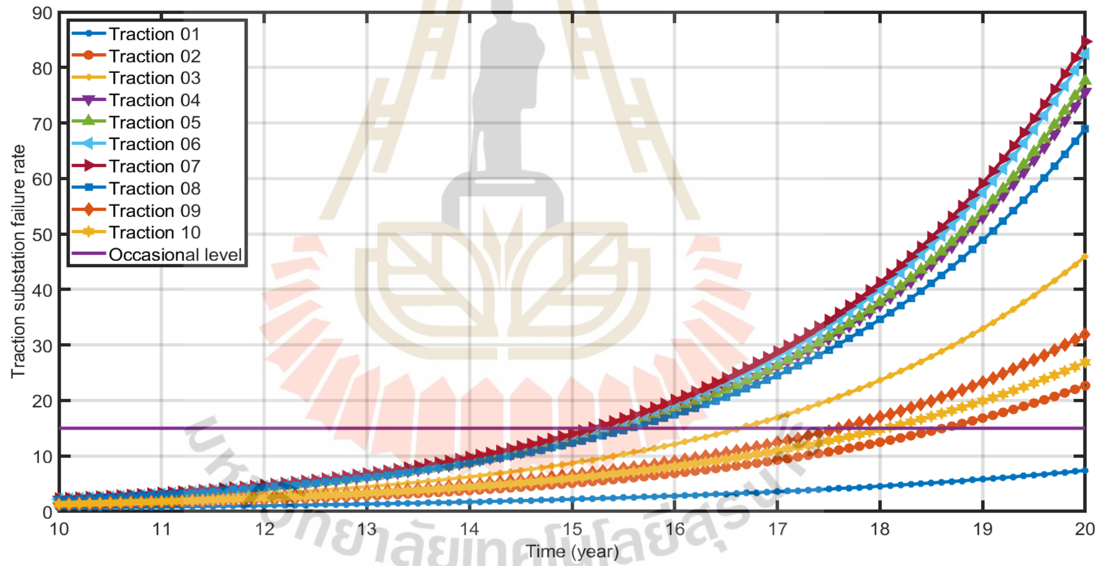

Figure 3. 21 Failure rate of all substations from 10 to 20 years of services

The failure rate calculation results of all traction substations showed that the failure rate was greater over time. As a result, the reliability of the traction substation is reduced. When bringing the failure rate results compared to the standard EN-50126:2017 with severity category is marginal level, so after 10 years without maintenance and frequency is rare level, the risk acceptance category of the Klong Bangphai traction substation is tolerable level because the failure rate is less than once per year, shown in Figure 3.20. At the risk acceptance can be tolerated and accepted with adequate control and the consent of the responsible railroad duty holders. The remaining traction substation is undesirable because the failure rate is greater than once per year, at undesirable level the risk shall be accepted if its reduction is impractical and with the approval of the railway duty holders or the responsible Safety Regulatory Authority. Up to 20 years have passed without maintenance. The risk tolerance category for the Klong Bangphai traction substation is undesirable because the failure rate is more than once per year, the risk tolerance category for the remaining traction substation is intolerable because the failure rate is greater than fifteen times per year the risk should be corrected immediately.

3.4 Power Supply Availability Assessment of Bangkok MRT Purple Line

In order to assess the reliability of the power supply system index to formulate LOLE, this is necessary to have data on load duration, which can be obtained through the multi-train simulations described in section 3.2, as well as data on system availability, which can be obtained through the reliability assessment described in section 3.3. Table 3.5 shows the traction substation failure rate data obtained from section 3.3 for use at typical times (after 5 years), and Table 3.6 shows the traction substation availability data. Both tables contain the data that were used to calculate the availability of the traction substations.

When the availability results for each traction substation in Table 3.6 are calculated, it is obvious that the availability is higher for the traction substations that are closer to the distribution substations than for traction substations that are farther away. This is due to the length of underground cables and the greater number of disconnection switches with the series connections. This makes the traction station farther away, with a higher failure rate and repair rate.

Table 3. 5 Reliability assessment of traction substation

Traction substation	Failure rate (Time per year)	MTTR (hours)	MTTF (hours)
Klong Bangphai	0.169018	3.049660	51828.71
Talad Bangyai	0.231219	3.033194	37886.13
Bangyai	0.285618	2.984382	30670.33
Bang Rakyai	0.338674	3.362090	25865.58
Saima	0.319514	2.616763	27416.67
Yak Nonthaburi	0.333518	2.730568	26265.48
Nonthaburi Center	0.353641	3.454195	24770.87
Yak Tiwanon	0.355466	3.028471	24643.71
Wongsawang	0.254292	3.079250	34448.60
Bangson	0.265803	2.731886	32956.76

Table 3. 6 Availability and unavailability of traction substation

Traction substation	Availability	Unavailability
Klong Bangphai	0.999941	0.000059
Talad Bangyai	0.999920	0.000080
Bangyai	0.999903	0.000097
Bang Rakyai	0.999870	0.000130
Saima	0.999905	0.000095
Yak Nonthaburi	0.999896	0.000104
Nonthaburi Center	0.999861	0.000139
Yak Tiwanon	0.999877	0.000123
Wongsawang	0.999911	0.000089
Bangson	0.999917	0.000083

Assessments of power supply system reliability are based on the results of system availability and power demand. To evaluate the reliability of the MRT Purple Line power supply system, simulation data obtained in Section 3.2, availability data from Table 3.6, and the methodology described in Section 2.4 were utilized. It begins with the development of a COPT that exploits computational availability shown in Table 3.7. After obtaining the table, the cumulative probability will be used to produce LOLP. In the final step, LOLE will be calculated by combining LOLP with the load duration curve obtained from the multi-train simulation. Each traction substation LOLE is shown in Table 3.8.

Table 3. 7 Capacity outage probability table of MRT Purple Line traction substation

Sub No.	Capacity Available	Capacity Unavailable	State Probability	Cumulative Probability
Klong Bangphai	2.5	0	0.999941	1.000000
	0	2.5	0.000059	0.000059
Talad Bangyai	2.5	0	0.999920	1.000000
	0	2.5	0.000080	0.000080
Bangyai	2.5	0	0.999903	1.000000
	0	2.5	0.000097	0.000097
Bang Rakyai	2.5	0	0.999870	1.000000
	0	2.5	0.000130	0.000130
Saima	2.5	0	0.999905	1.000000
	0	2.5	0.000095	0.000095
Yak Nonthaburi	2.5	0	0.999896	1.000000
	0	2.5	0.000104	0.000104
Nonthaburi Center	2.5	0	0.999861	1.000000
	0	2.5	0.000139	0.000139
Yak Tiwanon	2.5	0	0.999877	1.000000
	0	2.5	0.000123	0.000123
Wongsawang	2.5	0	0.999911	1.000000
	0	2.5	0.000089	0.000089
Bangson	2.5	0	0.999917	1.000000
	0	2.5	0.000083	0.000083

Table 3. 8 LOLE of traction substation

Traction substation	LOLE (Second per day)	LOLE (Day per year)
Klong Bangphai	3.9294	0.0166
Talad Bangyai	5.3280	0.0225
Bangyai	19.4589	0.0822
Bang Rakyai	8.6580	0.0366
Saima	6.3270	0.0267
Yak Nonthaburi	6.9264	0.0293
Nonthaburi Center	9.2574	0.0391
Yak Tiwanon	8.1918	0.0346
Wongsawang	5.9274	0.0250
Bangson	5.5278	0.0234
Combine all traction substations	$0.7\text{x}10^{-23}$	$0.3\text{x}10^{-25}$

The LOLE calculation results show how much availability the traction substation will be able to support the train service. As a result, the Bangyai traction substation was unable to supply power for the longest time at 0.0822 days per year, or approximately 118 minutes per year, and the Klong Bangphai traction substation was unable to supply power for the lowest time at 0.0166 days per year or about 24 minutes. Due to the availability effect described above, the Nonthaburi Center traction substation has the lowest availability, but the highest LOLE is the Bangyai traction substation because the Bangyai traction substation need to distribute electrical power of more than 2.5 MW at certain intervals.

Compare the results in Table 3.8 with NERC BAL-502-RF-03, which states that the highest acceptable LOLE for a power distribution system is 0.1 days per year, where all traction substation availability results qualify as acceptable. But the standard to be compared is the power system of a region not only the traction power supply. Consequently, it is prudent to establish an agreement between the authorities for the mass rapid transit system in each region based on the existing criteria.

According to the LOLE results of $0.3x10^{-25}$ days per year for the entire MRT Purple Line system, all traction substations can handle all electrical power loads. It is still possible to supply enough power even if one of the substations experiences a temporary failure.

3.5 Preventive Maintenance Assessment of Bangkok MRT Purple Line

Trains are powered by traction power supply systems in railway electrification systems, and their reliability is important to the efficiency of train service. The traction power supply system is comprised of a variety of components, ranging from the interface with the distribution substation to the traction substation, all of which are typically located along the rail line. Application of reliability-centered maintenance by comparing preventive maintenance intervals in railway traction power supply systems. When considering only the distribution substation to the traction substation, the service substation is not included. Every 1 year, 2 years, 3 years, 5 years, and 10 years the duration of preventive maintenance must be compared.

In this part, the results of calculations that were performed after strategies for reliability-centered maintenance in section 2.5 were applied are presented. Refer to Figures 3.20 and 3.21, when the preventative maintenance is determined, it is possible to reduce its failure rate down to 10 percent of its previous value. The outcomes are presented in figures respectively.

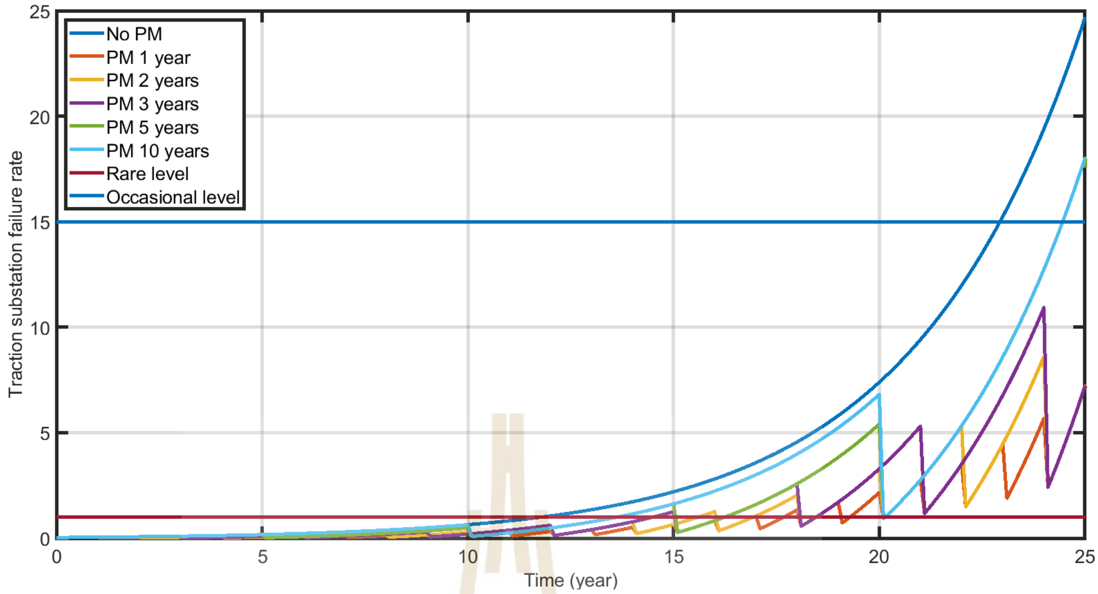

Figure 3. 22 Preventive maintenance of Klong Bangphai substation

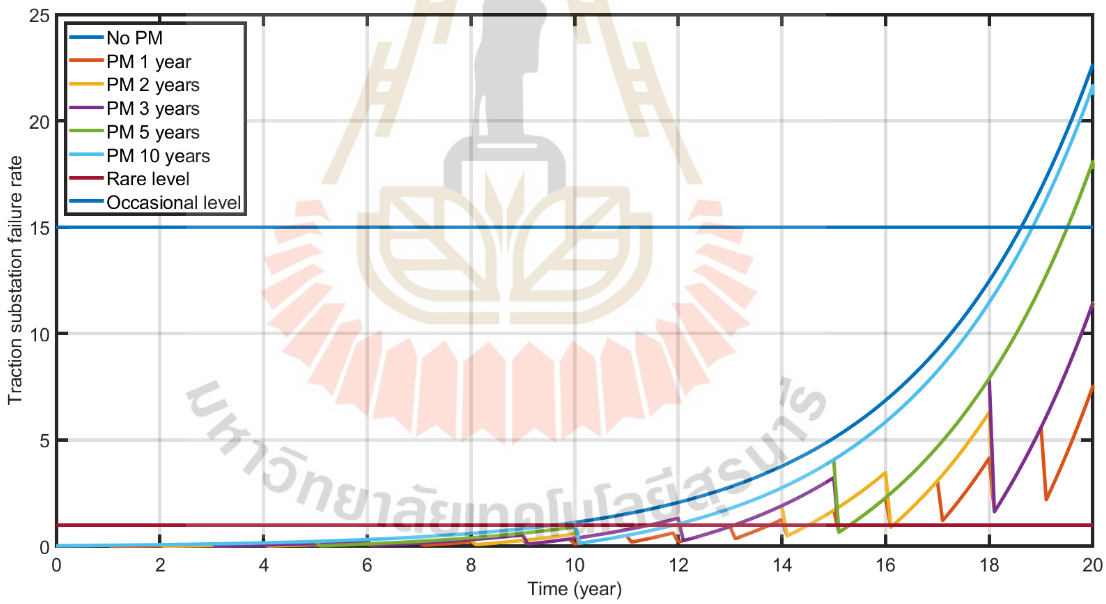

Figure 3. 23 Preventive maintenance of Talad Bangyai substation

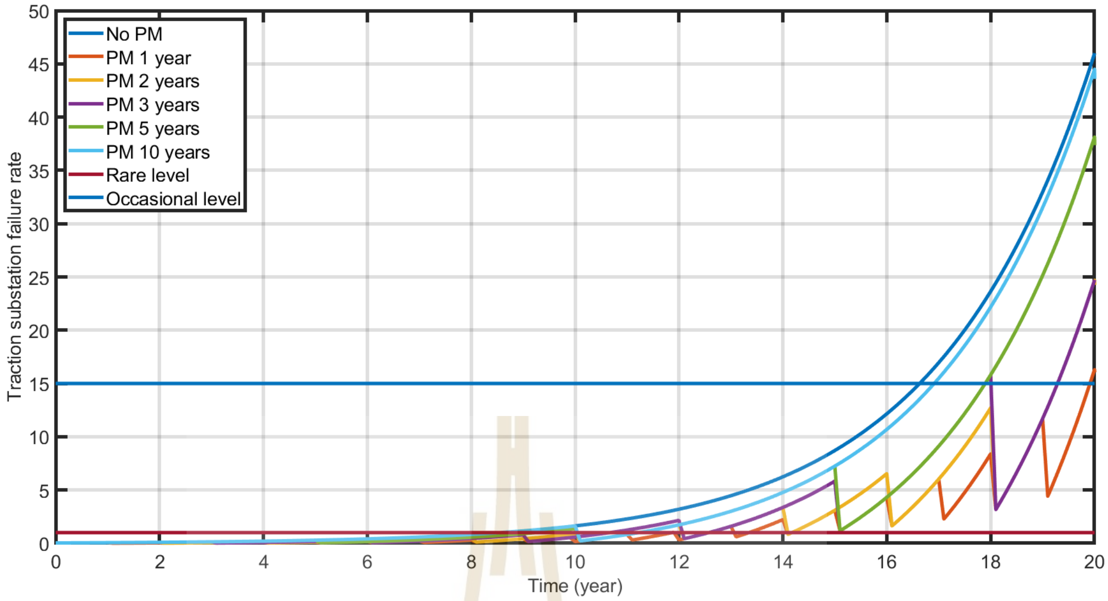

Figure 3. 24 Preventive maintenance of Bangyai substation

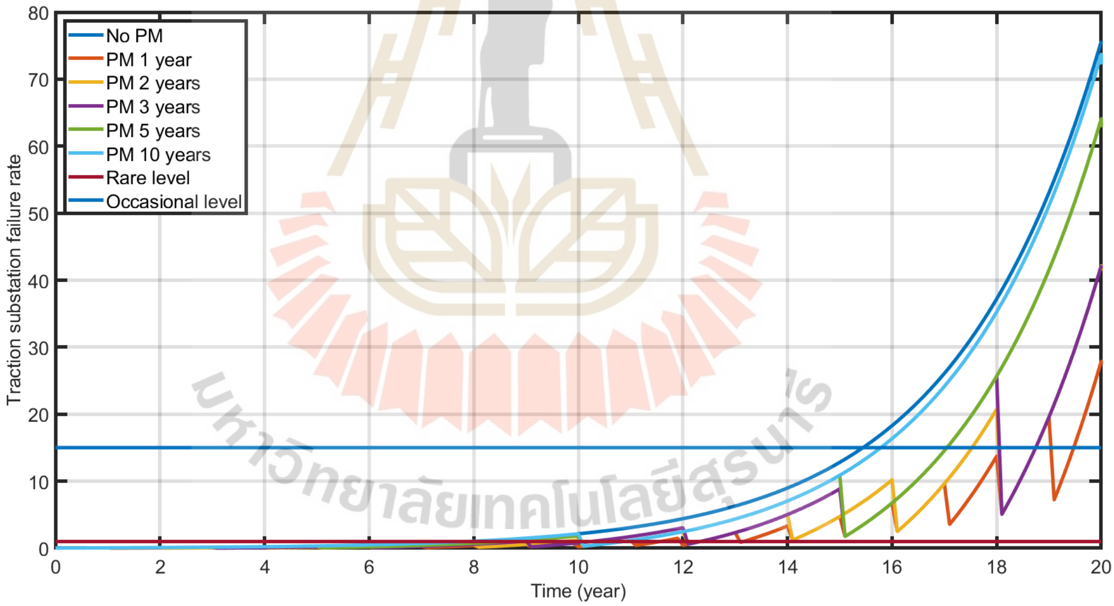

Figure 3. 25 Preventive maintenance of Bang Rakyai substation

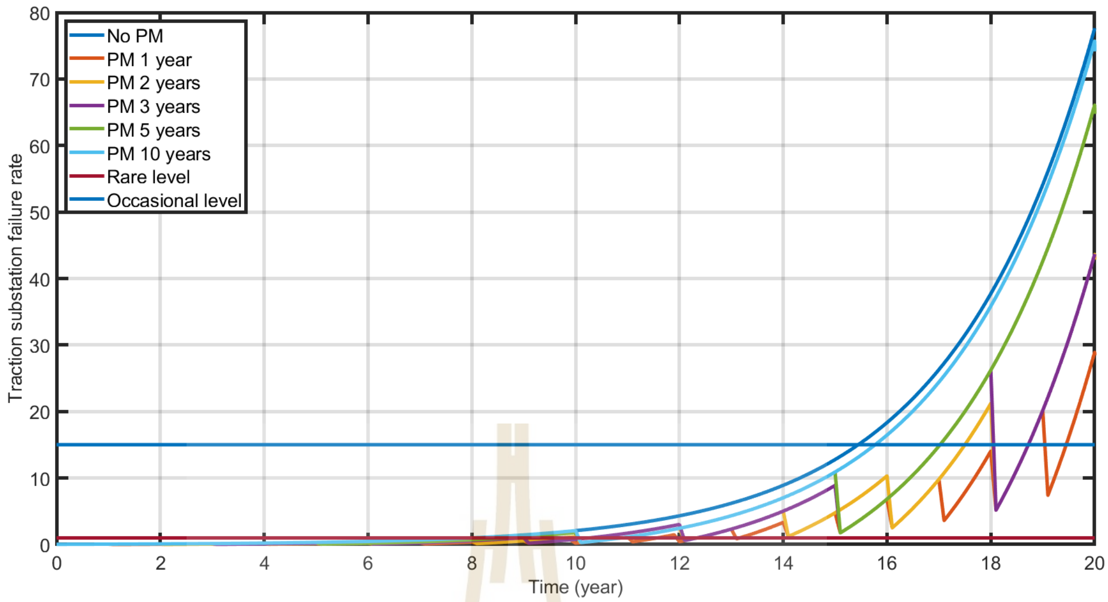

Figure 3. 26 Preventive maintenance of Saima substation

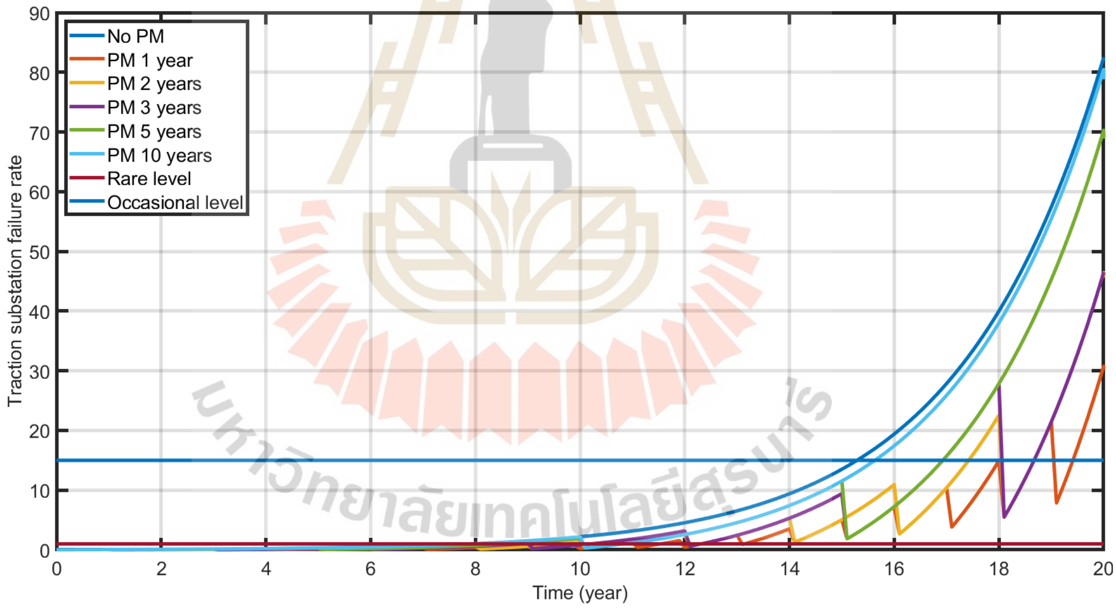

Figure 3. 27 Preventive maintenance of Yak Nonthaburi substation

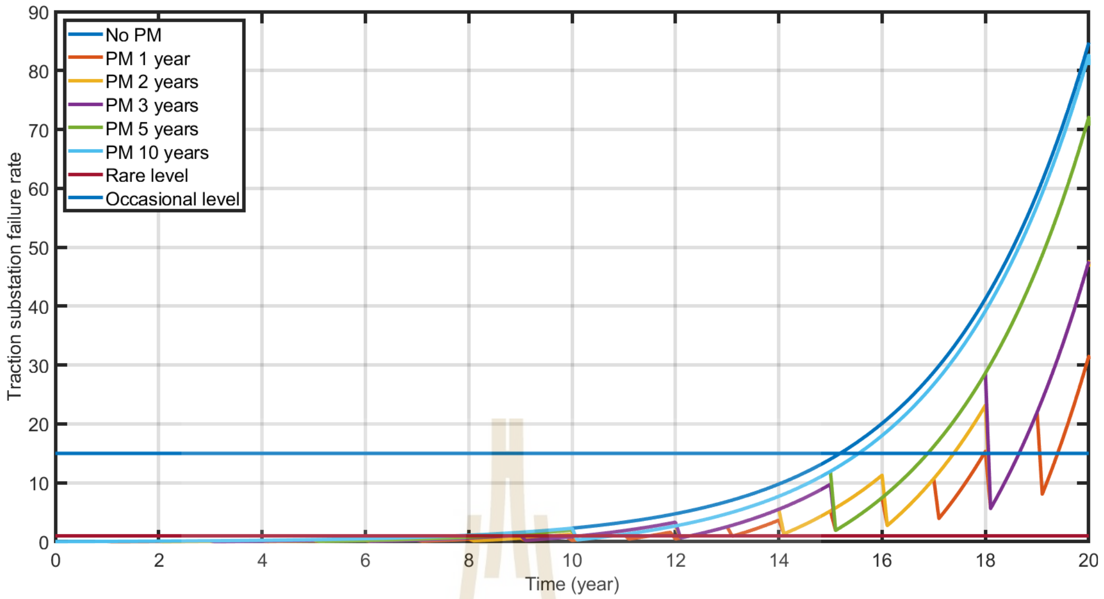

Figure 3. 28 Preventive maintenance of Nonthaburi Center substation

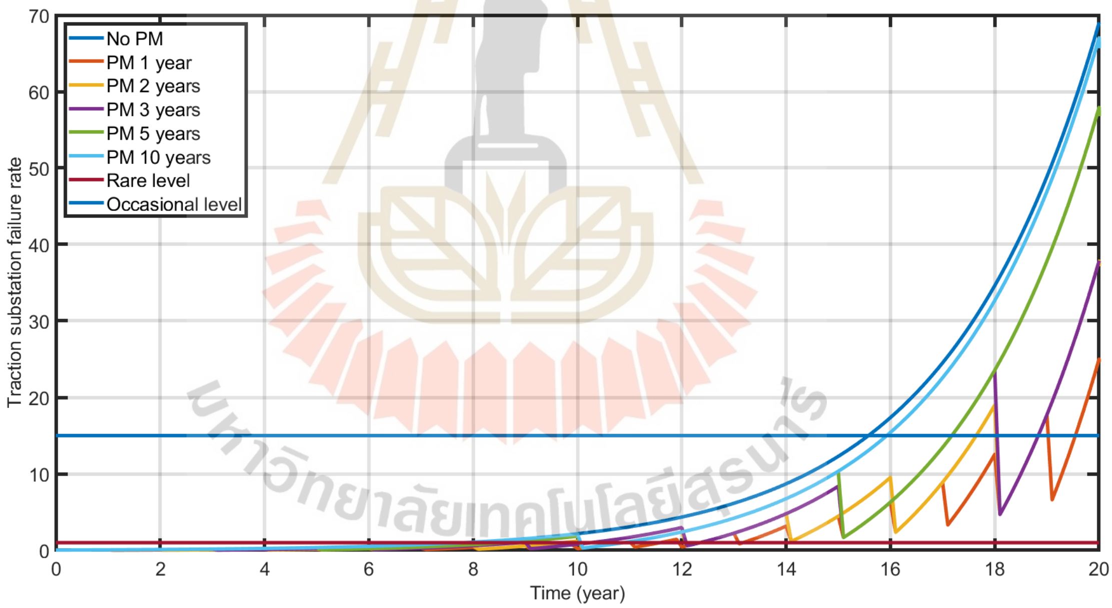

Figure 3. 29 Preventive maintenance of Yak Tiwanon substation

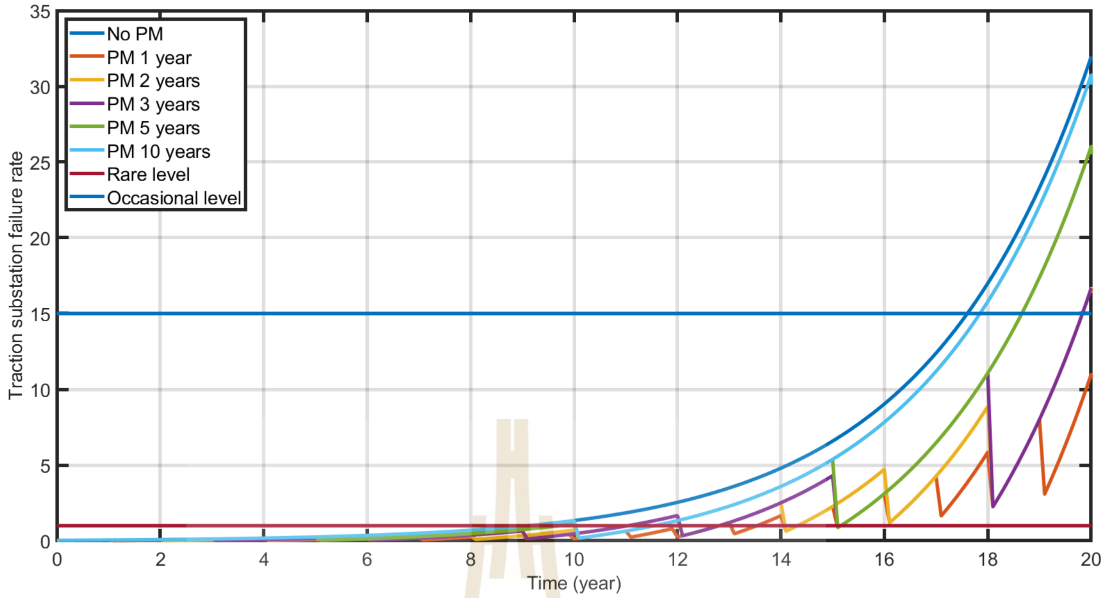

Figure 3. 30 Preventive maintenance of Wongsawang substation

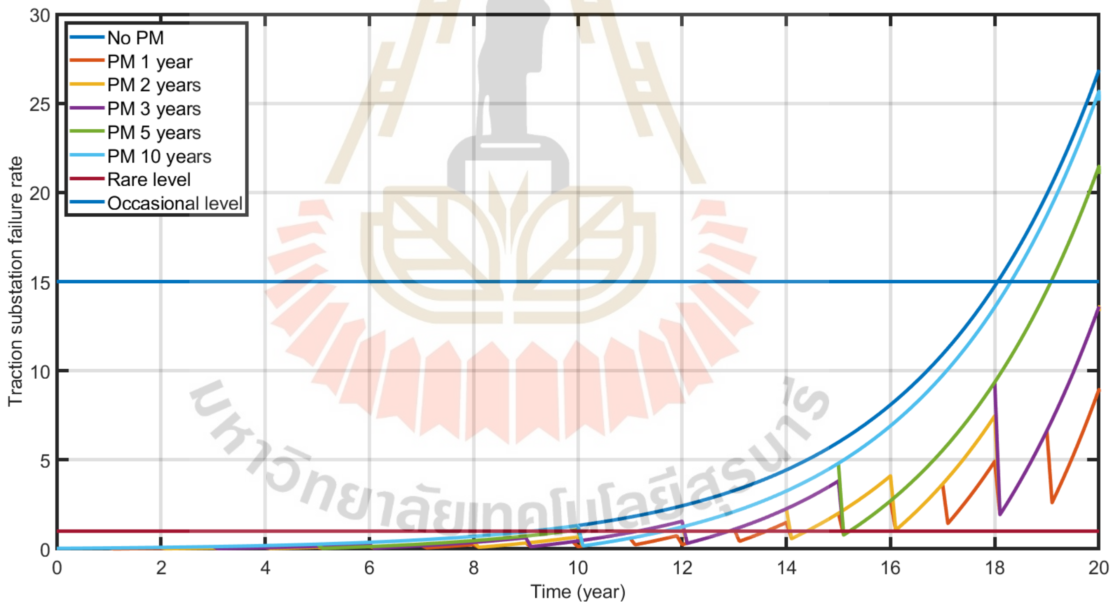

Figure 3. 31 Preventive maintenance of Bangson substation

As a result of calculating the failure rate of the traction substation when performing preventive maintenance. They are divided into different preventive maintenance periods every 1 year, 2 years, 3 years, 5 years, and 10 years. The results showed that preventive maintenance resulted in lower failure rates for all traction substations with every maintenance cycle. To compare different preventive maintenance intervals. Note that over a period of 20 years, preventive maintenance every 1-year results in lower failure rates than other periods which yield the same results for all traction substations.

Reliability assessment using failure rates compared to EN 50126 from section 3.3, traction substations 2 to 10, when no preventive maintenance, have a failure rate greater than 1 time per year or exceeds the rare level after service 7 years, but with preventive maintenance every 1 year, all traction substations need more than 10 years for the failure rate to exceed the rare level.

Table 3. 9 Total preventive maintenance cost multiplier of MRT Purple Line traction substations

Traction substation	Total preventive maintenance cost multiplier				
	1 year	2 years	3 years	5 years	10 years
Klong Bangphai	65.07	62.24	38.34	49.52	25.37
Talad Bangyai	132.95	140.93	75.77	104.81	42.52
Bangyai	228.42	243.83	119.01	168.65	58.62
Bang Rakyai	336.97	355.67	162.13	231.85	72.54
Saima	370.91	390.88	175.30	251.54	76.66
Yak Nonthaburi	381.85	400.66	178.69	256.00	77.50
Nonthaburi Center	367.65	386.22	173.38	248.15	75.89
Yak Tiwanon	292.92	306.90	143.08	202.26	65.98
Wongsawang	171.89	184.05	94.53	132.85	49.97
Bangson	142.60	148.90	78.82	107.89	43.10

The results indicated that the failure rate decreased with more frequent maintenance intervals. But because preventive maintenance needs to be costly for every maintenance, which is a condition that must choose a period of time used for maintenance to suit the cost set. Therefore, an approximate cost for maintenance planning must be calculated using the method from Section 2.5.2 to estimate the maintenance cost multiplier to multiply the actual cost to be used in each maintenance. The cost multiplier results used for preventive maintenance over all periods are shown in the following Table 3.9.

Preventive maintenance cost multiplier calculations can be used when actual cost data is available. The multiplier can be used in budget planning to determine the optimal timing. Budget to pay the result of calculating the cost multiplier for maintenance every 2 years uses the highest budget, while maintenance every 10 years uses the lowest budget. In terms of servicing once every year, the budget is slightly less than that of every two years as the lower failure rate means that the maintenance budget is less, but the maintenance is twice the frequency, therefore requiring a larger budget. From the results, it can be concluded that more frequent maintenance cycles will require a larger budget. In this case does not include a discounted rate and inflation rate.

3.6 Chapter Summary

Failure Rate, MTTF, MTTR, and Availability are used to assess MRT Purple Line reliability. Time-varying failure rate modeling calculated each substation failure rate and compared this to the EN 50126 standard. After 7 years, traction substation risk tolerance becomes Undesirable level. The provider agreement determines countermeasures for each risk level. LOLE is an index that indicates the ability to distribute power to the load, which may affect the operation, causing the system to stop working or not, the system may be overloaded but still able to continue working. To avoid system damage, the BAL-502-RF-03 standard requires a benchmark revision if LOLE exceeds 0.1 days per year. The traction substation in all case studies was standardized according to BAL-502-RF-03. The case study preventive maintenance failure rate calculations showed that higher maintenance frequencies maintained the benchmark longer. The case study is annual servicing cycle has the lowest failure rate and a reasonable maintenance budget. Because if the maintenance lasts longer than a year, the budget will rise, but the failure rate will not change much.

CHAPTER 4
RELIABILITY IMPROVEMENT OF BANGKOK MRT PURPLE LINE

4.1 Chapter Overview

This chapter presents case studies for improving the reliability of the MRT Purple Line. Section 4.2 is a case study for improving reliability by rearrangement of the distribution circuit in two formats. Section 4.3 presents the availability of traction substations with shorter headway effect for future plans.

4.2 Rearrangement of Medium Voltage Power Distribution Circuits

This chapter proposes an approach method for improving reliability using medium voltage distribution system circuit arrangements to reduce failure rate. Brown (2009) states that circuit connections directly affect the reliability of the power system. There are many forms of circuit connection in mass transit systems, as discussed in section 2.7, most of which are connected in a closed-loop distribution system, whereas MRT Purple Line uses a closed-loop distribution system. The result of the failure rate is passed the EN 50126 standard.

The formatting presented in this chapter is divided into two sections. The first section offers a reduction in the amount of equipment in the distribution circuit to reduce the budget used, then observes the result of the change in failure rate compared to the EN 50126 standard. The second section introduces distribution circuit improvements that reduce the failure rate by using an appropriate increase in the amount of equipment.

4.2.1 Radial Circuit

Radial circuit is the lowest reliable system in distribution circuit arrangement. But the format also uses the least budget due to the smaller amount of equipment in the circuit such as circuit breakers, disconnection switches, and under -

ground cables. The distribution circuit of the MRT Purple Line built is shown in Figure 4.1. Table 4.1 presents the amount of equipment used to connect the distribution circuits (count only the amount of equipment used to connect from the distribution substation to the traction substation) of the original scheme diagram used in section 3.3 and the amount of equipment in a radial circuit.

Table 4. 1 The amount of equipment used to connect with radial circuits

Equipment	Original circuit	Radial circuit
Circuit breaker	24 pcs.	20 pcs.
Disconnection switches	2 pcs.	2 pcs.
Underground cable	38,417 m.	21,490 m.

Table 4. 2 Reliability assessment for radial system of traction substation

Traction substation	Failure rate (Time per year) Original	Failure rate (Time per year) Radial	%Change
Klong Bangphai	0.169018	0.171880	1.69
Talad Bangyai	0.231219	0.248676	7.55
Bangyai	0.285618	0.332330	16.35
Bang Rakyai	0.338674	0.431431	27.39
Saima	0.319514	0.486386	52.23
Yak Nonthaburi	0.333518	0.491367	47.33
Nonthaburi Center	0.353641	0.468240	32.41
Yak Tiwanon	0.355466	0.402458	13.22
Wongsawang	0.254292	0.350107	37.68
Bangson	0.265803	0.303872	14.32

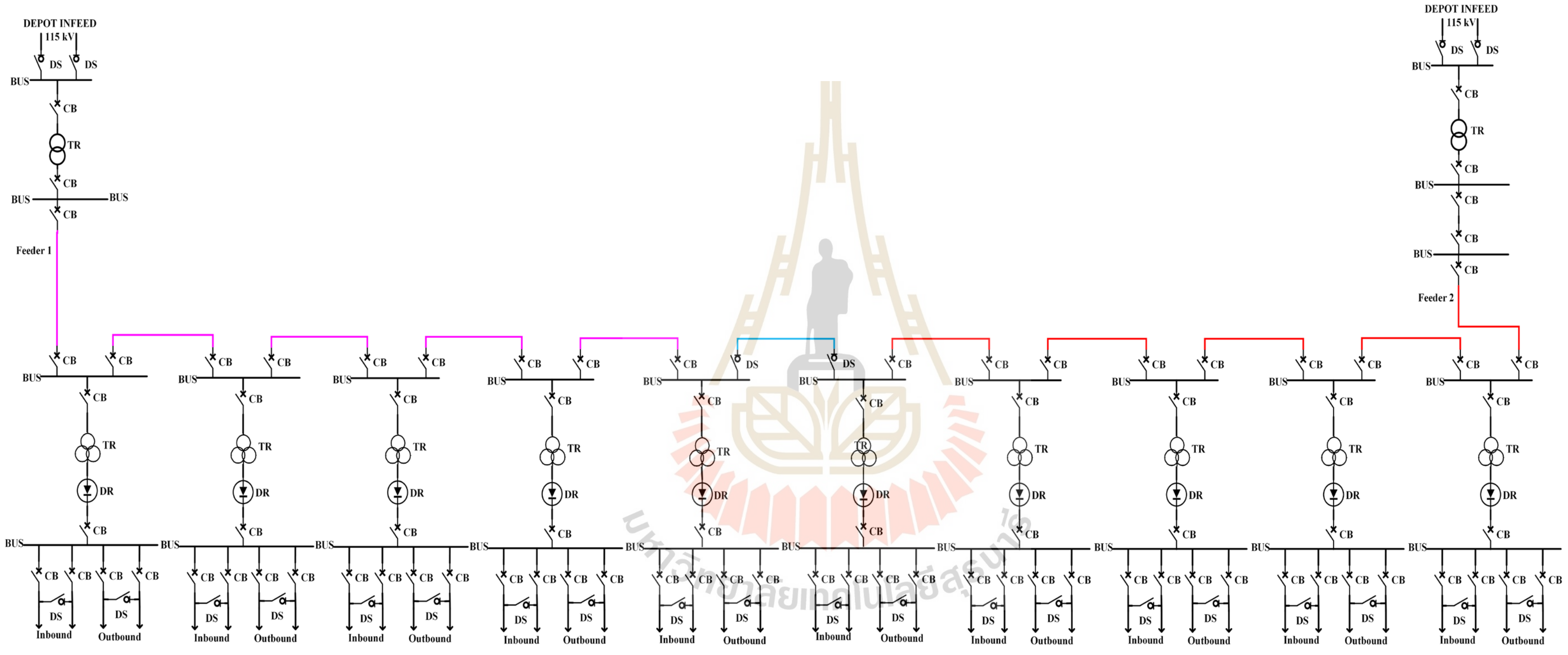

Figure 4. 1 Traction power circuit diagram of MRT Purple Line in radial circuit

Reliability assessment of distributed circuits with radial systems for failure rates uses typical data (after 5 years of service). From the results of the reliability assessment in Table 4.2, Klong Bangphai Substation and Talad Bangyai Substation had a failure rate of less than 10% due to the distance from the distribution substation of only 70 m and 1308 m respectively. The remaining traction substations had a failure rate greater than 10%. For example, the Saima substation increased by 52.23% with a distance of 8731 meters from the nearest distribution substation. The traction substation and the distribution substation have a direct effect on the failure rate of underground cables, thus giving the nearby substations the failure rate. Although a traction substation has two feeders that can be connected in parallel, the failure rate cannot be greatly reduced due to the excessive distance of underground cables.

Failure rates of the radial system connected traction substations were compared with the EN 50126 standard after five years of service. The results showed that the failure rate was at a rare level. The EN 50126, at a rare level, risk acceptance can be tolerated and accepted with adequate control (e.g., maintenance procedures or rules) and the consent of the responsible railroad duty holders, which require ongoing maintenance to maintain their level of risk to be within acceptable limits.

4.2.2 Open-Loop Circuit

Open-loop system of the distribution circuit is the highest reliable system in distribution circuit arrangement because the individual connections of the substation are all interconnected. System protection devices are specialized circuit breakers or disconnect switches used to disconnect the traction substation from another power supply system in the event of a failure. Various faults will be rectified without affecting any load service.

In the form of the original circuit arrangement of the MRT Purple Line, it is already in the form of a closed-loop system of the distribution circuit by dividing the distribution substation. By the closed-loop system of the substation. The 5th traction is connected to the 6th traction substation by the disconnect. The switches are parallel feeders to be used in the event of a failure of one of the distribution substations to provide power to the other side traction substation as shown in Figure 4.2.

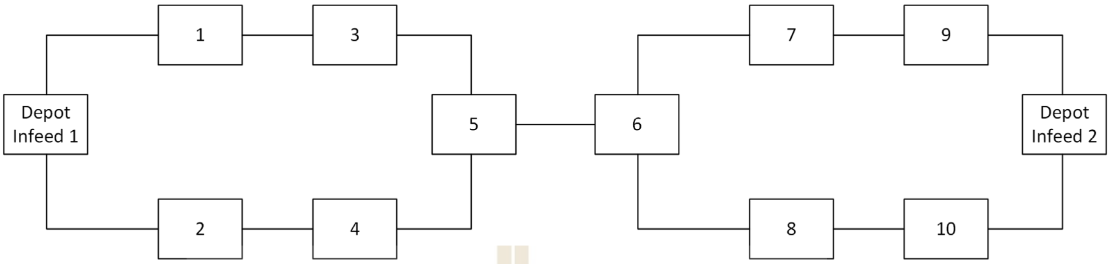

Figure 4. 2 Circuit block diagram in closed-loop system

To reorganize the distribution circuit to improve reliability, the principle of an open-loop system of the distribution circuit is applied by adding a connection point to each loop of the distribution substation on both sides as shown in figure 4.3.

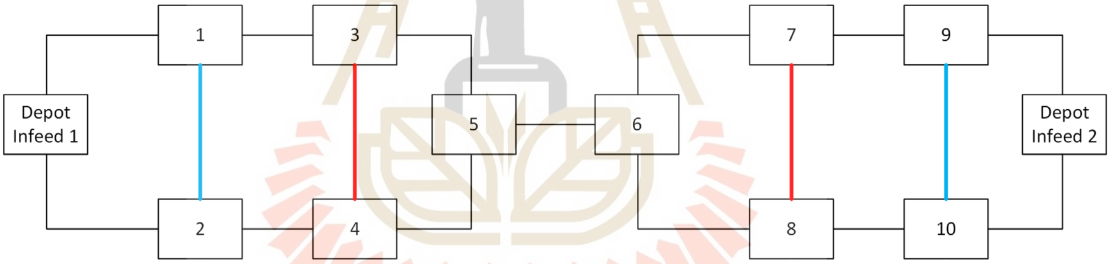

Figure 4. 3 Circuit block diagram in open-loop system

The improved circuit scheme is an open-loop system of the distribution circuit where the length of underground cables used parallel to the traction substation is shortened. The length of the cable directly affects the failure rate, the shorter the length, the lower the failure rate. A single line diagram of the MRT Purple Line in an open-loop system is shown in figure 4.4. This improved circuit uses an increased number of protective equipment and the length of underground cables required is more than the original scheme by the number of increases shown in Table 4.3.

Table 4. 3 The amount of equipment used to connect the distribution circuits

Equipment	Original system	Radial system	Open-loop system
Circuit breaker	24 pcs.	20 pcs.	32 pcs.
Disconnection switches	2 pcs.	2 pcs.	2 pcs.
Underground cable	38,417 m.	21,490 m.	47,001 m.

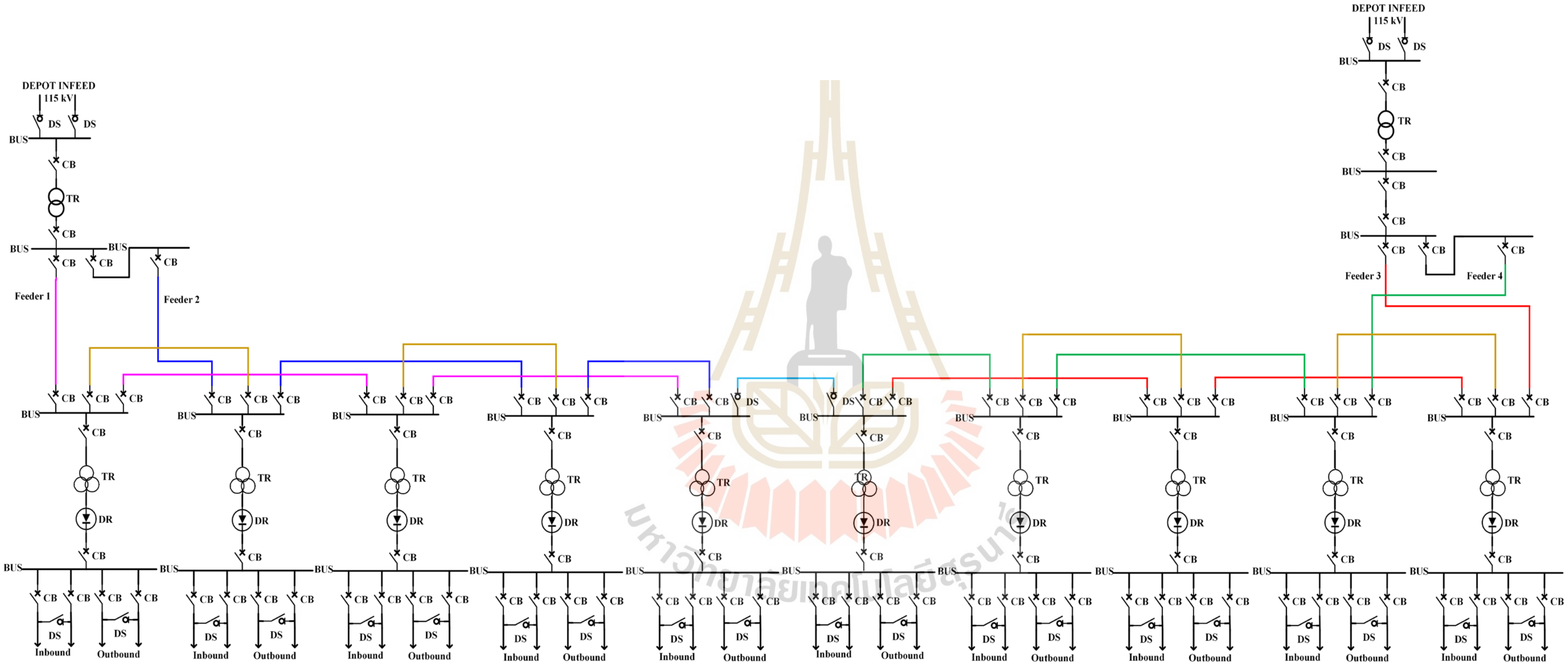

Figure 4. 4 Traction power circuit diagram of MRT Purple Line in open-loop circuit

Table 4. 4 Reliability assessment for open-loop system of traction substation

Traction substation	Failure rate (Time per year) original	Failure rate (Time per year) open-loop circuit	%Change
Klong Bangphai	0.169018	0.143655	-15.01
Talad Bangyai	0.231219	0.160781	-30.46
Bangyai	0.285618	0.235461	-17.56
Bang Rakyai	0.338674	0.263265	-22.27
Saima	0.319514	0.319514	0.00
Yak Nonthaburi	0.333518	0.333518	0.00
Nonthaburi Center	0.353641	0.289110	-18.25
Yak Tiwanon	0.355466	0.292158	-17.81
Wongsawang	0.254292	0.192894	-24.14
Bangson	0.265803	0.215124	-19.07

Reliability assessment of distributed circuits with open-loop systems for failure rates uses typical data (after 5 years of service). The results of the reliability assessment are in Table 4.4. As a result of connecting additional underground cables to form an open loop system, failure rates can be reduced in all traction substations where the additional circuit connections are made. For example, the Talad Bangyai traction substation reduced the failure rate by as much as 30.46%. This method of improving distribution circuits would necessitate an increase in the construction budget proportional to the number of built open-loops systems. The more open-loop systems that are built, the greater the budget requirements. The open-loop system created in Figure 4.4 requires a number of the circuit breaker 8 more pieces and 8,584 meters of underground cable used. Choosing the right open-loop system layout depends on the need to reduce the failure rate to a range that fits the existing budget.

4.3 Headway Effect

The mass transit system will increase the number of service users every year, resulting in the need for metro service to increase service cycles. The increase in service cycles is the change in headways to be more frequent, allowing more trains to operate at the same time. As the number of trains increased during the same period, the traction substation had to handle the increased load, thus directly affecting the LOLE of each substation. The purpose of this chapter is to study how increased load affects the load of a traction substation. To assess the future availability of the traction substation to support this increased load and compare the results with the BAL-502-RF-03 standard. The failure rates and availability rates are based on Table 3.5 and Table 3.6. The current headway of the MRT Purple Line during normal hours is 9 minutes and peak hours are 6 minutes. In this case study, the headway was changed to a normal time of 5 minutes and a rush hour of 3 minutes, and there were 36 trains ready in service. The load of the traction substation after the headway has been shortened is shown in Figure 4.5 to Figure 4.14.

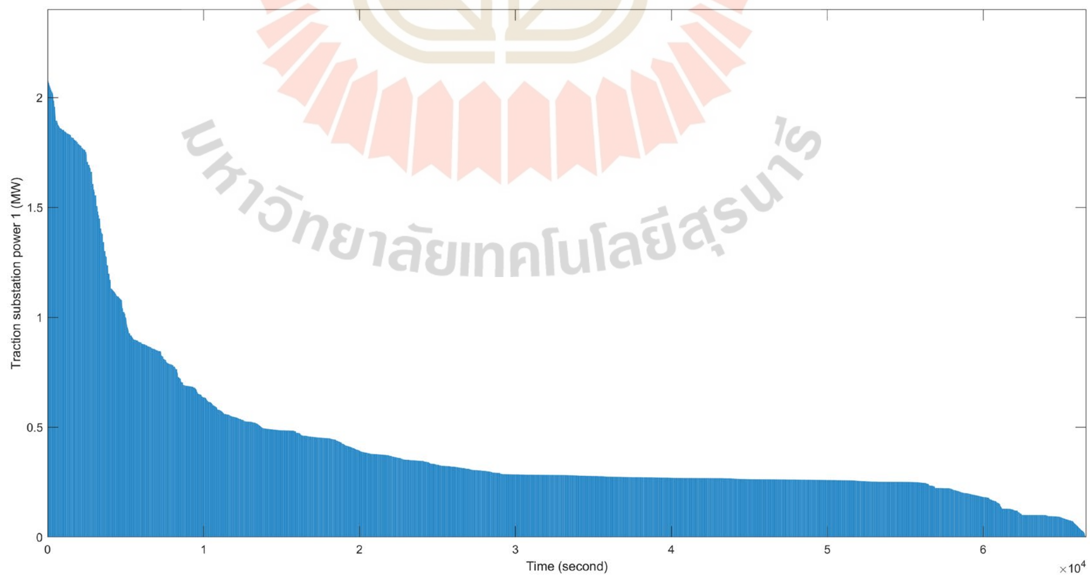

Figure 4. 5 Klong Bangphai traction substation load duration curve with shortened headway

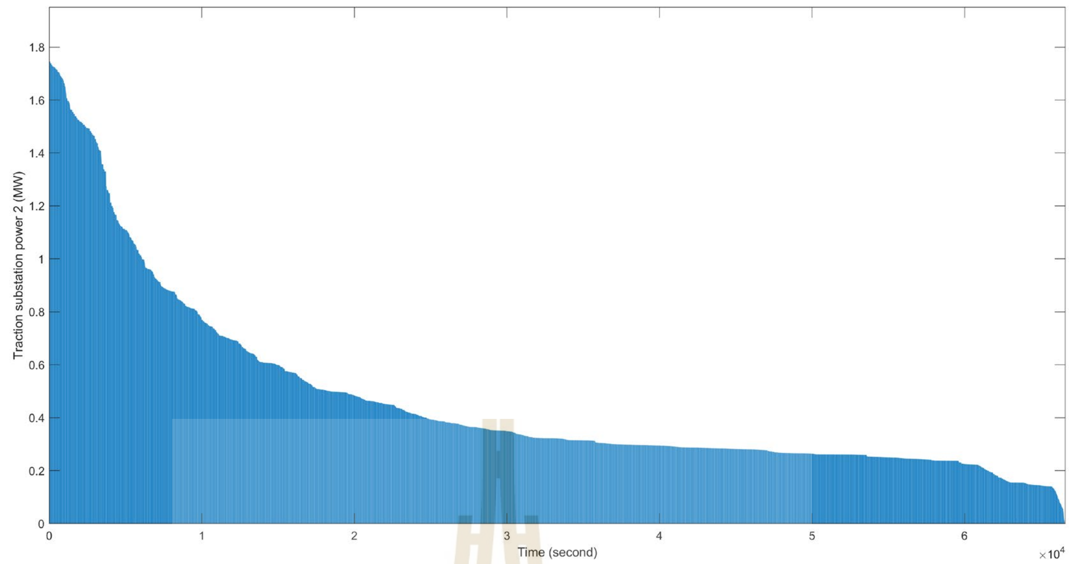

Figure 4. 6 Talad Bangyai traction substation load duration curve with shortened headway

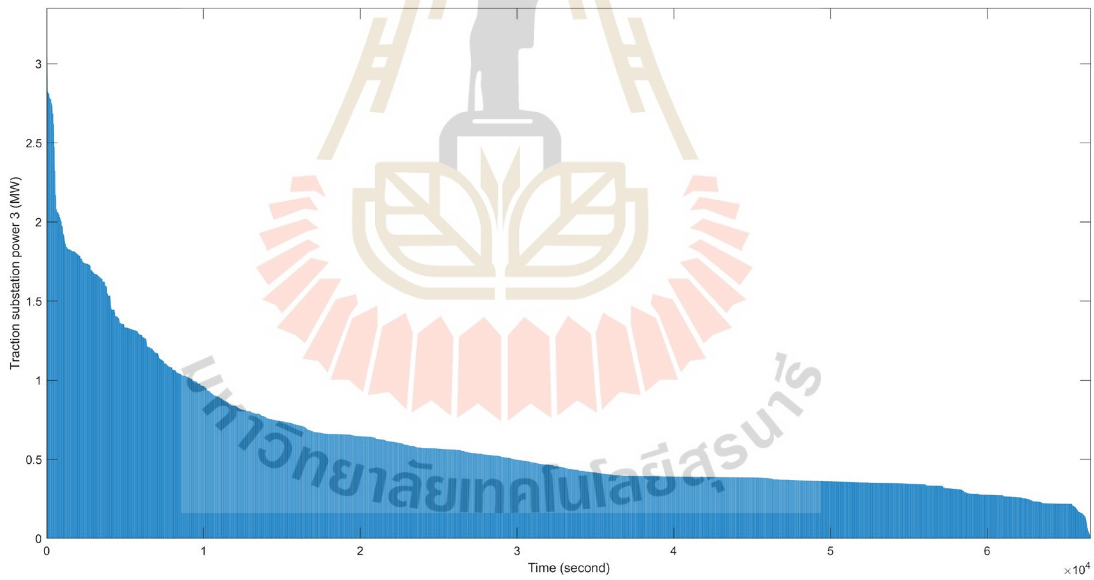

Figure 4. 7 Bangyai traction substation load duration curve with shortened headway

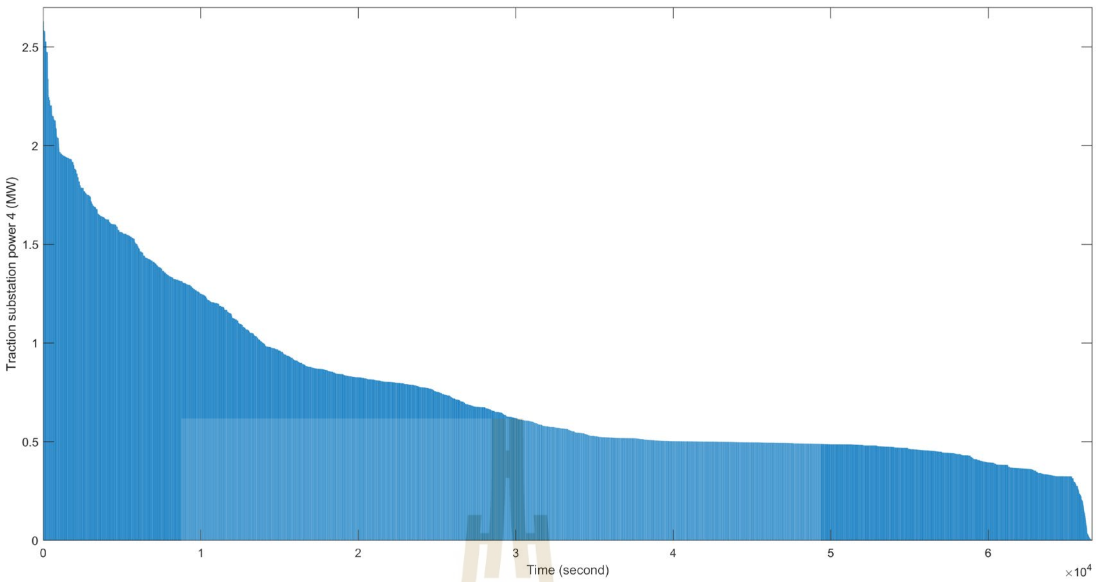

Figure 4. 8 Bang Rakyai traction substation load duration curve with shortened headway

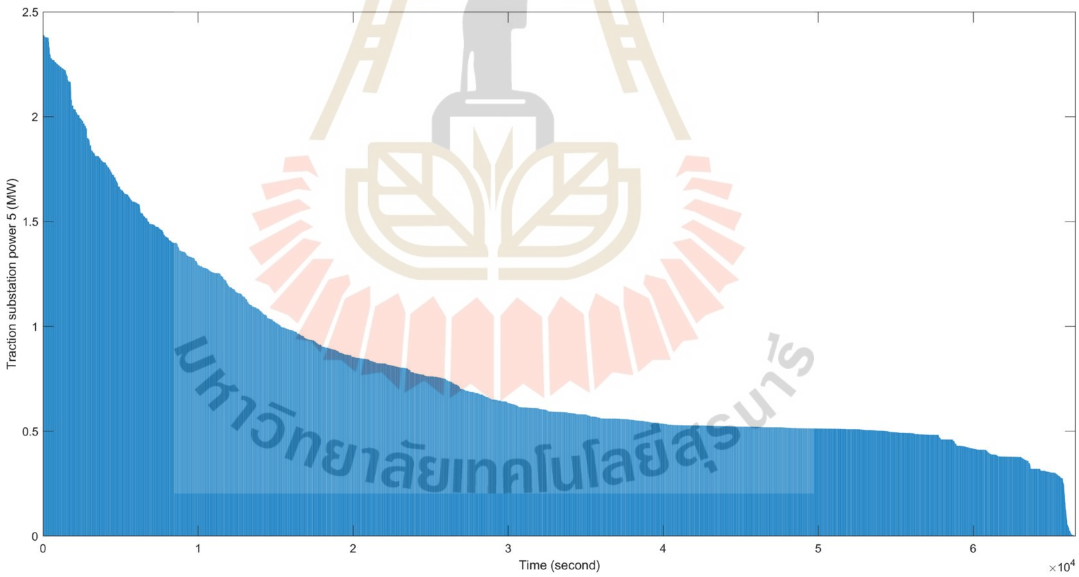

Figure 4. 9 Saima traction substation load duration curve with shortened headway

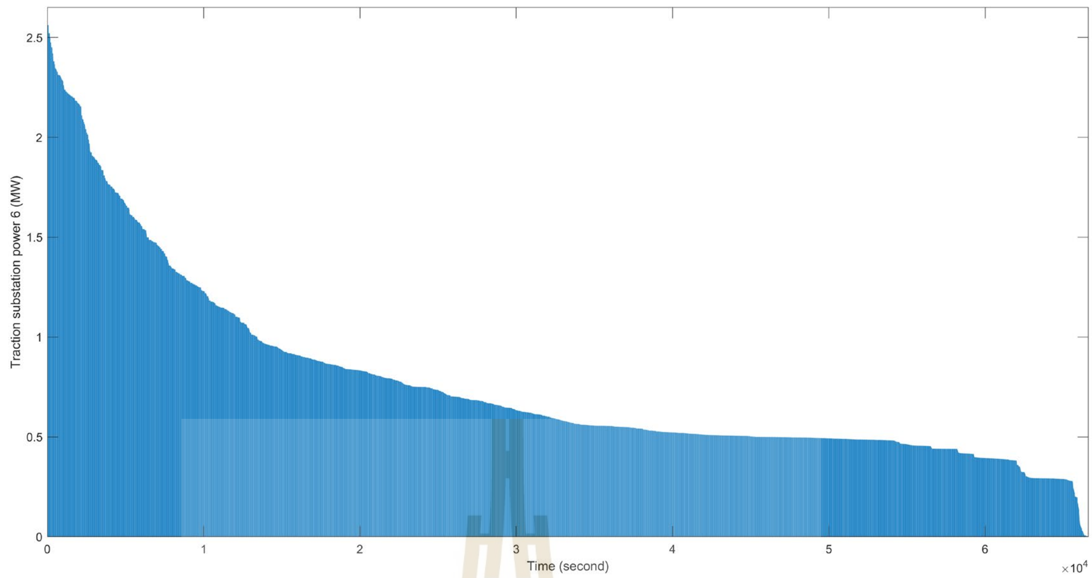

Figure 4. 10 Yak Nonthaburi traction substation load duration curve with shortened headway

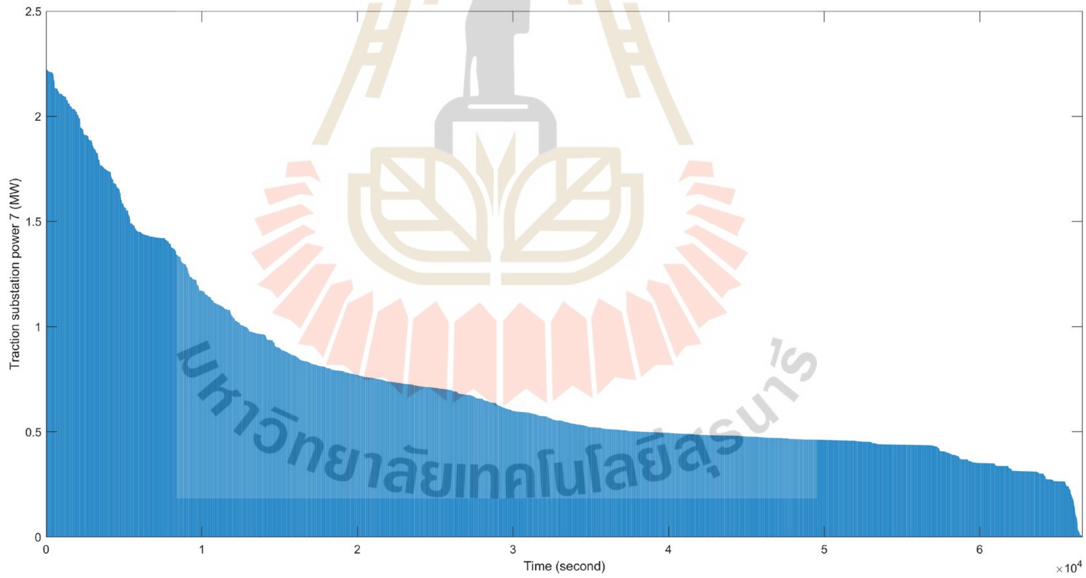

Figure 4. 11 Nonthaburi Center traction substation load duration curve with shortened headway

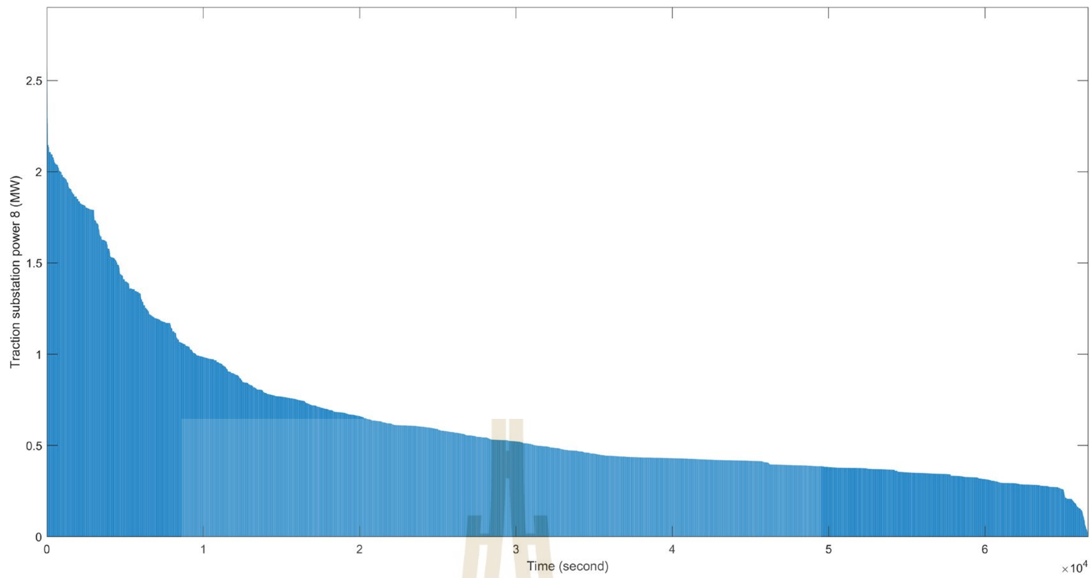

Figure 4. 12 Yak Tiwanon traction substation load duration curve

with shortened headway

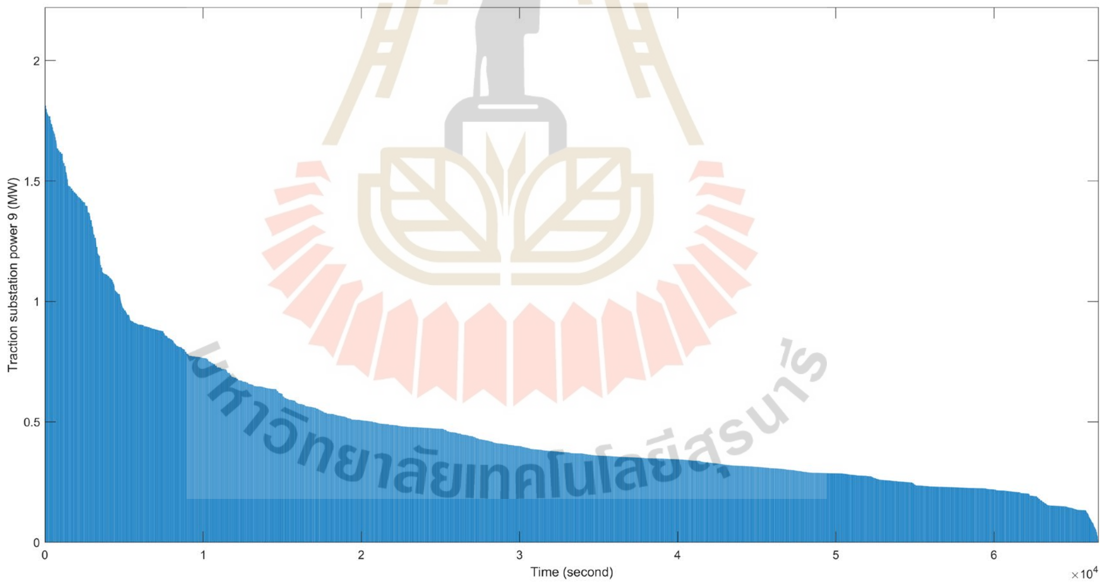

Figure 4. 13 Wongsawang traction substation load duration curve

with shortened headway

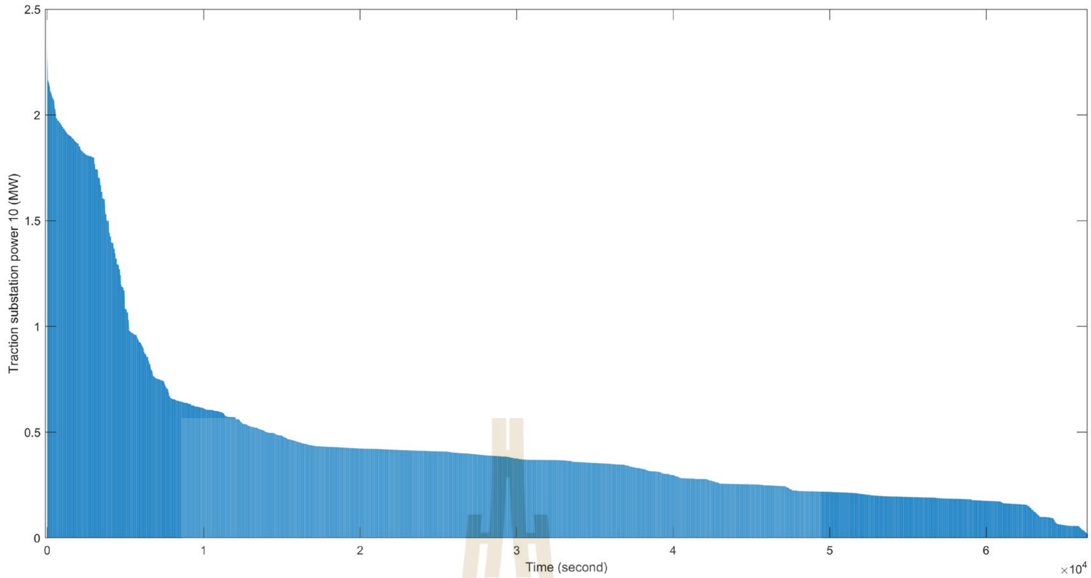

Figure 4. 14 Bangson traction substation load duration curve with shortened headway

Table 4. 5 LOLE of traction substation with shortened headway

Traction substation	LOLE (Day per year) Headway (9 and 6 minute)	LOLE (Day per year) Headway (5 and 3 minute)
Klong Bangphai	0.0166	0.0166
Talad Bangyai	0.0225	0.0225
Bangyai	0.0822	1.9957
Bang Rakyai	0.0366	0.9109
Saima	0.0267	0.0267
Yak Nonthaburi	0.0293	0.7093
Nonthaburi Center	0.0391	0.0391
Yak Tiwanon	0.0346	0.1656
Wongsawang	0.0250	0.0250
Bangson	0.0234	0.0234
Combine all traction substations	0.3×10^{-25}	0.6×10^{-17}

Availability assessments of traction substations serviced with shorter headways are based on the load duration curve in Figures 4.5 to Figure 4.14, together with the reliability and availability index data of the traction substation from section 3.4 to formulate LOLE. The results of the LOLE assessment are shown in Table 4.5. As a result, the LOLE of the 3rd, 4th, 6th, and 8th traction substations increased, while the remaining traction substations remained the same.

From the LOLE results, it can be indicated that the traction substation with increased LOLE values for a period of time throughout the day in service is unable to support the power load, for example, the 3^{rd} station has the highest LOLE of 1.9957 days per year, and because the power load exceeds 2.5 MW for 932 seconds, the traction substation is overloaded. Although shortening the headway, the LOLE results for the entire MRT Purple Line system of 0.0000 days per year anyway. Overloading at the traction substation has a detrimental effect on the entire system, requiring nearby traction substations to carry the additional load to supply the excess power. This results in a lot of power loss in underground cables. When taking the results from Table 4.5 Compare with the standard BAL-502-RF-03 The 3^{rd}, 4^{th}, 6^{th}, and 8^{th} traction substations exceed the set standards by 0.1 days per year.

According to the BAL-502-RF-03 evaluation of traction substations when the headway was shortened, four substations were non-standard. To plan the installation or modification of the electrical power supply, all four substations that do not comply with the standards must be considered. Future expansion of the traction substation electrical capacity.

4.4 Chapter Summary

A case study for improving the distribution circuit layout of a traction substation revealed that choosing a radial system can significantly reduce the construction budget and can bring the failure rate passed standard the EN 50126 but requires strict preventive maintenance conditions. Alternatively, opting for an open-loop traction substation distribution circuit arrangement would greatly reduce the failure rate but at the cost of an increased construction budget.

A case study of the future availability of traction substations to accommodate more passengers requires increasing the frequency of service cycles by shortening the headway. This results in an increase in the electrical power load of the traction substation from the assessment LOLE found that four stations failed to pass the benchmark. BAL-502-RF-03. Therefore, it can be planned in the future as to how to improve the station that does not meet the standard availability. May be used to increase the size of the transformer, add more parallel transformers, or choose to use batteries to supply the electric power at certain times.

CHAPTER 5
CONCLUSION AND RECOMMENDATION

5.1 Chapter Overview

This chapter provides an overview of this research, the importance of each topic in this thesis, and future work that can be applied further.

5.2 Conclusion

This thesis presents the MRT Purple Line reliability assessment using the strengths of the RBD method for calculating the reliability that can be specified as individual blocks of equipment or a combination of all devices connected in the system to achieve reliability. Once basic system reliability indices such as failure rate, MTTR, and MTTF can be calculated, such indices can be used to assess availability using the LOLE index in estimating the substation potential to handle the electrical power load. In addition to providing services, it is necessary to have proper substation preventive maintenance planning in order to set up a budget plan and maintenance intervals at each point. To extend the service life and reduce the failure rate of substation equipment.

Chapter 1 explains the importance of traction substation reliability assessments in assessing reliability, availability, and maintenance (RAM) for planning from project inception to completion planning for future improvements and maintenance. Therefore, the objective, limitation, and scope of this research are obtained.

Chapter 2 describes the reliability index assessment theory utilized in planning the MRT Purple Line power distribution system. It can be concluded that the method used to evaluate basic indexes such as failure rates, MTTF, MTTR, and availability is a base area reliability index used to evaluate reliability in a variety of ways.

The RBD method was selected for calculating the reliability index in this study due to its ability to calculate individual blocks of each device or combine blocks of each connected device into a single block when evaluating the substation reliability.

After obtaining the underlying reliability index, it can be utilized to evaluate the availability in the form of LOLE. Determine if an existing traction substation can supply electrical power loads.

The failure rate is an index that rises with time, and if no maintenance is performed, the failure rate will exceed the EN 50126 standard. Therefore, preventive maintenance is used to maintain failure rates. Using literature reviews of equipment failure rate data, this study proposes a method for calculating maintenance failure rates.

Chapter 3 presents the MRT Purple Line reliability assessment process by starting with the assessment of reliability indices such as Failure Rate, MTTF, MTTR, and Availability. The failure rate calculation by time-varying failure rate modeling yielded the failure rate of each substation and was compared with the EN 50126 standard. The level of risk tolerance of the traction substations is at a Tolerable level during the first 7 years and after that, it enters an Undesirable level. Each level of risk has different countermeasures depending on the provider agreement.

Once a basic index of reliability has been obtained, it can be used to assess the availability and failure rate with preventive maintenance during each period. To assess availability, an index in the form of LOLE is used to indicate the availability to support the power load of each station. LOLE is an index used to indicate the availability of electrical power at each station. The BAL-502-RF-03 standard specifies that if LOLE is higher than 0.1 days per year it fails, the benchmark should be revised to prevent damage to the overall system. Every traction substation of the case study passed the standard BAL-502-RF-03.

The case study preventive maintenance failure rate calculations showed that the higher the frequencies of maintenance, the longer the failure rate was maintained within the benchmark. The failure rate of the case study in servicing every year produces the best results as it increases the failure rate less than other maintenance cycles and also utilizes a reasonable maintenance budget. Because if the maintenance is more than 1 year, the budget will increase a lot, but in exchange for the failure rate that is not much different.

Chapter 4 presents the reliability improvements of the MRT Purple Line, divided into 2 case studies. The first case study was the improvement of the traction substation distribution circuit, with the first model being a radial system. Distribution circuits in radial systems use a lower budget compared to other models and have a failure rate that meets the EN 50126 standard but must be maintained on an ongoing basis to maintain the failure rate within the range of standard. The second distribution circuit is the open-loop system has a very high budget due to the increased amount of equipment and length of underground cables required. An open-loop system is a system that results in greatly reduced failure rates.

Case study 2 presents an assessment of the availability of traction substations to the number of service providers that will increase in the future, requiring increased service cycles. The shortening of the headway causes the traction substation to bear an additional load of electrical power, directly affecting the LOLE index. Some traction substations are unable to supply the total power load of the station, increasing the LOLE index. To assess the availability of this LOLE, it is possible to plan for a traction substation to accommodate future increases in subway passengers. Future plans to accommodate passengers include a variety of plans, such as installing parallel transformers in substations to increase their capacity to accommodate increased power loads or choosing to install batteries to supply power at certain times of the service day.

5.3 Future Work

This thesis presents the reliability indices of the distribution system which can be applied to other systems that are not power distribution systems. It can be used from the start of construction planning in a project to plans for future maintenance.

The evaluation methods in this thesis can support their application in project planning.

1. Determination of the substation location with optimal traction by finding ways to arrange the interconnection of distribution circuits or determining the distance of substations for optimum improvement of the failure rate.

2. Selection of substation sizes suitable for power loads adapted to changing headway frequencies to support the increase in the number of trips in service.

3. Determining the appropriate time to install energy storage to support the increased load as an alternative to having to add transformers in parallel to the substation.

REFFERENCE

REFFERENCE

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APPENDIX A

MRT PURPLE LINE TRACTION SUBSTATION LOAD FLOW

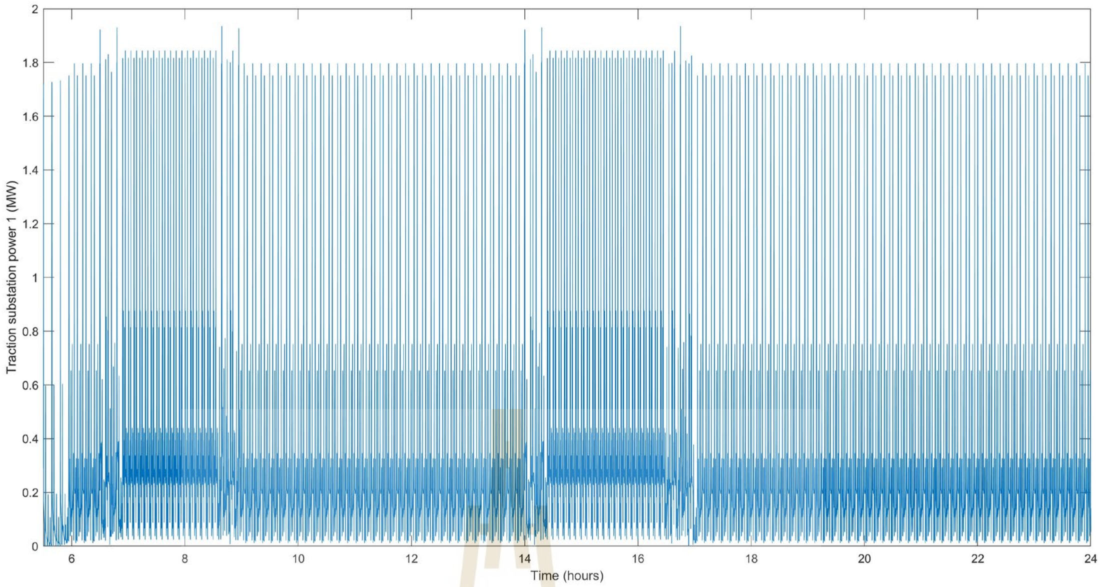

Figure A. 1 Klong Bangphai traction substation load curve

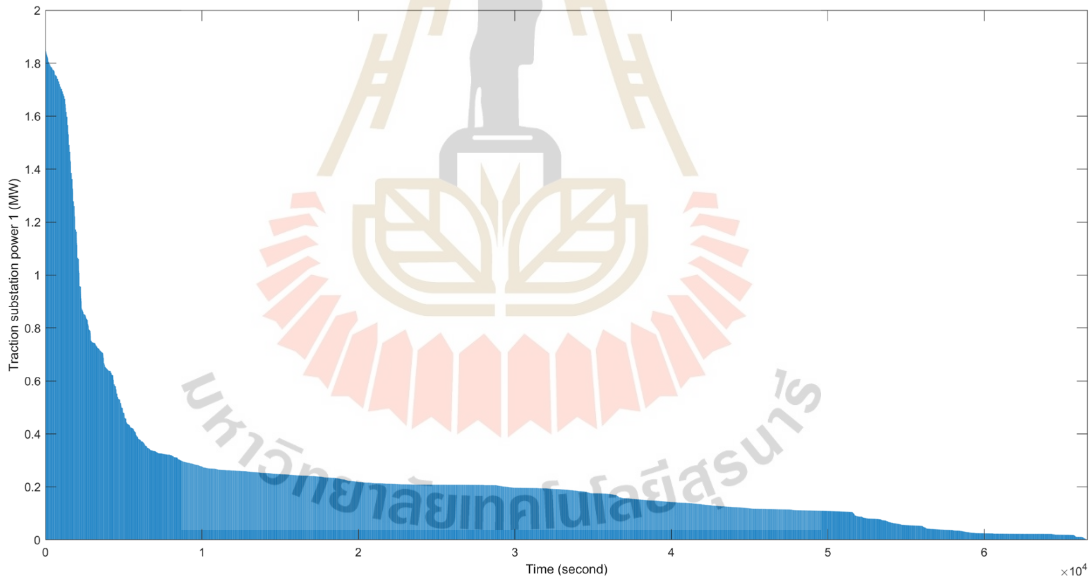

Figure A. 2 Klong Bangphai traction substation load duration curve

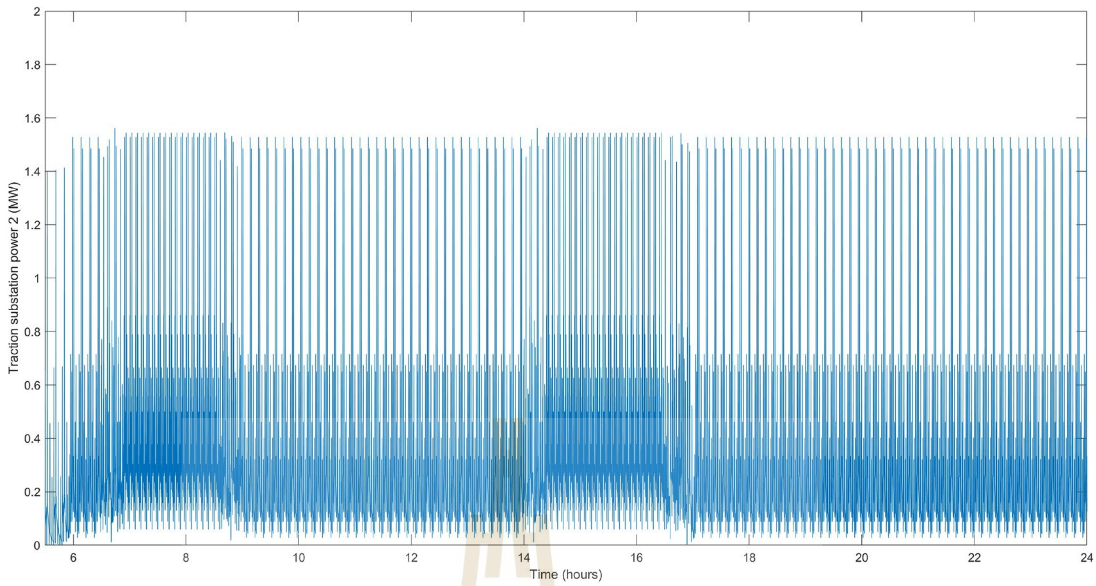

Figure A. 3 Talad Bangyai traction substation load curve

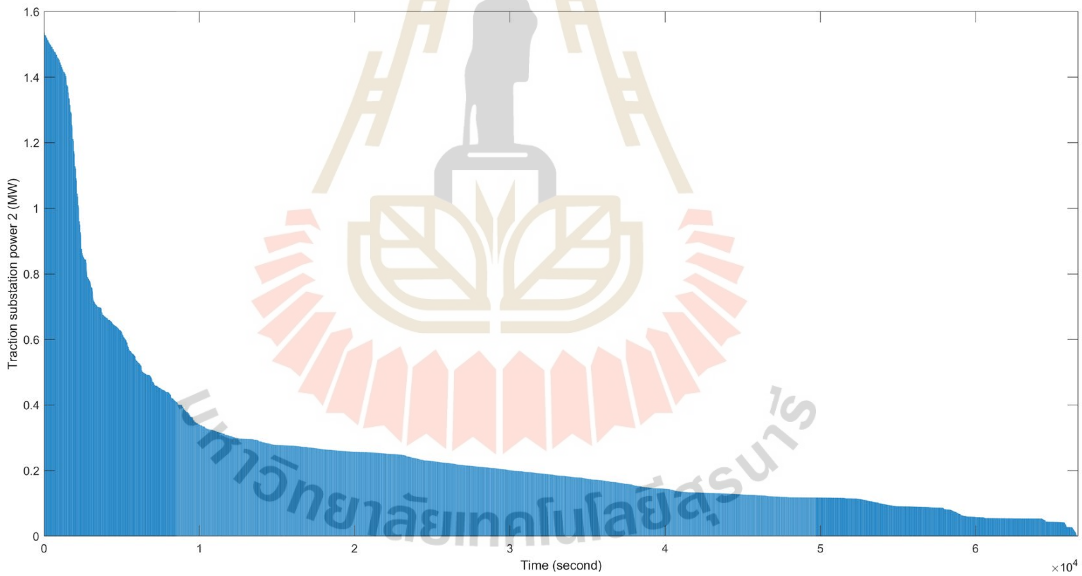

Figure A. 4 Talad Bangyai traction substation load duration curve

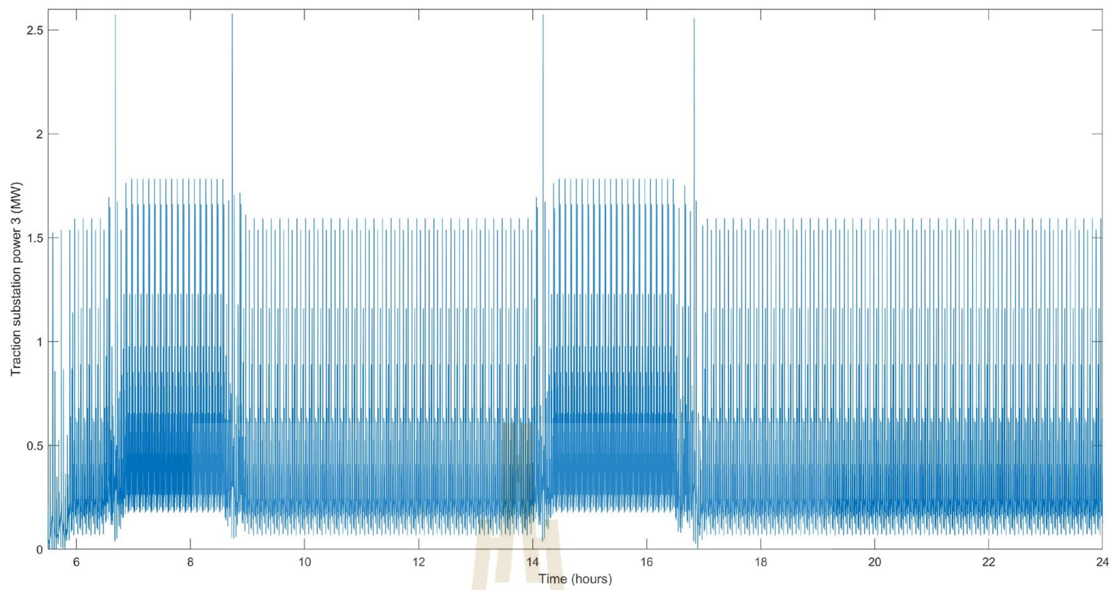

Figure A. 5 Bangyai traction substation load curve

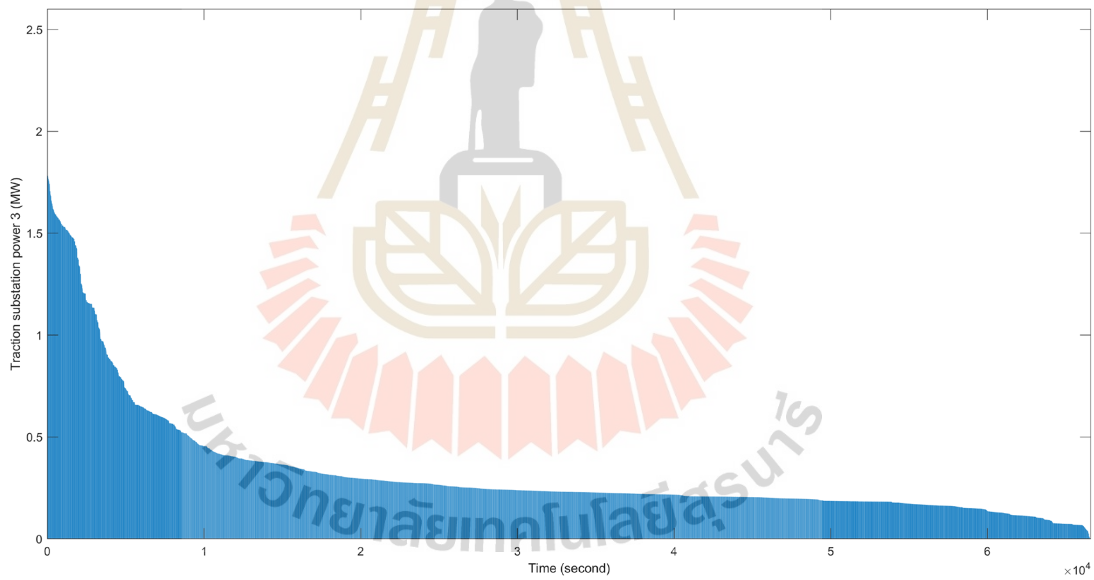

Figure A. 6 Bangyai traction substation load duration curve

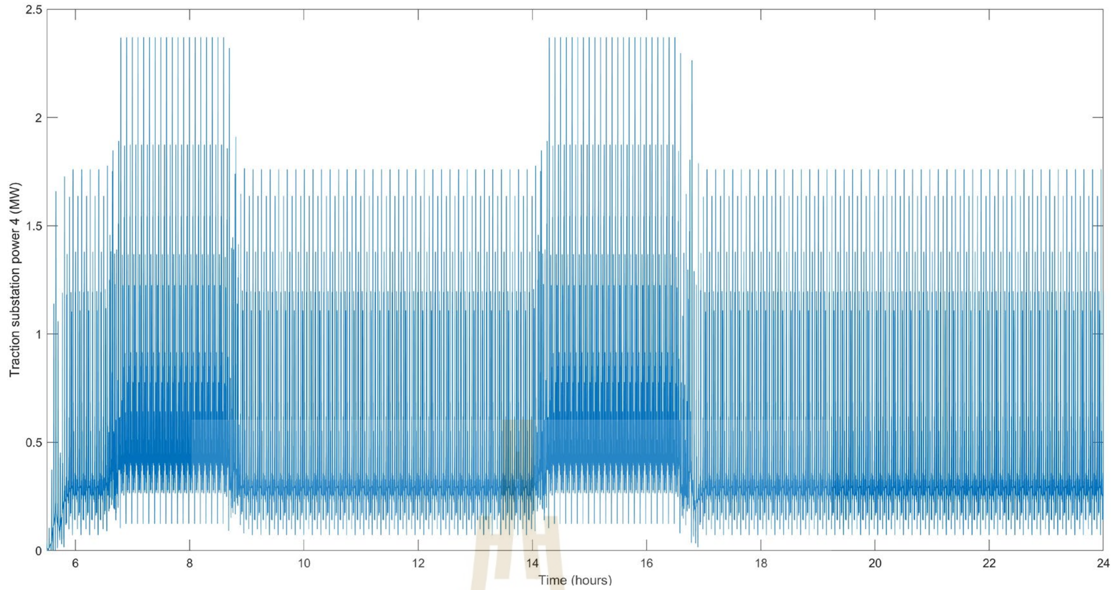

Figure A. 7 Bang Rakyai traction substation load curve

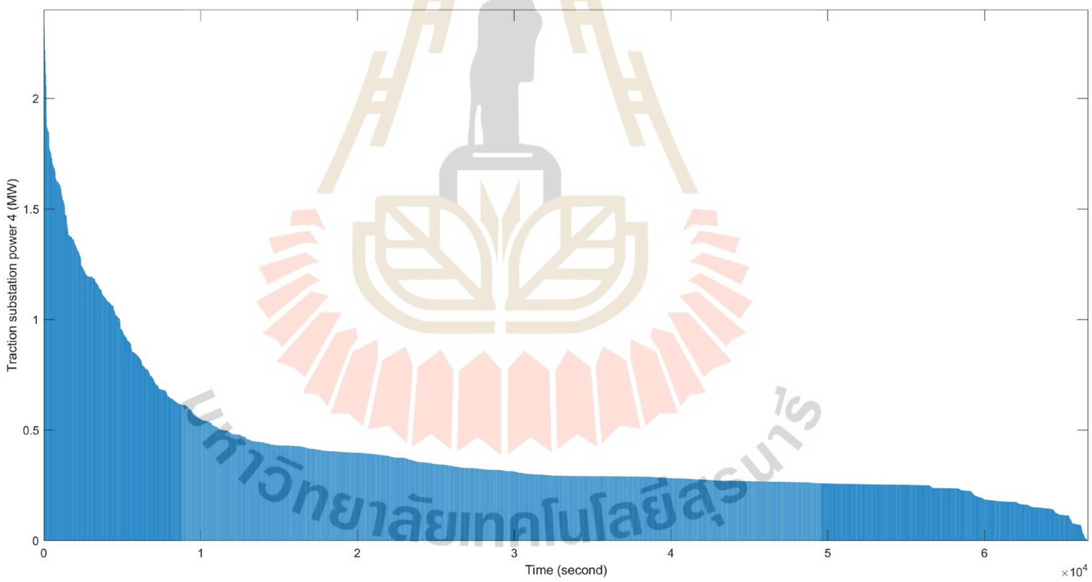

Figure A. 8 Bang Rakyai traction substation load duration curve

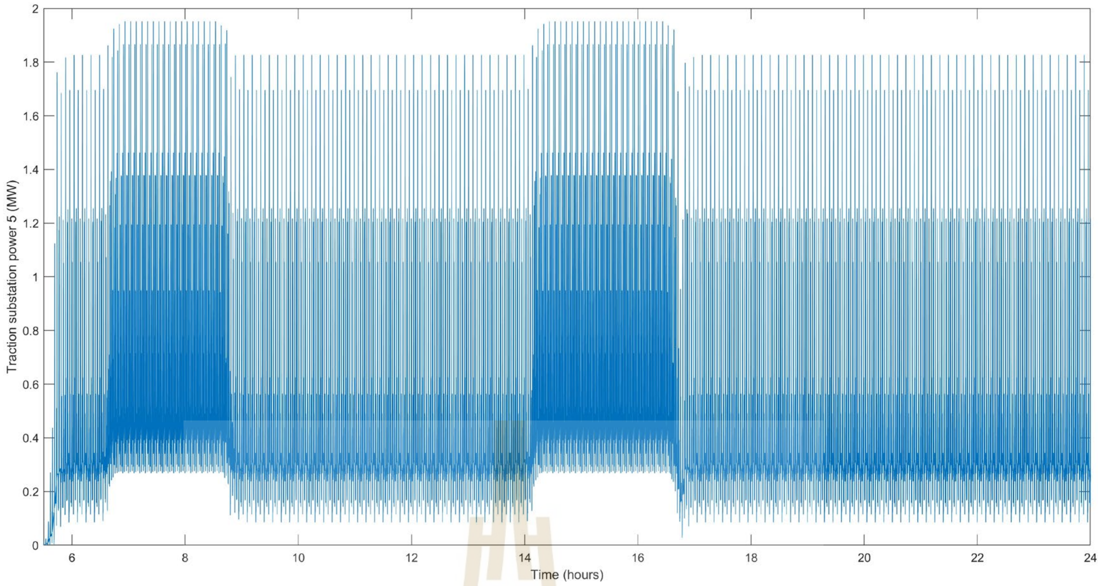

Figure A. 9 Saima traction substation load curve

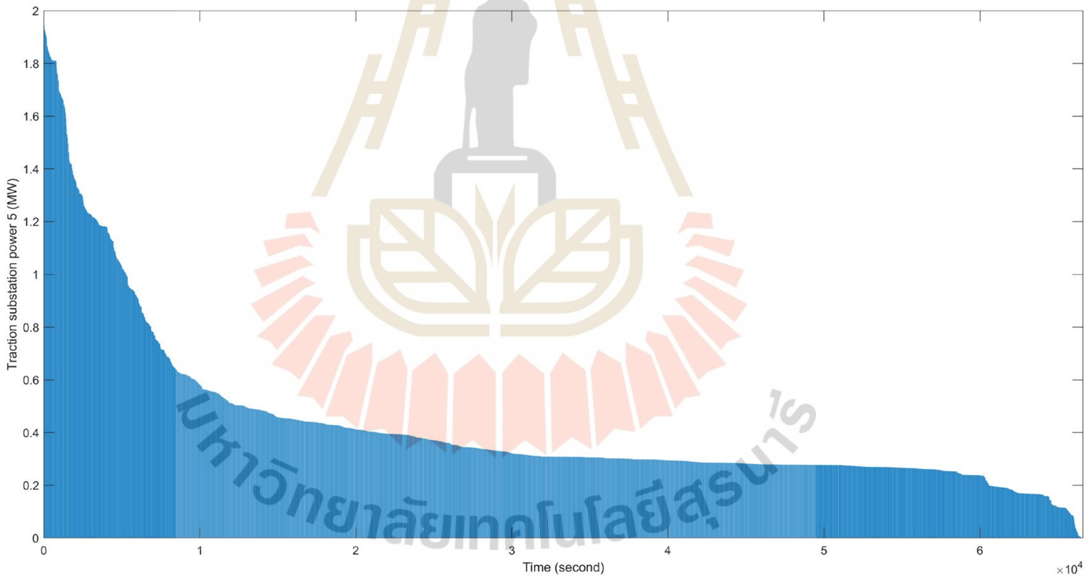

Figure A. 10 Saima traction substation load duration curve

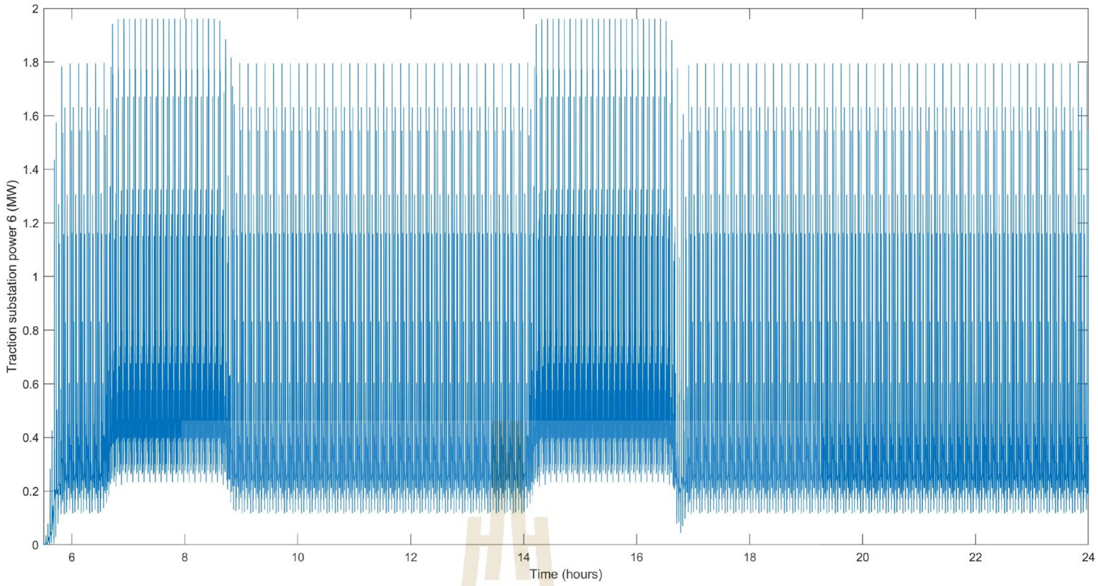

Figure A. 11 Yak Nonthaburi traction substation load curve

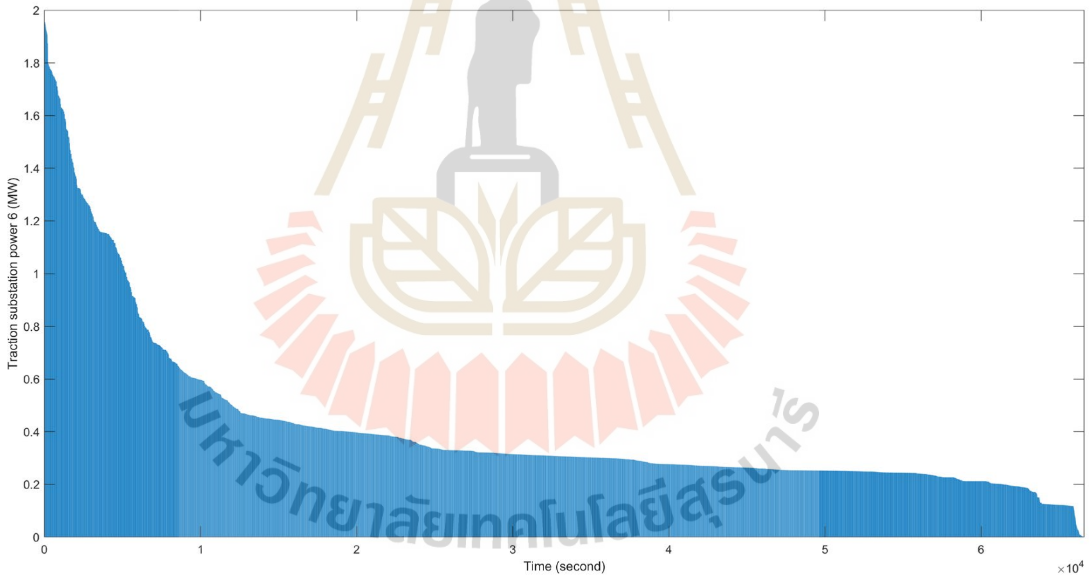

Figure A. 12 Yak Nonthaburi traction substation load duration curve

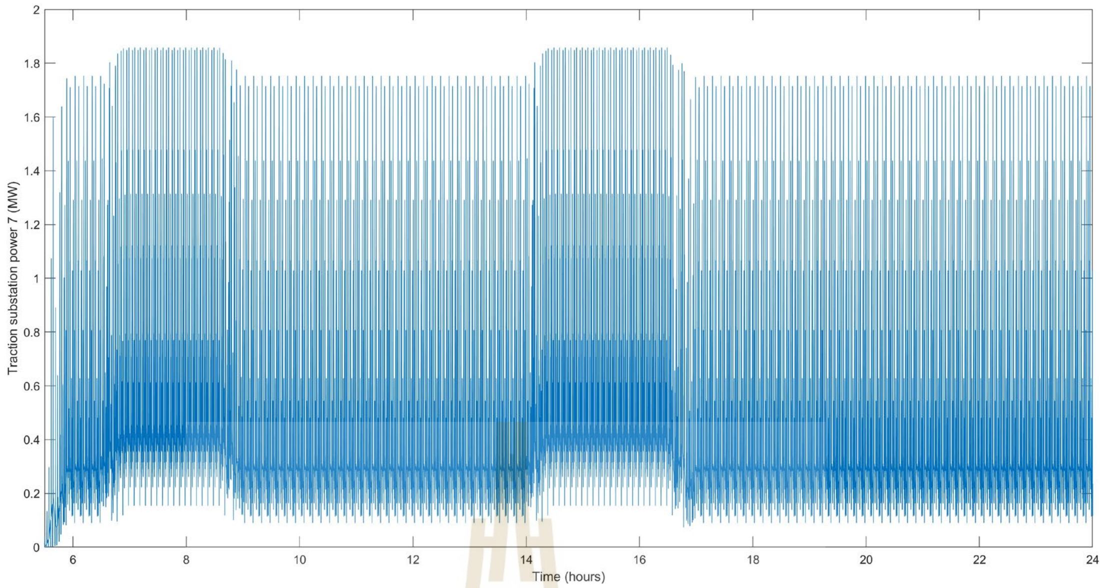

Figure A. 13 Nonthaburi Center traction substation load curve

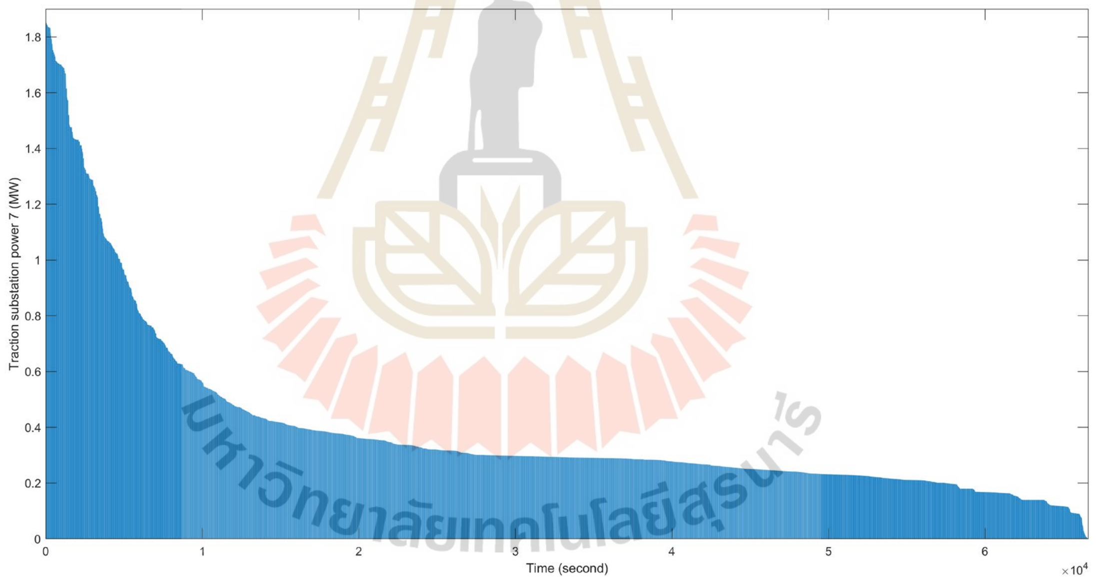

Figure A. 14 Nonthaburi Center traction substation load duration curve

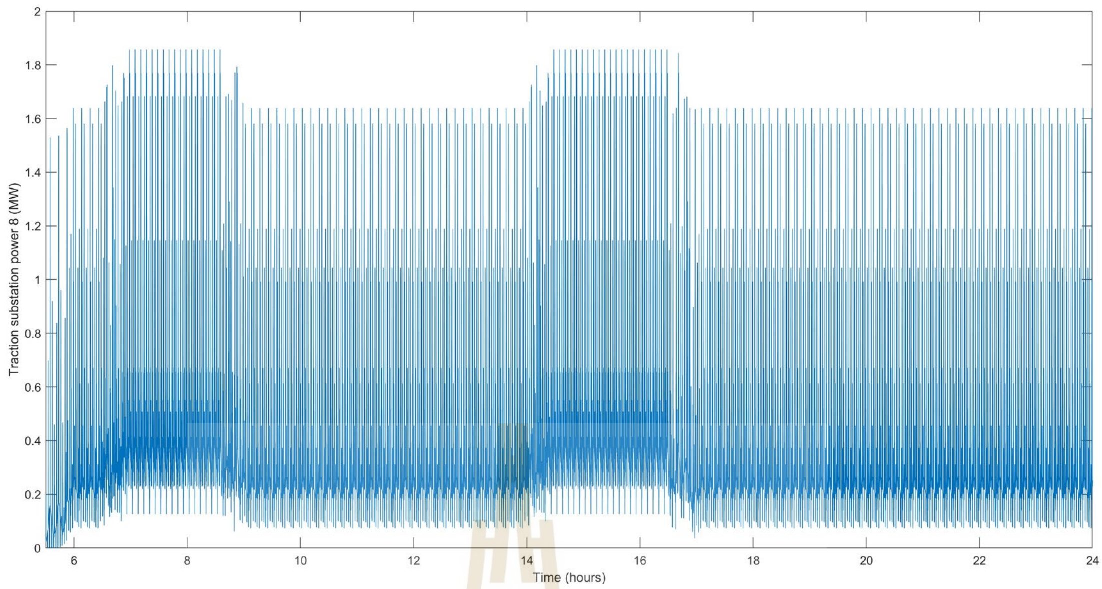

Figure A. 15 Yak Tiwanon traction substation load curve

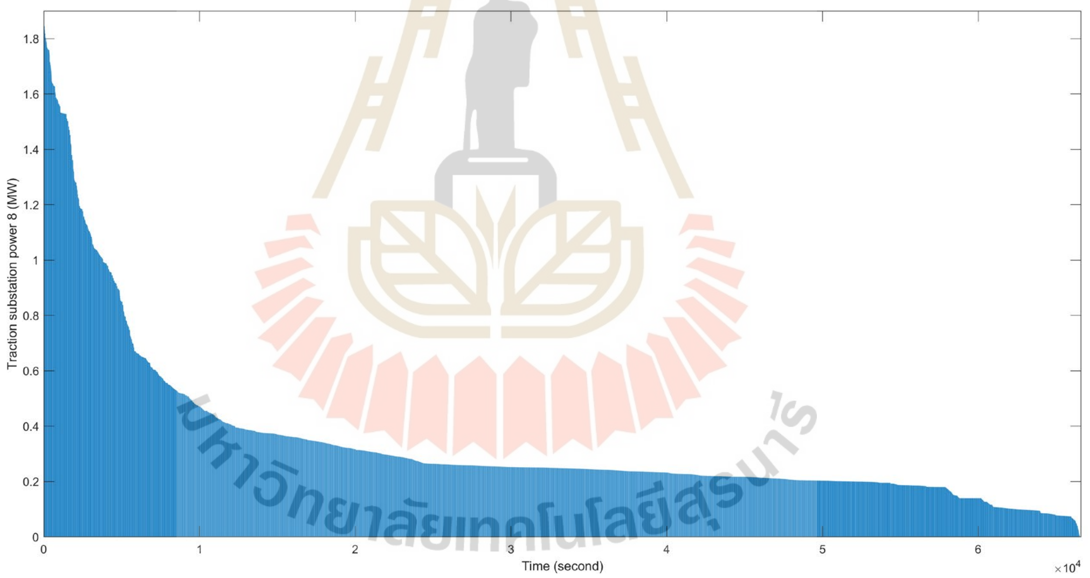

Figure A. 16 Yak Tiwanon traction substation load duration curve

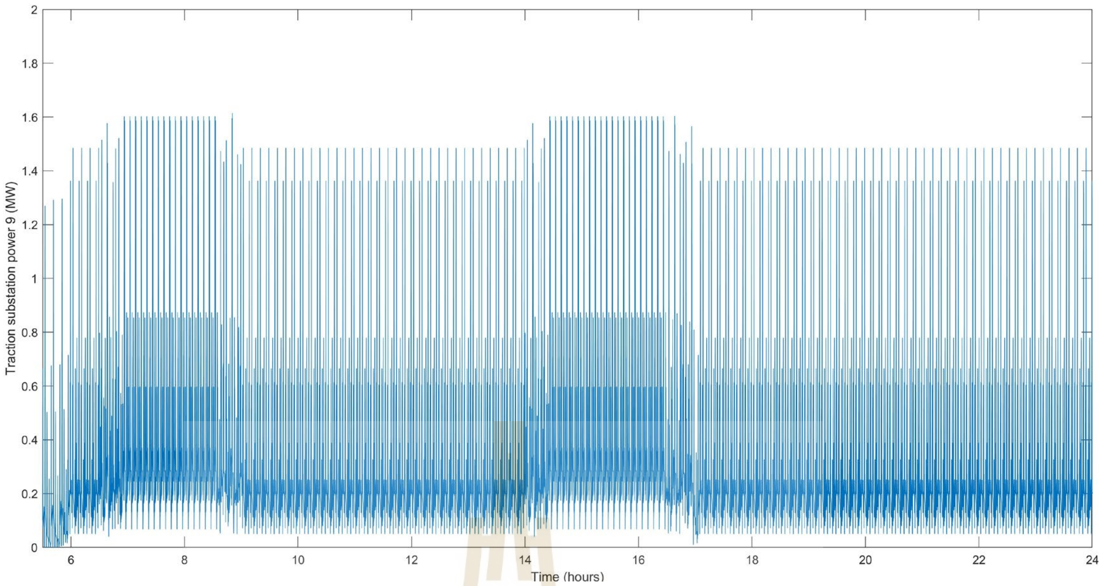

Figure A. 17 Wongsawang traction substation load curve

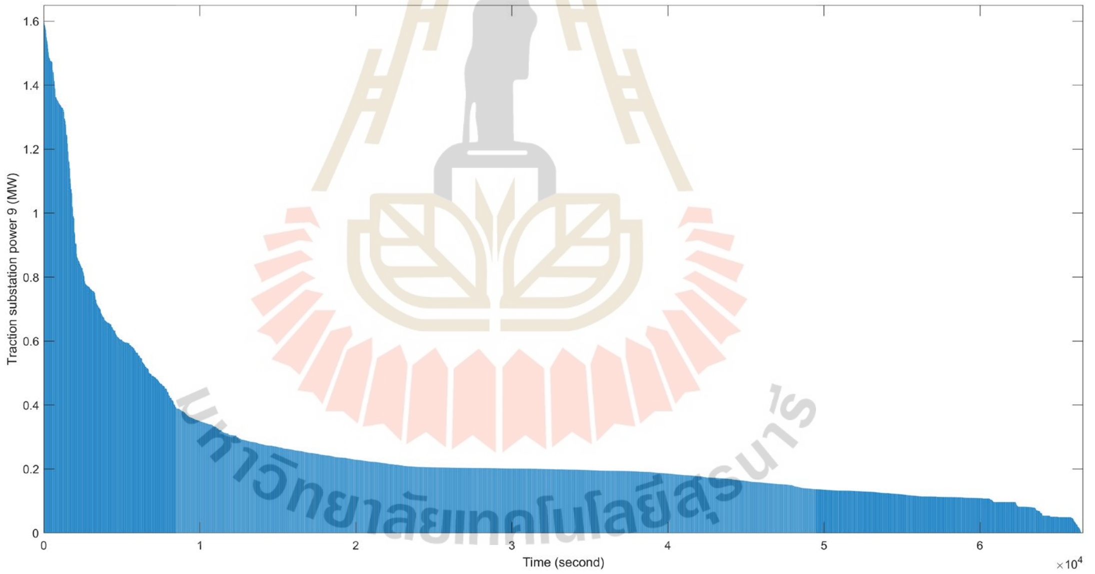

Figure A. 18 Wongsawang traction substation load duration curve

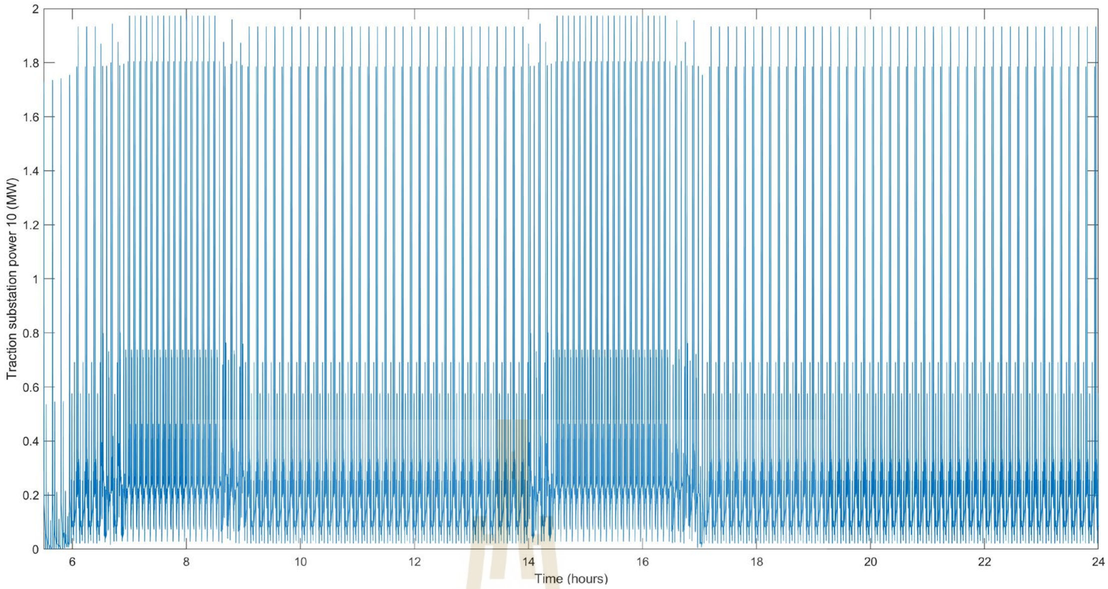

Figure A. 19 Bangson traction substation load curve

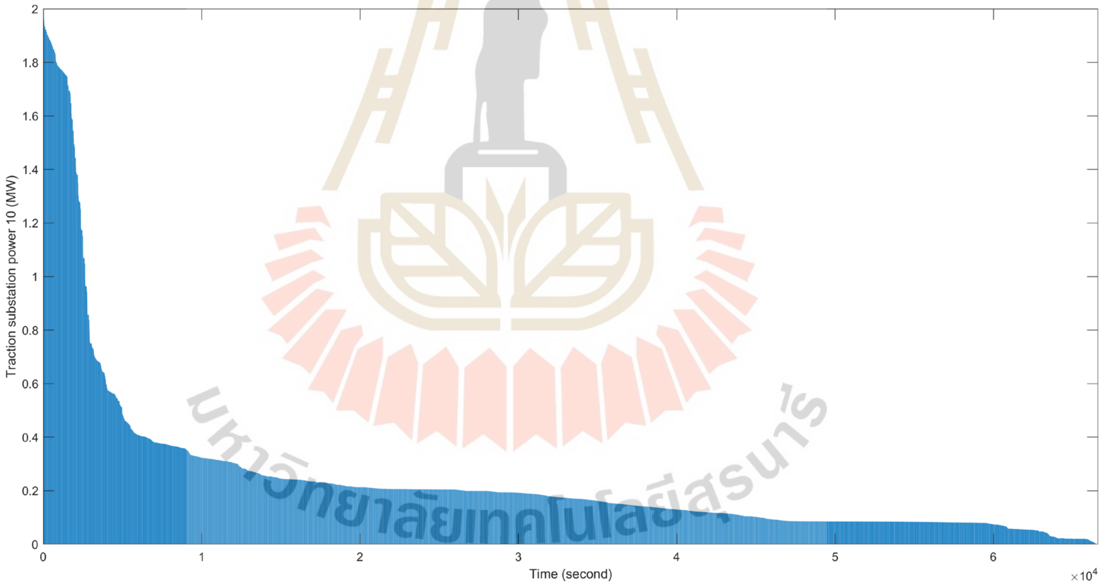

Figure A. 20 Bangson traction substation load duration curve

APPENDIX B

PREVENTIVE MAINTENANCE FAILURE RATE OF MRT PURPLE LINE TRACTION SUBSTATION

Table B. 1 Preventive maintenance failure rate of Klong Bangphai traction substation

t	No PM	PM every 1 year	PM every 2 years	PM every 3 years	PM every 5 years	PM every 10 years
0	0.028072	0.028072	0.028072	0.028072	0.028072	0.028072
1	0.044531	0.044531	0.044531	0.044531	0.044531	0.044531
2	0.065465	0.025387	0.065465	0.065465	0.065465	0.065465
3	0.092090	0.033171	0.033171	0.092090	0.092090	0.092090
4	0.125952	0.043071	0.067033	0.043071	0.125952	0.125952
5	0.169018	0.055662	0.055662	0.086137	0.169018	0.169018
6	0.223792	0.071675	0.110435	0.140911	0.071675	0.223792
7	0.293454	0.092041	0.092041	0.092041	0.141337	0.293454
8	0.382052	0.117944	0.180640	0.180640	0.229936	0.382052
9	0.494734	0.150887	0.150887	0.293322	0.342618	0.494734
10	0.638047	0.192786	0.294200	0.192786	0.485930	0.638047
11	0.820316	0.246074	0.246074	0.375055	0.246074	0.246074
12	1.052131	0.313847	0.477889	0.606870	0.477889	0.477889
13	1.346960	0.400042	0.400042	0.400042	0.772718	0.772718
14	1.721933	0.509668	0.775015	0.775015	1.147690	1.147690
15	2.198834	0.649094	0.649094	1.251916	1.624591	1.624591
16	2.805370	0.826420	1.255631	0.826420	0.826420	2.231128
17	3.576781	1.051948	1.051948	1.597831	1.597831	3.002539
18	4.557884	1.338781	2.033051	2.578934	2.578934	3.983642
19	5.805680	1.703584	1.703584	1.703584	3.826730	5.231438
20	7.392663	2.167551	3.290567	3.290567	5.413713	6.818421

Table B. 2 Preventive maintenance failure rate of Talad Bangyai traction substation

t	No PM	PM every 1 year	PM every 2 years	PM every 3 years	PM every 5 years	PM every 10 years
0	0.029907	0.029907	0.029907	0.029907	0.029907	0.029907
1	0.050242	0.050242	0.050242	0.050242	0.050242	0.050242
2	0.077635	0.032418	0.077635	0.077635	0.077635	0.077635
3	0.114538	0.044666	0.044666	0.114538	0.114538	0.114538
4	0.164250	0.061166	0.094379	0.061166	0.164250	0.164250
5	0.231219	0.083394	0.083394	0.128135	0.231219	0.231219
6	0.321434	0.113337	0.173609	0.218350	0.113337	0.321434
7	0.442965	0.153674	0.153674	0.153674	0.234868	0.442965
8	0.606683	0.208014	0.317392	0.317392	0.398586	0.606683
9	0.827230	0.281216	0.281216	0.537939	0.619133	0.827230
10	1.124335	0.112433	0.578320	0.379828	0.916237	1.124335
11	1.524571	0.512670	0.512670	0.780064	0.512670	0.512670
12	2.063739	0.206374	1.051838	1.319232	1.051838	1.051838
13	2.790064	0.932699	0.932699	0.932699	1.778163	1.778163
14	3.768514	1.257456	1.911149	1.911149	2.756613	2.756613
15	5.086607	1.694944	1.694944	3.229242	4.074706	4.074706
16	6.862241	2.284294	3.470578	2.284294	2.284294	5.850339
17	9.254238	3.078221	3.078221	4.676291	4.676291	8.242337
18	12.476553	4.147739	6.300536	7.898607	7.898607	11.464652
19	16.817409	5.588511	5.588511	5.588511	12.239462	15.805508
20	22.665077	7.529409	11.436179	11.436179	18.087130	21.653175

Table B. 3 Preventive maintenance failure rate of Bangyai traction substation

t	No PM	PM every 1 year	PM every 2 years	PM every 3 years	PM every 5 years	PM every 10 years
0	0.030469	0.030469	0.030469	0.030469	0.030469	0.030469
1	0.054041	0.054041	0.054041	0.054041	0.054041	0.054041
2	0.086902	0.038265	0.086902	0.086902	0.086902	0.086902
3	0.132714	0.054502	0.054502	0.132714	0.132714	0.132714
4	0.196581	0.077138	0.118369	0.077138	0.196581	0.196581
5	0.285618	0.108695	0.108695	0.166176	0.285618	0.285618
6	0.409746	0.152689	0.232823	0.290303	0.152689	0.409746
7	0.582793	0.214022	0.214022	0.214022	0.325736	0.582793
8	0.824038	0.299525	0.455267	0.455267	0.566982	0.824038
9	1.160361	0.418726	0.418726	0.791590	0.903305	1.160361
10	1.629230	0.162923	0.887596	0.584906	1.372174	1.629230
11	2.282884	0.816577	0.816577	1.238560	0.816577	0.816577
12	3.194148	0.319415	1.727840	2.149823	1.727840	1.727840
13	4.464546	1.589813	1.589813	1.589813	2.998239	2.998239
14	6.235617	2.217525	3.360884	3.360884	4.769310	4.769310
15	8.704679	3.092623	3.092623	5.829946	7.238371	7.238371
16	12.146814	4.312603	6.534759	4.312603	4.312603	10.680507
17	16.945518	6.013385	6.013385	9.111307	9.111307	15.479210
18	23.635423	8.384457	12.703290	15.801212	15.801212	22.169115
19	32.961863	11.689983	11.689983	11.689983	25.127652	31.495556
20	45.963916	16.298239	24.692036	24.692036	38.129705	44.497609

Table B. 4 Preventive maintenance failure rate of Bang Rakyai traction substation

t	No PM	PM every 1 year	PM every 2 years	PM every 3 years	PM every 5 years	PM every 10 years
0	0.030979	0.030979	0.030979	0.030979	0.030979	0.030979
1	0.057769	0.057769	0.057769	0.057769	0.057769	0.057769
2	0.095960	0.043968	0.095960	0.095960	0.095960	0.095960
3	0.150405	0.064041	0.064041	0.150405	0.150405	0.150405
4	0.228023	0.092658	0.141659	0.092658	0.228023	0.228023
5	0.338674	0.133454	0.133454	0.203309	0.338674	0.338674
6	0.496418	0.191612	0.291198	0.361054	0.191612	0.496418
7	0.721299	0.274522	0.274522	0.274522	0.416492	0.721299
8	1.041888	0.392719	0.595111	0.595111	0.737081	1.041888
9	1.498920	0.561221	0.561221	1.052143	1.194113	1.498920
10	2.150464	0.215046	1.212765	0.801436	1.845658	2.150464
11	3.079306	1.143888	1.143888	1.730278	1.143888	1.143888
12	4.403462	0.440346	2.468044	3.054434	2.468044	2.468044
13	6.291178	2.328062	2.328062	2.328062	4.355760	4.355760
14	8.982306	3.320245	5.019190	5.019190	7.046888	7.046888
15	12.818775	4.734700	4.734700	8.855660	10.883357	10.883357
16	18.288045	6.751147	10.203970	6.751147	6.751147	16.352627
17	26.085033	9.625792	9.625792	14.548135	14.548135	24.149615
18	37.200415	13.723886	20.741175	25.663517	25.663517	35.264997
19	53.046499	19.566125	19.566125	19.566125	41.509601	51.111081
20	75.636668	27.894819	42.156295	42.156295	64.099771	73.701250

Table B. 5 Preventive maintenance failure rate of Saima traction substation

t	No PM	PM every 1 year	PM every 2 years	PM every 3 years	PM every 5 years	PM every 10 years
0	0.028408	0.028408	0.028408	0.028408	0.028408	0.028408
1	0.053365	0.053365	0.053365	0.053365	0.053365	0.053365
2	0.089149	0.041121	0.089149	0.089149	0.089149	0.089149
3	0.140458	0.060224	0.060224	0.140458	0.140458	0.140458
4	0.214027	0.087615	0.133793	0.087615	0.214027	0.214027
5	0.319514	0.126889	0.126889	0.193101	0.319514	0.319514
6	0.470765	0.183203	0.278140	0.344353	0.183203	0.470765
7	0.687635	0.263947	0.263947	0.263947	0.400073	0.687635
8	0.998593	0.379722	0.574905	0.574905	0.711031	0.998593
9	1.444458	0.545724	0.545724	1.020770	1.156896	1.444458
10	2.083759	0.208376	1.185025	0.783746	1.796197	2.083759
11	3.000415	1.125032	1.125032	1.700403	1.125032	1.125032
12	4.314756	0.431476	2.439374	3.014744	2.439374	2.439374
13	6.199315	2.316035	2.316035	2.316035	4.323933	4.323933
14	8.901477	3.322093	5.018196	5.018196	7.026094	7.026094
15	12.775952	4.764623	4.764623	8.892671	10.900569	10.900569
16	18.331341	6.832984	10.320011	6.832984	6.832984	16.455958
17	26.296895	9.798689	9.798689	14.798538	14.798538	24.421512
18	37.718249	14.051043	21.220042	26.219892	26.219892	35.842866
19	54.094676	20.148252	20.148252	20.148252	42.596319	52.219293
20	77.575900	28.890692	43.629476	43.629476	66.077543	75.700517

Table B. 6 Preventive maintenance failure rate of Yak Nonthaburi traction substation

t	No PM	PM every 1 year	PM every 2 years	PM every 3 years	PM every 5 years	PM every 10 years
0	0.028934	0.028934	0.028934	0.028934	0.028934	0.028934
1	0.054969	0.054969	0.054969	0.054969	0.054969	0.054969
2	0.092340	0.042868	0.092340	0.092340	0.092340	0.092340
3	0.145983	0.062878	0.062878	0.145983	0.145983	0.145983
4	0.222985	0.091601	0.139880	0.091601	0.222985	0.222985
5	0.333518	0.132831	0.132831	0.202133	0.333518	0.333518
6	0.492180	0.192014	0.291494	0.360796	0.192014	0.492180
7	0.719931	0.276969	0.276969	0.276969	0.419766	0.719931
8	1.046855	0.398917	0.603893	0.603893	0.746689	1.046855
9	1.516135	0.573965	0.573965	1.073173	1.215969	1.516135
10	2.189759	0.218976	1.247589	0.825237	1.889593	2.189759
11	3.156707	1.185924	1.185924	1.792186	1.185924	1.185924
12	4.544705	0.454471	2.573922	3.180184	2.573922	2.573922
13	6.537096	2.446862	2.446862	2.446862	4.566314	4.566314
14	9.397059	3.513672	5.306824	5.306824	7.426276	7.426276
15	13.502369	5.045016	5.045016	9.412134	11.531586	11.531586
16	19.395303	7.243172	10.937951	7.243172	7.243172	17.424520
17	27.854270	10.398497	10.398497	15.702138	15.702138	25.883487
18	39.996627	14.927784	22.540854	27.844495	27.844495	38.025844
19	57.426277	21.429313	21.429313	21.429313	45.274145	55.455494
20	82.445531	30.761881	46.448566	46.448566	70.293399	80.474748

Table B. 7 Preventive maintenance failure rate of Nonthaburi Center traction substation

t	No PM	PM every 1 year	PM every 2 years	PM every 3 years	PM every 5 years	PM every 10 years
0	0.031092	0.031092	0.031092	0.031092	0.031092	0.031092
1	0.058825	0.058825	0.058825	0.058825	0.058825	0.058825
2	0.098545	0.045603	0.098545	0.098545	0.098545	0.098545
3	0.155438	0.066747	0.066747	0.155438	0.155438	0.155438
4	0.236926	0.097031	0.148235	0.097031	0.236926	0.236926
5	0.353641	0.140408	0.140408	0.213747	0.353641	0.353641
6	0.520814	0.202537	0.307581	0.380919	0.202537	0.520814
7	0.760256	0.291524	0.291524	0.291524	0.441979	0.760256
8	1.103212	0.418981	0.634480	0.634480	0.784935	1.103212
9	1.594430	0.601539	0.601539	1.125698	1.276153	1.594430
10	2.298006	0.229801	1.305115	0.863019	1.979729	2.298006
11	3.305743	1.237538	1.237538	1.870756	1.237538	1.237538
12	4.749134	0.474913	2.680929	3.314147	2.680929	2.680929
13	6.816515	2.542294	2.542294	2.542294	4.748309	4.748309
14	9.777641	3.642778	5.503420	5.503420	7.709436	7.709436
15	14.018886	5.219010	5.219010	9.744666	11.950681	11.950681
16	20.093658	7.476660	11.293781	7.476660	7.476660	18.025452
17	28.794602	10.710311	10.710311	16.177605	16.177605	26.726397
18	41.257038	15.341895	23.172746	28.640040	28.640040	39.188832
19	59.107087	21.975753	21.975753	21.975753	46.490089	57.038881
20	84.673859	31.477481	47.542526	47.542526	72.056862	82.605654

Table B. 8 Preventive maintenance failure rate of Yak Tiwanon traction substation

t	No PM	PM every 1 year	PM every 2 years	PM every 3 years	PM every 5 years	PM every 10 years
0	0.032653	0.032653	0.032653	0.032653	0.032653	0.032653
1	0.061520	0.061520	0.061520	0.061520	0.061520	0.061520
2	0.102261	0.046894	0.102261	0.102261	0.102261	0.102261
3	0.159764	0.067728	0.067728	0.159764	0.159764	0.159764
4	0.240921	0.097134	0.148886	0.097134	0.240921	0.240921
5	0.355466	0.138637	0.138637	0.211678	0.355466	0.355466
6	0.517132	0.197212	0.300302	0.373344	0.197212	0.517132
7	0.745304	0.279885	0.279885	0.279885	0.425385	0.745304
8	1.067342	0.396568	0.601923	0.601923	0.747423	1.067342
9	1.521860	0.561252	0.561252	1.056442	1.201941	1.521860
10	2.163359	0.216336	1.202751	0.793685	1.843439	2.163359
11	3.068758	1.121735	1.121735	1.699084	1.121735	1.121735
12	4.346621	0.434662	2.399598	2.976947	2.399598	2.399598
13	6.150174	2.238215	2.238215	2.238215	4.203151	4.203151
14	8.695674	3.160517	4.783715	4.783715	6.748651	6.748651
15	12.288345	4.462238	4.462238	8.376386	10.341322	10.341322
16	17.358973	6.299463	9.532867	6.299463	6.299463	15.411950
17	24.515563	8.892487	8.892487	13.456053	13.456053	22.568540
18	34.616241	12.552234	18.993165	23.556730	23.556730	32.669218
19	48.872147	17.717531	17.717531	17.717531	37.812637	46.925124
20	68.992666	25.007734	37.838050	37.838050	57.933156	67.045643

Table B. 9 Preventive maintenance failure rate of Wongsawang traction substation

t	No PM	PM every 1 year	PM every 2 years	PM every 3 years	PM every 5 years	PM every 10 years
0	0.030450	0.030450	0.030450	0.030450	0.030450	0.030450
1	0.052066	0.052066	0.052066	0.052066	0.052066	0.052066
2	0.081695	0.034836	0.081695	0.081695	0.081695	0.081695
3	0.122309	0.048784	0.048784	0.122309	0.122309	0.122309
4	0.177981	0.067902	0.104455	0.067902	0.177981	0.177981
5	0.254292	0.094109	0.094109	0.144214	0.254292	0.254292
6	0.358895	0.130033	0.198713	0.248817	0.130033	0.358895
7	0.502280	0.179274	0.179274	0.179274	0.273417	0.502280
8	0.698823	0.246771	0.375817	0.375817	0.469960	0.698823
9	0.968234	0.339293	0.339293	0.645228	0.739371	0.968234
10	1.337526	0.133753	0.708586	0.466116	1.108664	1.337526
11	1.843732	0.639959	0.639959	0.972322	0.639959	0.639959
12	2.537611	0.253761	1.333838	1.666201	1.333838	1.333838
13	3.488742	1.204891	1.204891	1.204891	2.284968	2.284968
14	4.792498	1.652630	2.508647	2.508647	3.588724	3.588724
15	6.579613	2.266365	2.266365	4.295763	5.375839	5.375839
16	9.029291	3.107639	4.716043	3.107639	3.107639	7.825517
17	12.387173	4.260810	4.260810	6.465521	6.465521	11.183399
18	16.989968	5.841513	8.863606	11.068316	11.068316	15.786194
19	23.299222	8.008251	8.008251	8.008251	17.377570	22.095448
20	31.947594	10.978294	16.656623	16.656623	26.025942	30.743820

Table B. 10 Preventive maintenance failure rate of Bangson traction substation

t	No PM	PM every 1 year	PM every 2 years	PM every 3 years	PM every 5 years	PM every 10 years
0	0.031166	0.031166	0.031166	0.031166	0.031166	0.031166
1	0.054792	0.054792	0.054792	0.054792	0.054792	0.054792
2	0.086659	0.037346	0.086659	0.086659	0.086659	0.086659
3	0.129640	0.051647	0.051647	0.129640	0.129640	0.129640
4	0.187612	0.070936	0.109619	0.070936	0.187612	0.187612
5	0.265803	0.096952	0.096952	0.149127	0.265803	0.265803
6	0.371265	0.132043	0.202415	0.254589	0.132043	0.371265
7	0.513510	0.179372	0.179372	0.179372	0.274288	0.513510
8	0.705367	0.243208	0.371229	0.371229	0.466145	0.705367
9	0.964140	0.329309	0.329309	0.630001	0.724917	0.964140
10	1.313166	0.131317	0.678335	0.445440	1.073943	1.313166
11	1.783924	0.602075	0.602075	0.916199	0.602075	0.602075
12	2.418873	0.241887	1.237023	1.551147	1.237023	1.237023
13	3.275276	1.098291	1.098291	1.098291	2.093427	2.093427
14	4.430374	1.482626	2.253389	2.253389	3.248525	3.248525
15	5.988344	2.001007	2.001007	3.811359	4.806495	4.806495
16	8.089698	2.700188	4.102361	2.700188	2.700188	6.907849
17	10.923956	3.643228	3.643228	5.534447	5.534447	9.742107
18	14.746739	4.915178	7.466011	9.357229	9.357229	13.564890
19	19.902821	6.630756	6.630756	6.630756	14.513311	18.720972
20	26.857226	8.944688	13.585161	13.585161	21.467717	25.675377

APPENDIX C

PREVENTIVE MAINTENANCE COST OF MRT PURPLE LINE TRACTION SUBSTATION

Table C. 1 Preventive maintenance cost multiplier of Klong Bangphai traction substation

Time (year)	Preventive maintenance cost of Khlong Bangphai substation				
	1 year	2 years	3 years	5 years	10 years
1	1.20	0.00	0.00	0.00	0.00
2	1.11	1.40	0.00	0.00	0.00
3	1.15	0.00	1.60	0.00	0.00
4	1.19	1.41	0.00	0.00	0.00
5	1.25	0.00	0.00	2.00	0.00
6	1.32	1.67	1.92	0.00	0.00
7	1.41	0.00	0.00	0.00	0.00
8	1.53	2.10	0.00	0.00	0.00
9	1.68	0.00	2.91	0.00	0.00
10	1.87	2.80	0.00	3.88	3.00
11	2.11	0.00	0.00	0.00	0.00
12	2.41	3.92	4.95	0.00	0.00
13	2.80	0.00	0.00	0.00	0.00
14	3.29	5.74	0.00	0.00	0.00
15	3.92	0.00	9.16	10.61	0.00
16	4.71	8.67	0.00	0.00	0.00
17	5.72	0.00	0.00	0.00	0.00
18	7.01	13.42	17.80	0.00	0.00
19	8.65	0.00	0.00	0.00	0.00
20	10.73	21.11	0.00	33.03	22.37
Total	65.07	62.24	38.34	49.52	25.37

Table C. 2 Preventive maintenance cost multiplier of Talad Bangyai traction substation

Time (year)	Preventive maintenance cost of Talad Bangyai substation				
	1 year	2 years	3 years	5 years	10 years
1	1.20	0.00	0.00	0.00	0.00
2	1.13	1.40	0.00	0.00	0.00
3	1.18	0.00	1.60	0.00	0.00
4	1.24	1.49	0.00	0.00	0.00
5	1.33	0.00	0.00	2.00	0.00
6	1.45	1.89	2.14	0.00	0.00
7	1.61	0.00	0.00	0.00	0.00
8	1.83	2.64	0.00	0.00	0.00
9	2.12	0.00	3.82	0.00	0.00
10	1.45	3.98	0.00	4.96	3.00
11	3.04	0.00	0.00	0.00	0.00
12	1.82	6.42	7.91	0.00	0.00
13	4.71	0.00	0.00	0.00	0.00
14	6.01	10.85	0.00	0.00	0.00
15	7.75	0.00	17.92	18.62	0.00
16	10.09	18.88	0.00	0.00	0.00
17	13.25	0.00	0.00	0.00	0.00
18	17.51	33.46	42.38	0.00	0.00
19	23.25	0.00	0.00	0.00	0.00
20	30.97	59.92	0.00	79.23	39.52
Total	132.95	140.93	75.77	104.81	42.52

Table C. 3 Preventive maintenance cost multiplier of Bangyai traction substation

Time (year)	Preventive maintenance cost of Bangyai substation				
	1 year	2 years	3 years	5 years	10 years
1	1.20	0.00	0.00	0.00	0.00
2	1.14	1.40	0.00	0.00	0.00
3	1.20	0.00	1.60	0.00	0.00
4	1.29	1.54	0.00	0.00	0.00
5	1.40	0.00	0.00	2.00	0.00
6	1.57	2.07	2.31	0.00	0.00
7	1.79	0.00	0.00	0.00	0.00
8	2.11	3.10	0.00	0.00	0.00
9	2.55	0.00	4.58	0.00	0.00
10	1.60	5.09	0.00	5.80	3.00
11	4.02	0.00	0.00	0.00	0.00
12	2.18	8.95	10.72	0.00	0.00
13	6.88	0.00	0.00	0.00	0.00
14	9.21	16.47	0.00	0.00	0.00
15	12.45	0.00	27.36	26.34	0.00
16	16.96	31.08	0.00	0.00	0.00
17	23.26	0.00	0.00	0.00	0.00
18	32.03	59.47	72.44	0.00	0.00
19	44.26	0.00	0.00	0.00	0.00
20	61.32	114.65	0.00	134.50	55.62
Total	228.42	243.83	119.01	168.65	58.62

Table C. 4 Preventive maintenance cost multiplier of Bang Rakyai traction substation

Time (year)	Preventive maintenance cost of Bang Rakyai substation				
	1 year	2 years	3 years	5 years	10 years
1	1.20	0.00	0.00	0.00	0.00
2	1.15	1.40	0.00	0.00	0.00
3	1.22	0.00	1.60	0.00	0.00
4	1.32	1.59	0.00	0.00	0.00
5	1.46	0.00	0.00	2.00	0.00
6	1.66	2.21	2.44	0.00	0.00
7	1.95	0.00	0.00	0.00	0.00
8	2.36	3.48	0.00	0.00	0.00
9	2.94	0.00	5.20	0.00	0.00
10	1.74	6.06	0.00	6.45	3.00
11	4.96	0.00	0.00	0.00	0.00
12	2.52	11.29	13.18	0.00	0.00
13	9.06	0.00	0.00	0.00	0.00
14	12.49	21.92	0.00	0.00	0.00
15	17.39	0.00	36.33	33.14	0.00
16	24.37	43.53	0.00	0.00	0.00
17	34.33	0.00	0.00	0.00	0.00
18	48.51	87.46	103.38	0.00	0.00
19	68.74	0.00	0.00	0.00	0.00
20	97.57	176.72	0.00	190.27	69.54
Total	336.97	355.67	162.13	231.85	72.54

Table C. 5 Preventive maintenance cost multiplier of Saima traction substation

Time (year)	Preventive maintenance cost of Saima substation				
	1 year	2 years	3 years	5 years	10 years
1	1.20	0.00	0.00	0.00	0.00
2	1.15	1.40	0.00	0.00	0.00
3	1.23	0.00	1.60	0.00	0.00
4	1.33	1.60	0.00	0.00	0.00
5	1.48	0.00	0.00	2.00	0.00
6	1.69	2.25	2.47	0.00	0.00
7	1.99	0.00	0.00	0.00	0.00
8	2.42	3.58	0.00	0.00	0.00
9	3.05	0.00	5.36	0.00	0.00
10	1.78	6.32	0.00	6.62	3.00
11	5.22	0.00	0.00	0.00	0.00
12	2.62	11.95	13.88	0.00	0.00
13	9.68	0.00	0.00	0.00	0.00
14	13.45	23.52	0.00	0.00	0.00
15	18.86	0.00	38.99	35.12	0.00
16	26.61	47.30	0.00	0.00	0.00
17	37.72	0.00	0.00	0.00	0.00
18	53.66	96.21	113.00	0.00	0.00
19	76.51	0.00	0.00	0.00	0.00
20	109.28	196.76	0.00	207.81	73.66
Total	370.91	390.88	175.30	251.54	76.66

Table C. 6 Preventive maintenance cost multiplier of Yak Nonthaburi traction substation

Time (year)	Preventive maintenance cost of Yak Nonthaburi substation				
	1 year	2 years	3 years	5 years	10 years
1	1.20	0.00	0.00	0.00	0.00
2	1.16	1.40	0.00	0.00	0.00
3	1.23	0.00	1.60	0.00	0.00
4	1.33	1.61	0.00	0.00	0.00
5	1.48	0.00	0.00	2.00	0.00
6	1.70	2.26	2.48	0.00	0.00
7	2.01	0.00	0.00	0.00	0.00
8	2.45	3.62	0.00	0.00	0.00
9	3.09	0.00	5.41	0.00	0.00
10	1.80	6.40	0.00	6.67	3.00
11	5.31	0.00	0.00	0.00	0.00
12	2.65	12.15	14.07	0.00	0.00
13	9.90	0.00	0.00	0.00	0.00
14	13.78	23.99	0.00	0.00	0.00
15	19.36	0.00	39.68	35.58	0.00
16	27.35	48.38	0.00	0.00	0.00
17	38.83	0.00	0.00	0.00	0.00
18	55.31	98.64	115.44	0.00	0.00
19	78.97	0.00	0.00	0.00	0.00
20	112.93	202.21	0.00	211.76	74.50
Total	381.85	400.66	178.69	256.00	77.50

Table C. 7 Preventive maintenance cost multiplier of Nonthaburi Center traction substation

Time (year)	Preventive maintenance cost of Nonthaburi Center substation				
	1 year	2 years	3 years	5 years	10 years
1	1.20	0.00	0.00	0.00	0.00
2	1.16	1.40	0.00	0.00	0.00
3	1.23	0.00	1.60	0.00	0.00
4	1.33	1.60	0.00	0.00	0.00
5	1.48	0.00	0.00	2.00	0.00
6	1.69	2.25	2.47	0.00	0.00
7	1.99	0.00	0.00	0.00	0.00
8	2.42	3.58	0.00	0.00	0.00
9	3.05	0.00	5.35	0.00	0.00
10	1.78	6.30	0.00	6.60	3.00
11	5.21	0.00	0.00	0.00	0.00
12	2.61	11.88	13.79	0.00	0.00
13	9.64	0.00	0.00	0.00	0.00
14	13.39	23.34	0.00	0.00	0.00
15	18.74	0.00	38.61	34.79	0.00
16	26.42	46.84	0.00	0.00	0.00
17	37.41	0.00	0.00	0.00	0.00
18	53.16	95.06	111.55	0.00	0.00
19	75.72	0.00	0.00	0.00	0.00
20	108.02	193.98	0.00	204.76	72.89
Total	367.65	386.22	173.38	248.15	75.89

Table C. 8 Preventive maintenance cost multiplier of Yak Tiwanon traction substation

Time (year)	Preventive maintenance cost of Yak Tiwanon substation				
	1 year	2 years	3 years	5 years	10 years
1	1.20	0.00	0.00	0.00	0.00
2	1.15	1.40	0.00	0.00	0.00
3	1.22	0.00	1.60	0.00	0.00
4	1.32	1.58	0.00	0.00	0.00
5	1.45	0.00	0.00	2.00	0.00
6	1.64	2.17	2.40	0.00	0.00
7	1.91	0.00	0.00	0.00	0.00
8	2.29	3.35	0.00	0.00	0.00
9	2.82	0.00	4.97	0.00	0.00
10	1.70	5.70	0.00	6.19	3.00
11	4.65	0.00	0.00	0.00	0.00
12	2.41	10.39	12.18	0.00	0.00
13	8.28	0.00	0.00	0.00	0.00
14	11.27	19.71	0.00	0.00	0.00
15	15.51	0.00	32.46	30.09	0.00
16	21.48	38.29	0.00	0.00	0.00
17	29.91	0.00	0.00	0.00	0.00
18	41.81	75.29	89.47	0.00	0.00
19	58.60	0.00	0.00	0.00	0.00
20	82.30	149.01	0.00	163.98	62.98
Total	292.92	306.90	143.08	202.26	65.98

Table C. 9 Preventive maintenance cost multiplier of Wongsawang traction substation

Time (year)	Preventive maintenance cost of Yak Wongsawang substation				
	1 year	2 years	3 years	5 years	10 years
1	1.20	0.00	0.00	0.00	0.00
2	1.13	1.40	0.00	0.00	0.00
3	1.19	0.00	1.60	0.00	0.00
4	1.26	1.51	0.00	0.00	0.00
5	1.36	0.00	0.00	2.00	0.00
6	1.50	1.97	2.22	0.00	0.00
7	1.69	0.00	0.00	0.00	0.00
8	1.95	2.84	0.00	0.00	0.00
9	2.30	0.00	4.17	0.00	0.00
10	1.51	4.47	0.00	5.36	3.00
11	3.46	0.00	0.00	0.00	0.00
12	1.97	7.53	9.17	0.00	0.00
13	5.63	0.00	0.00	0.00	0.00
14	7.35	13.28	0.00	0.00	0.00
15	9.71	0.00	22.07	22.14	0.00
16	12.94	24.09	0.00	0.00	0.00
17	17.37	0.00	0.00	0.00	0.00
18	23.44	44.40	55.30	0.00	0.00
19	31.76	0.00	0.00	0.00	0.00
20	43.17	82.56	0.00	103.35	46.97
Total	171.89	184.05	94.53	132.85	49.97

Table C. 10 Preventive maintenance cost multiplier of Bangson traction substation

Time (year)	Preventive maintenance cost of Yak Bangson substation				
	1 year	2 years	3 years	5 years	10 years
1	1.20	0.00	0.00	0.00	0.00
2	1.14	1.40	0.00	0.00	0.00
3	1.19	0.00	1.60	0.00	0.00
4	1.26	1.51	0.00	0.00	0.00
5	1.35	0.00	0.00	2.00	0.00
6	1.48	1.93	2.18	0.00	0.00
7	1.65	0.00	0.00	0.00	0.00
8	1.89	2.71	0.00	0.00	0.00
9	2.20	0.00	3.92	0.00	0.00
10	1.48	4.13	0.00	5.04	3.00
11	3.20	0.00	0.00	0.00	0.00
12	1.88	6.71	8.18	0.00	0.00
13	5.01	0.00	0.00	0.00	0.00
14	6.41	11.40	0.00	0.00	0.00
15	8.30	0.00	18.64	19.08	0.00
16	10.86	19.94	0.00	0.00	0.00
17	14.30	0.00	0.00	0.00	0.00
18	18.94	35.46	44.31	0.00	0.00
19	25.20	0.00	0.00	0.00	0.00
20	33.65	63.71	0.00	81.77	40.10
Total	142.60	148.90	78.82	107.89	43.10

APPENDIX D

AN EXAMPLE OF CALCULATION RESULTS COMPARED TO THE ETAP

In this appendix, we will present an example of the failure rate calculation method used in this thesis compared with the calculation result from ETAP. An example of a simple circuit used in the calculation is shown in Figure D.1 and the reliability parameters are given in Table D.1.

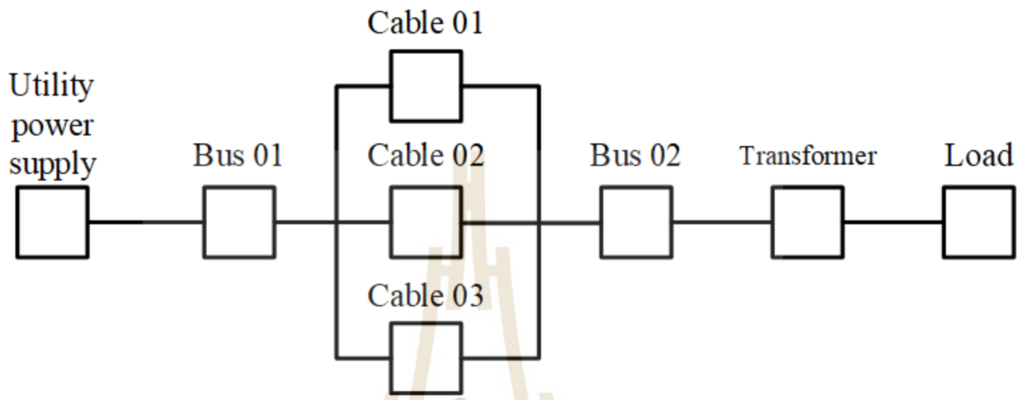

Figure D. 1 Simple circuit block for calculation in ETAP

Table D. 1 Reliability parameters for calculation in ETAP

Component	Failure rate (failure/year)	Repair time (hour/failure)
Utility power supply	0.5	0.5
Bus 01	1	2
Bus 02	1	2
Bus 03	1	2
Cable 01	1	2
Cable 02	1	2
Cable 03	1	2
Transformer	0.5	10

This section shows how to calculate the following failure rates and repair times using the reliability block diagram method.

Step 1: Parallel three cable block

$$MTTF_{All\ Cable}=\frac{1}{\lambda_{Cable1}+\lambda_{Cable2}+\lambda_{Cable3}}-\frac{1}{\lambda_{Cable1}+\lambda_{Cable2}}-\frac{1}{\lambda_{Cable1}+\lambda_{Cable3}}-\frac{1}{\lambda_{Cable2}+\lambda_{Cable3}}+\frac{1}{\lambda_{Cable1}}+\frac{1}{\lambda_{Cable2}}+\frac{1}{\lambda_{Cable3}}$$

$$MTTF_{All\ Cable}=\frac{1}{1+1+1}-\frac{1}{1+1}-\frac{1}{1+1}-\frac{1}{1+1}+\frac{1}{1}+\frac{1}{1}+\frac{1}{1}$$

$$MTTF_{All\ Cable}=1.83$$

$$\lambda_{All\ Cable}=\frac{1}{MTTF_{All\ Cable}}=\frac{1}{1.83}=0.5454\ \ failure\ /\ year$$

Step 2: Combine all series block with Utility, Bus 01, All Cable, Bus 02, Transformer, Bus 03

$$\lambda_{System}=\lambda_{Utility}+\lambda_{Bus01}+\lambda_{All\ Cable}+\lambda_{Bus02}+\lambda_{Transformer}+\lambda_{Bus03}$$

$$\lambda_{System}=0.5+1+0.5454+1+0.5+1=4.5454\ \ failure\ /\ year$$

$$r_{System}=\frac{\lambda_{Utility}r_{Utility}+\lambda_{Bus01}r_{Bus01}+\lambda_{All\ Cable}r_{All\ Cable}+\lambda_{Bus02}r_{Bus02}+\lambda_{Transformer}r_{Transformer}+\lambda_{Bus03}r_{Bus03}}{\lambda_{System}}$$

$$r_{System}=\frac{(0.5*0.5)+(1*2)+(0.5454*2)+(1*2)+(0.5*10)+(1*2)}{4.5454}$$

$$r_{System}=2.715\ hour\ /\ failure$$

$$\text{Unavailability}_{System}=\lambda_{System}r_{System}=4.5454*2.715=12.34\ \ hour\ /\ year$$

A failure rate of 4.5454 failures per year and an unavailability of 12.34 hours per year have been calculated using the reliability block diagram approach. The ETAP calculation results shown in Figure D.2 resulted in a failure rate of 4.0003 failures/year and an unavailability of 11.3 hours/year. It can be seen from the comparative results that the results are not the same because the equations used to calculate the parallel blocks of the ETAP program are different by using the estimation according to the equations of Roy and Ronald, 1996. Repair time was used to estimate the failure rate of parallel blocks. The reliability block diagram method uses parallel block computations with a reliability function as a computational function using only the computational failure rate, which is more reliable.

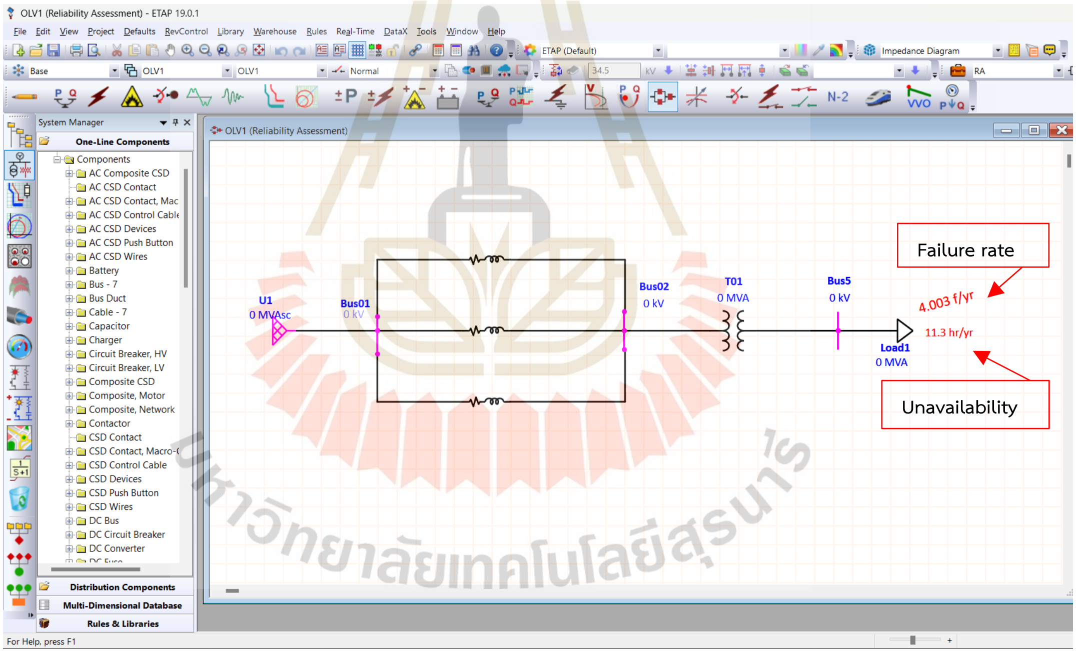

Figure D. 2 Reliability assessment results from ETAP

APPENDIX E

LIST OF PUBLICATION

A. Kingmaneerat, T. Ratniyomchai, and T. Kulworawanichpong, (2021) Reliability Assessment of Railway Traction Substations Using Reliability Block Diagram, 2021 International Conference on Power, Energy and Innovations (ICPEI 2021) October 20-22, 2021, Nakhon Ratchasima, Thailand, pp. 69-72.

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Reliability Assessment of Railway Traction Substations Using Reliability Block Diagram

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***Abstract*— Reliability is a key element in the design and planning of railway traction substation systems. High reliability is an important criterion to guarantee the quality and cost-effectiveness of railway services. This paper describes assessing the reliability of railway traction substations, we propose as a solution to this problem an approach for assessing the reliability in each substation using the reliability block diagram method and risk assessment from EN 50126-1 standard. The approach developed is then applied to the case study MRT blue line extension project in Bangkok, Thailand. The results obtained are solutions to assessing the reliability of planning the construction of future projects.**

Keywords*— *power system reliability, reliability block diagram, railway traction substation

NOMENCLATURE

A	availability
TR	power transformer
DS	disconnected switch
CB	circuit breaker
DR	diode rectifier
BUS	busbar
UGC	underground cable
$R_s(t)$	reliability function in series circuit,
m_s	mean time to failure (MTTF) in series circuit
λ_s	failure rate in series circuit
r_s	mean time to repair (MTTR) in series circuit
$R_p(t)$	reliability function in parallel circuit
m_p	mean time to failure (MTTF) in parallel circuit
λ_p	failure rate in parallel circuit
r_p	mean time to repair (MTTR) in parallel circuit
t	time in hours
λ_1	failure rate of the first block
r_1	MTTR of the first block
λ_2	failure rate of the second block
r_2	MTTR of the second block

I. INTRODUCTION

Transportation becomes one of the most important issues in today's modern metro cities. The subway and light rail transportation system ensures that it does not cause traffic congestion compared to the traffic on urban land routes. Reliable, efficient, and safe railway transportation perceptibly needs a suitable power supply system. The railway traction substation, in general, are designed to meet all the requirements of an electric railway system. But the main role of the power system is to provide reliable and uninterrupted electrical energy to meet the traction load [1].

The EN 50126-1:2017 standard was developed by the CLC/TC 9X "Electrical and Electronic Applications for Railways" to address rail traction substation dependability to offer a reliable continuous system and risk assessment. [2].

In this study, the reliability model of the railway traction substation is developed. It is based on the reliability block diagram procedure for performing the reliability index assessment [3], [4]. Equipment failure rate models used in this paper are based on averaging in nature but adds a fundamental level of richness and usefulness to reliability modeling [5–7]. To analyze the failure rate, MTTF, MTTR, risk assessment, and reliability behavior of railway traction substations, the MRT Blue Line Extension Project in Bangkok serves as a case study for reliability assessment and risk assessment.

The remainder of this paper will address the reliability block diagram method in Section II. Case study is shown in section III. Finally, the results and discussions and conclusion is put in section IV, and section V respectively.

II. RELIABILITY BLOCK DIAGRAM METHOD

Reliability block diagram represents a system by using a graphical representation to analyze the probability of system failure. The system operation can be considered in various forms, herein, electrical energy or power flowing from a traction substation to serve a specific load is the main emphasis. The blocks within the block diagram are linked depending on their effects on the system [3]. Each block represents by reliability, availability, unavailability, failure rate, and mean time to repair. To calculate reliability, MTTR,

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MTTF, and failure rate of the series and parallel connected block are presented as follow:

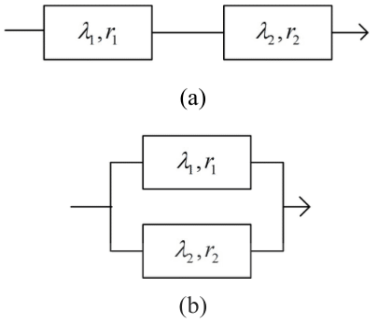

Fig. 1. Reliability block diagram (a) series connected blocks (b) parallel connected blocks

A. Series connected blocks

$$R_s(t) = R_1(t)R_2(t) = e^{-\lambda_1 t} e^{-\lambda_2 t} \tag{1}$$

$$m_s = \int_0^\infty R_s(t)dt = \frac{1}{\lambda_1 + \lambda_2} \tag{2}$$

$$\lambda_s = \lambda_1 + \lambda_2 \tag{3}$$

$$r_s = \frac{\lambda_1 r_1 + \lambda_2 r_2}{\lambda_1 + \lambda_2} \tag{4}$$

B. Parallel connected blocks

$$R_p(t) = 1 - (1 - R_1(t))(1 - R_2(t))$$

$$R_p(t) = e^{-\lambda_1 t} + e^{-\lambda_2 t} - e^{-(\lambda_1 + \lambda_2)t} \tag{5}$$

$$m_p = \int_0^\infty R_p(t)dt = \frac{1}{\lambda_1} + \frac{1}{\lambda_2} - \frac{1}{\lambda_1 + \lambda_2} \tag{6}$$

$$\lambda_p = \frac{1}{m_p} \tag{7}$$

$$r_p = \frac{r_1 r_2}{r_1 + r_2} \tag{8}$$

III. CASE STUDY

The Bangkok Mass Rapid Transit (MRT) Blue Line project is the first underground MRT in Bangkok. it will be implemented in conjunction with other systems being undertaken by the Mass Rapid Transit Authority of Thailand (MRTA).

The MRT blue line extension project has a total of 14 railway traction substations shown in Fig. 2. The power distribution system is divided into two areas as Depot feeder and Tha Phra feeder. TABLE I gives reliability parameters of each component from equipment inspection data for reliability assessment [5–7]. TABLE II gives a distance of underground cable between the traction substation from the case study.

TABLE I. ELECTRICAL POWER SYSTEM COMPONENT RELIABILITY PARAMETER

Equipment	**Failure rate (per year)**	**MTTR (hours)**
Underground Cable	0.07[a]	10
Power Transformers	0.03	70
Circuit Breakers	0.01	12
Disconnect Switches	0.01	4
Busbar	0.01	4
Diode Rectifier	0.0131	12.45

[a] The failure rate for underground cable is per circuit mile

TABLE II. DISTANCE BETWEEN THE TRACTION SUBSTATION

Traction substation	**Distance (km)**	
	Depot feeder 1	**Depot feeder 2**
Bang Khae	3.75	8.51
Phet Khasem 48	6.30	6.00
Depot	0.00	14.61
Main Workshop	0.00	14.61
Bang Phai	8.70	3.60
Sanam Chai	7.42	11.41
Wat Mangkon	11.41	11.41
	Tha Phra feeder 1	**Tha Phra feeder 2**
Tha Phra 1	0.00	21.29
Tha Phra 2	0.00	21.29
Charan 13	21.29	1.23
Bang Khun Non	3.98	17.31
Sirindhorn	15.37	5.92
Bang Or	9.64	11.65
Bang Pho	11.26	10.03

IV. RESULTS AND DISCUSSIONS

TABLE III. presents the failure rate, MTTR, MTTF, and availability of each traction substation calculated using (1) to (4) in a series circuit and using (5) to (8) in a parallel circuit. To calculate availability using equation (9).

$$A = \frac{m}{m + r} \tag{9}$$

From the calculation results in TABLE III, it was found that the traction substations far from the power distribution substation have a higher failure rate than those near the power distribution substation. For example, Wat Mangkon traction substation has a higher failure rate than that of the Depot traction substation. It can be seen that feeding distance has more impact on the failure rate.

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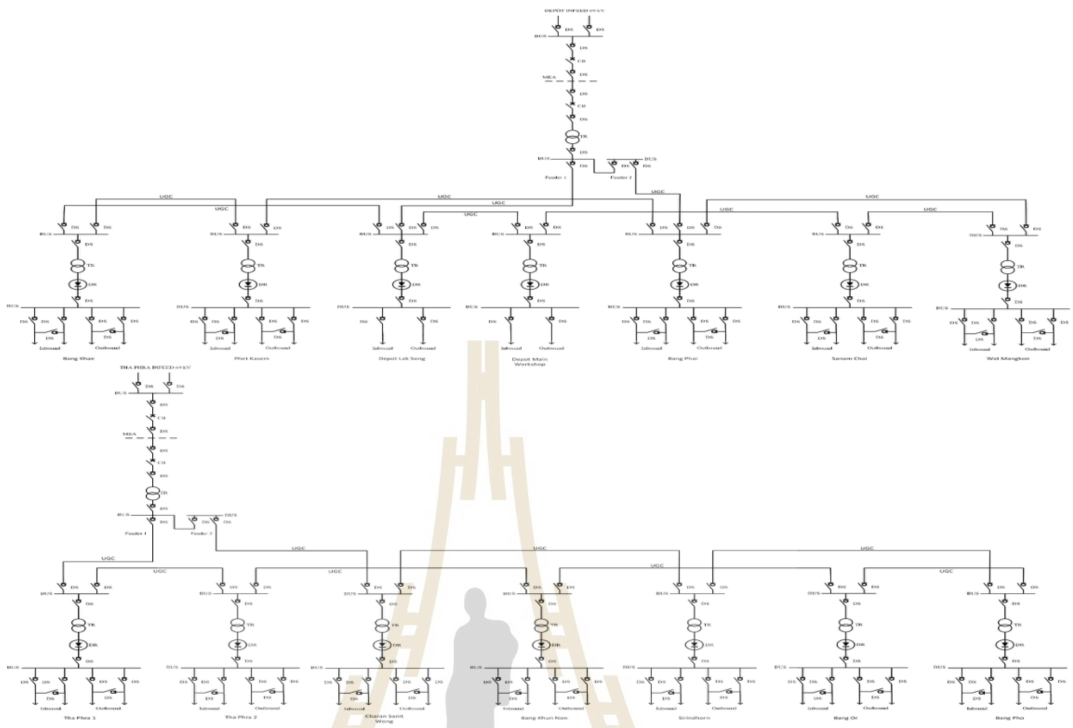

Fig. 2. The single line diagram of MRT blue line extension project

For risk assessment, the EN 50126-1:2017 standard uses the failure rate to compare the frequency of occurrence hazardous events. A case study found that the frequency of occurrence of hazardous events is occasional, occurring once every 1 to 10 years, and that the severity categories of traction substation failure consequences to persons or the environment have no possibility of fatality, severe or minor injuries only. As a result, uses the failure rate to compare the frequency of occurrence of hazardous occurrences, risk acceptance categories is undesirable. The failure rate can be reduced by modifying the outline or adding redundancy equipment.

TABLE IV. is a calculation regarding the reliability behavior. The reliability values have been calculated to obtain these results considering the failure rate is constant during 10 years.

From the reliability behavior shown in Fig. 3. and Fig. 4., it is possible to observe, that the degradation trend of the different railway traction substations is similar. Consequently, during 10 years traction substations far from the distribution substation have reliability behavior less than traction substation nearby the distribution substation.

From the assessment of the preliminary design system, it can be seen that the failure rate is still too high. This makes the risk assessment results unacceptable. To achieve a lower failure rate, a redundant system must be paralleled at the traction substation [7]. Hence, the system reliability deteriorates over time. To maintain this level of reliability, a system maintenance plan is required.

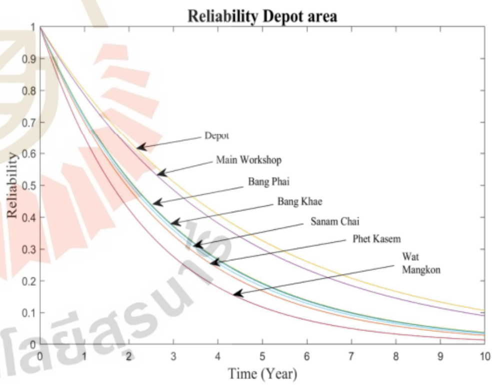

Fig. 3. Reliability behavior Depot area

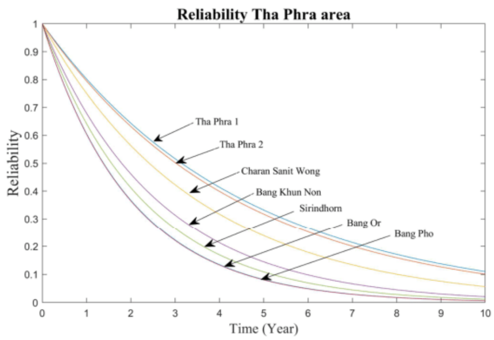

Fig. 4. Reliability behavior Tha Phra area

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TABLE III. RESULTS OF RAILWAY TRACTION SUBSTATION RELIABILITY PARAMETER

Traction substations	Failure rate (per year)	MTTR (hours)	MTTF (years)	Availability
Bang Khae	0.33115	7.6403	3.0197	0.99971
Phet Khasem 48	0.35684	7.5354	2.8024	0.99969
Depot	0.22385	6.5978	4.4673	0.99983
Main workshop	0.24089	6.6014	4.1512	0.99982
Bang Phai	0.32874	7.6482	3.0420	0.99971
Sanam Chai	0.34105	9.2833	2.9321	0.99964
Wat Mangkon	0.42855	8.1066	2.3334	0.99960
Tha Phra 1	0.22051	6.9170	4.5350	0.99983
Tha Phra 2	0.22967	6.8647	4.3541	0.99982
Charan 13	0.28710	5.8752	3.4831	0.99981
Bang Khun Non	0.38675	6.2286	2.5856	0.99973
Sirindhorn	0.44354	5.7637	2.2546	0.99971
Bang Or	0.50060	5.8592	1.9976	0.99967
Bang Pho	0.50348	5.8097	1.9862	0.99967

TABLE IV. RESULTS OF RAILWAY TRACTION SUBSTATION RELIABILITY BEHAVIOR

Traction substation	Reliability (year)					
	0	1	2	4	8	10
Bang Khae	0.99996	0.718	0.516	0.266	0.071	0.036
Phet Khasem 48	0.99996	0.700	0.490	0.240	0.058	0.028
Depot	0.99997	0.799	0.639	0.408	0.167	0.107
Main Workshop	0.99997	0.786	0.618	0.382	0.146	0.090
Bang Phai	0.99996	0.720	0.518	0.268	0.072	0.037
Sanam Chai	0.99996	0.711	0.506	0.256	0.065	0.033
Wat Mangkon	0.99995	0.651	0.424	0.180	0.032	0.014
Tha Phra 1	0.99997	0.802	0.643	0.414	0.171	0.110
Tha Phra 2	0.99997	0.795	0.632	0.399	0.159	0.101
Charan 13	0.99997	0.750	0.563	0.317	0.101	0.057
Bang Khun Non	0.99996	0.679	0.461	0.213	0.045	0.021
Sirindhorn	0.99995	0.642	0.412	0.170	0.029	0.012
Bang Or	0.99994	0.606	0.367	0.135	0.018	0.007
Bang Pho	0.99994	0.604	0.365	0.133	0.018	0.007

V. CONCLUSION

This work presents the reliability block diagram method to determine the reliability parameters (reliability behavior, failure rate, MTTR, and MTTF) in each railway traction substation of the MRT blue line extension project by using data from equipment inspection data. The proposed approach can be applied successfully to the provided case study and satisfactory results can be obtained. The results shows that over time the reliability of railway traction substations will decrease. These results can be used in planning stage to determine maintenance intervals or restructure to meet the required reliability of the minimum requirement. The use of the reliability block diagram method can be greatly facilitating this effort. There is also an opportunity to use the presented approach for a number of other practical applications, such as replacement strategy, space planning, risk assessment, etc.

This proposed reliability approach will give a strong evidence to guarantee the quality and cost-effectiveness of the traction power supply system planning.

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Traction Power Substation Outage and Reliability Evaluation for a DC Mass Rapid Transit System

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ABSTRACT

In this study, a methodology is proposed for the reliability evaluation of traction power substations for mass rapid transit in order to calculate the reliability index. The technique for calculating failure rate, mean time to failure, mean time to repair, availability, and unavailability is the Reliability Block Diagram. This method is utilized in the process of determining the reliability index. Utilize the reliability index to determine the capacity outage probability table, loss of load probability, and loss of load expectation for each traction substation. This will allow to determine the estimated number of days per year that the substation will be unable to satisfy its demand load. The component reliability data of the traction power substation have been taken from previous research published in the relevant field. This research is solely focusing on the distribution substations that connect to the DC traction substations; it does not take service substations into consideration. Evaluation of the dependability of a traction power substation was carried out for a genuine system in Bangkok, Thailand, known as the MRT Purple line. When measured against the BAL-502-RF-03 standard developed by the North American Electric Reliability Corporation, the outcomes meet the criteria for acceptance.

Nomenclature

CB	is circuit breaker
TR	is power transformer
DS	is disconnected switch
BUS	is busbar
UGC	is underground cable
DR	is diode rectifier
t	time in second
$R_{system}(t)$	is the total system's reliability
$R_n(t)$	is the reliability of components "n"
$Q_{system}(t)$	is the total system's probability of failure
$Q_n(t)$	is the probability of failure components "n"
λ_n	is failure rate of components "n"
r_n	is repair rate of components "n"
MTTF	is mean time to failure
MTTR	is mean time to repair
COPT	is Capacity outage probability table
LOLP	is Loss of load probability
LOLE	is Loss of load expectation
$P(X)$	is the probability of a specific capacity outage state on a cumulative basis of X MW
C_i	is the capacity unit MW of each substation "i"
U_i	is the unavailability of each substation "i"
RS_i	is the system reserved capacity of each substation "i"
x_i	is the capacity outage in COPT of each substation "i"
T_i	is the period of loss of power offered in the variety of time units
V_j	is voltage at bus j
V_i	is voltage at bus i
$P_{tr,j}$	is the power load of the train connected at bus j
$G_{k,ij}$	is an element i to j of the bus conductance matrix
$I_{ss,i}$	is short-circuit capacity of the substation at bus i
$[I]$	is the current matrix
$[V]$	is the voltage matrix
$[G]$	is the conductance matrix

1. INTRODUCTION

The railway system is a large system with a long history. Over the last century, it has become one of the most popular mass transit systems. The demand for both short and long-

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term rail transportation for passengers grows year after year. Driving efficiency, service speed, and dependability are all factors to consider. A suitable traction power substation is required for reliable, efficient, and safe railway transportation. [1].

For the efficient operation of systems, power system experts are depending increasingly on reliability evaluation. It is becoming one of the most important industrial activities in both developed and emerging nations, thus reliability issues are complex, time-consuming, and require a budget, tools, and pooled data [2-5]. Planning for reliability facilitates the alignment of project strategy and capital investment.

Reliability is among the most important aspects of the designing, planning, operation, and maintenance of an electric power system [6-7]. The nature of the problem is to evaluate the system's ability to meet load demand while considering random occurrences that impact capacity factors and variable load over time [8]. To determine whether the designed system can handle the load demand. As a result, the power supply system's reliability must be evaluated [9].

A common representation of a power supply system reliability model is a capacity outage probability table (COPT) containing the available or unavailable capacity levels and their accompanying probabilities [10]. Loss of load is the most frequently accepted definition of failure when evaluating power supply capacity adequacy [11-13].

To evaluate the traction power substation's reliability for mass rapid transit. Therefore, the researcher would like to present a technique for assessing the reliability of the traction power supply for use in planning before starting the project. It offers an easy way to evaluate complex systems without the need to spend time collecting data for evaluation. By using reliability data for electrical components from the literature for a reliability assessment. The availability of serviceable systems is used to determine the probability that consolidates will not satisfy power expectations.

2. METHODOLOGY

2.1. Multi-train and DC traction power supply simulation

For the load duration curve, the multi-train movement is simulated. The three most significant dynamic factors in train movement to collect a traction substation load are position, speed, and acceleration rate. The correlations between these components are only subservient to Newton's 2nd law of motion's basic kinematic equation during single train motion. The corresponding circuit of the DC traction power supply is shown in Fig. 1. Despite the fact that mass rapid transit networks can approach one hundred nodes of trains and traction substations during peak hours [14], useful DC railway load flow calculation is required due to the computationally complex nature of multi-train modeling and simulation. The present injection approach is employed in this study to calculate power flow with a multi-conductor system is given by

$$I_{ss,i} - \frac{P_{tr,j}}{V_j} = \sum_{i=1}^{n} G_{k,ij} V_i \tag{1}$$

$$[I] = [G][V] \tag{2}$$

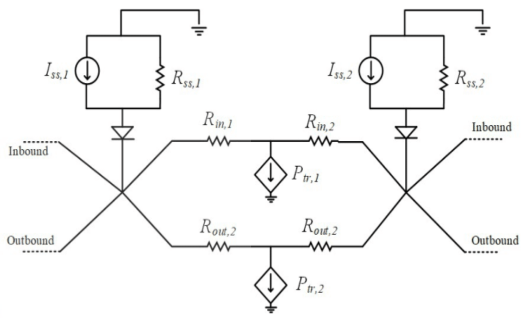

Fig. 1 The equivalent circuit of DC traction power supply

2.1. Reliability Block Diagram (RBD)

This method explains a system by calculating the probability of system failure using a graphical representation. The primary focus is on the transfer of electrical power from a distribution substation to a traction power supply system [15]. The system's performance can be evaluated from a variety of perspectives. The blocks in the block diagram are determined by their system influence [16]. Each block displays the failure rate (λ), reliability, availability, unavailability, mean time to failure (MTTF), and mean time to repair (MTTR). For the purpose of calculating reliability index, failure rate, MTTR, and MTTF of the parallel and series-connected blocks are reported as follows.

Components of a system have series reliability in a series block diagram if the failure of one or more components can result in system failure. [17]. To obtain that from the input side to the output side schematically, one must pass through every element, as shown in Fig. 2 (a).

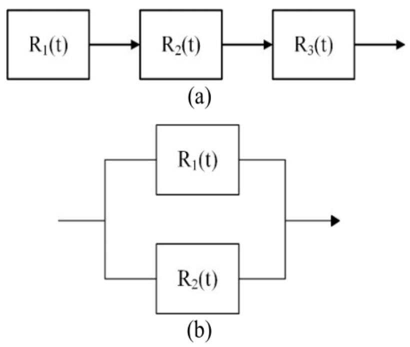

Fig. 2 (a) series connected blocks (b) parallel connected blocks

The mathematical expression for the series reliability is the total system's reliability as follow:

$$R_{system}(t) = R_1(t) \times R_2(t) \times R_3(t) \ldots \times R_n(t) \tag{3}$$

If the components' failure rates are proportional to their exponential failure probabilities, $\lambda_1, \lambda_2, \lambda_3$ to λ_n, then the system reliability as:

$$R_{system}(t) = e^{-\lambda_1 t} \times e^{-\lambda_2 t} \times e^{-\lambda_3 t} \times \ldots \times e^{-\lambda_n t} \tag{4}$$

$$\lambda_{system} = \lambda_1 + \lambda_2 + \lambda_3 + \ldots + \lambda_n \tag{5}$$

MTTF of a series component can be computed by [1]

$$MTTF_{system} = \int_0^\infty R(t)_{system}\, dt = \frac{1}{\lambda_{system}} \tag{6}$$

MTTR of a series component can be computed by [18]

$$MTTR_{system} = \frac{\sum_{i=1}^{n} (\lambda_i r_i)}{\lambda_{system}} \tag{7}$$

The term parallel block diagram refers to the fact that for the system to work, just one of the parallel connections components must be operational. As shown in Fig. 2 (b), there are several different ways to get from the system's input side to the output side [3]. Redundancy increases overall system reliability because all elements in the parallel connection must fail therefore for the system to stop working. If the failures are unrelated, the chance that they all fail is equal to the amount of the failure probabilities of all individual components. If Q(t) denotes the probability of failure in each period or unreliability is defined as:

$$R(t)_{system} = 1 - Q(t)_{system} \tag{8}$$

$$Q(t)_{system} = Q_1(t) \times Q_2(t) \times Q_3(t) \times \ldots \times Q_n(t) \tag{9}$$

If the components' failure rates are proportional to their exponential failure probabilities, then the system failure rate can be expressed by example, when there are two independent components in a parallel system is defined [19], for this formulation shown in (10) and (11).

$$R(t)_{system} = 1 - (Q(t)_1 Q(t)_2)$$

$$= 1 - ((1 - R(t)_1)(1 - R(t)_2))$$

$$R(t)_{system} = R(t)_1 + R(t)_2 - (R(t)_1 R(t)_2) \tag{10}$$

$$R(t)_{system} = e^{-\lambda_1 t} + e^{-\lambda_2 t} - (e^{-\lambda_1 t} e^{-\lambda_2 t}) \tag{11}$$

MTTF can be used in parallel system to calculate the failure rate as follow:

$$MTTF_{system} = \int_0^\infty R(t)_{system}\, dt$$

$$MTTF_{system} = \int_0^\infty (e^{-\lambda_1 t} + e^{-\lambda_2 t} - (e^{-\lambda_1 t} + e^{-\lambda_2 t}))dt$$

$$MTTF_{system} = \frac{1}{\lambda_1} + \frac{1}{\lambda_1} - \frac{1}{\lambda_1 + \lambda_2} \tag{12}$$

$$\lambda_{system} = \frac{1}{MTTF_{system}} \tag{13}$$

2.2. Power supply system reliability assessment

Loss of load is the most widely accepted definition of failure when evaluating power supply capacity adequacy, which is an outage caused by capacity inadequacy [20]. Loss of load expectation (LOLE), the reliability index represents how long an incident will cause the available power to be supplied in the system to be less than the demand [21]. To calculate the LOLE reliability index, COPT, LOLP, and daily load duration curve are used instead of the power supply system.

2.2.1 A recursive algorithm for COPT

The power supply model needed in the loss of load strategy is referred to as a COPT. It's just a list of capacity requirements and the probability of them occurring [18]. A simple algorithm for a multi-state unit, i.e., a unit that has one or more derated or partial outage states, in addition fully up and fully down states, can be used to create the COPT, the result is given by

$$P(X) = (1 - U_i)P'(X) + U_i P'(X - C_i) \tag{14}$$

$$U = \frac{MTTR}{MTTF + MTTR} \tag{15}$$

$$A = 1 - U \tag{16}$$

where *P'(X)* and *P(X)* represent the probability of a particular capacity outage state on a cumulative basis of *X* MW prior to and after the addition of the *i* unit is used and *P'(X - C_i)* represents the probability well before installation of *i* unit is added. For (17) has been initialized.

$$\begin{aligned} P'(X) &= 1.0 \quad \text{for} \quad X \le 0 \\ P'(X) &= 0.0 \quad \text{for} \quad X > 0 \end{aligned} \tag{17}$$

2.2.2 Loss of load probability (LOLP)

This method combines the appropriate system COPT with the system load duration curve to predict the expected risk of load loss. The load duration curve is utilized, and the time units are in seconds or hours. A capacity outage refers to a loss of power supply there may not be a load loss as a result of this. This condition is determined by the system load level and the power supply capacity reserve margin. A LOLP occurs only if the load demand surpasses the system's capacity of the remaining power supply capacity [18]. The formula for calculating LOLP is as follows

$$LOLP = \text{Cumulative probabilities of } [x > RS] \tag{18}$$

$$RS = \text{Full capacity (MW) - Load reserve (MW)} \tag{19}$$

2.2.3 Loss of load expectation (LOLE)

LOLE refers to the possibility that consolidates will fail to meet expectations power requirements. The terms LOLE and LOLP are a close relation. If the LOLP quantity is expressed in terms of time units rather than proportional values. The capacity outage probability table and peak time loads can be combined to determine the number of hours in each period during which peak time loads exceed availability. In this case, the index is referred to as the LOLE. The LOLE can be expressed as given in (20) where $LOLP_i$ is that the individual per period and T_i is the duration of power outage provided in a range of time units (second, minute, or hours) [11].

$$LOLE = \sum_{i=1}^{n} LOLP_i \cdot T_i \qquad (20)$$

3. Results and Discussion

3.1. The multi-train movement simulation

The simulation in this paper was performed with MATLAB. Study the simulation of the movement of the mass transit train. Using the route of the MRT Purple line as the data for the simulation. There are a total of sixteen passenger stations ranging from first station, Khlong Bangphai passenger station to station 16, Taopoon passenger station, and a total of 10 traction substations, transit route of the MRT Purple line is shown in Fig. 3, single line diagram of traction substation shown in Fig 4. [22]. Position of passenger stations and traction substations are shown in Table 1. A total of 16 trains operating in the system were simulated in the simulation at different speeds for each segment of the passenger terminal. The simulation parameters for the Purple Line MRT train and the traction substation are presented in Tables 2 and Table 3.

Table 1. Position of passenger stations and traction substations of MRT Purple line

Passenger station	Position of passenger stations (km)	Position of traction substation (km)
Klong Bangphai	0.00	0.00
Talad Bangyai	1.27	1.27
Bangyai	2.83	2.83
Bangphu	4.40	-
Bang Rakyai	5.60	5.60
Bang Raknoi	6.85	-
Saima	8.10	8.10
Pha Nungklao Bridge	9.57	-
Yak Nonthaburi	11.20	11.20
Bang Kasor	12.46	-
Nonthaburi Center	13.36	13.36
Ministry of Public Health	15.15	-
Yak Tiwanon	16.35	16.35
Wongsawang	18.07	18.07
Bangson	19.36	19.36
Taopoon	20.94	-

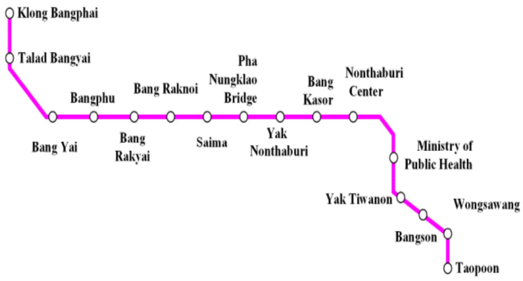

Fig. 3 MRT Purple line service route

For a typical train service hours of MRT Purple line are between 5.30 a.m. and 12.00 a.m. (18.5 hours), in normal hour average headway is 9 minutes per train and peak hour (06.30 a.m. to 08.30 a.m. and 05.00 p.m. to 07.30 p.m.) average headway is 6 minutes per train. The simulation results of the MRT Purple line will present only the information necessary to assess reliability. By taking an example of first traction substation. Fig. 5 shows the load of the first traction substation (Klong Bang Phai) after 1 day of service. A load of traction substation obtained from simulation sorted in descending order of load size will get the load duration curve shown in Fig. 6. The power traction substation must be able to handle the peak load demands of Fig. 6 within a short period of time.

Table 2. MRT Purple line train parameters

Parameter	Value	Unit
Max speed	80	km/h
Max deceleration	0.9	m/s^2
Max acceleration	1.2	m/s^2
Total passenger mass	75	ton
Total train car mass	153	ton
Max braking effort	168.8	kN
Max tractive effort	228.8	kN
Power auxiliary	270	kW
Efficiency of traction motor	0.86	-

Table 3. MRT Purple line traction substation parameter

Parameter	Value	Unit
No load voltage	750	V
Power transformer	2.5	MW
Short circuit capacity	50	MW
Running rail resistance	0.0175	Ω/km
Rail to earth conductance	0.1	S/km
3rd Rail resistance	0.007	Ω/km

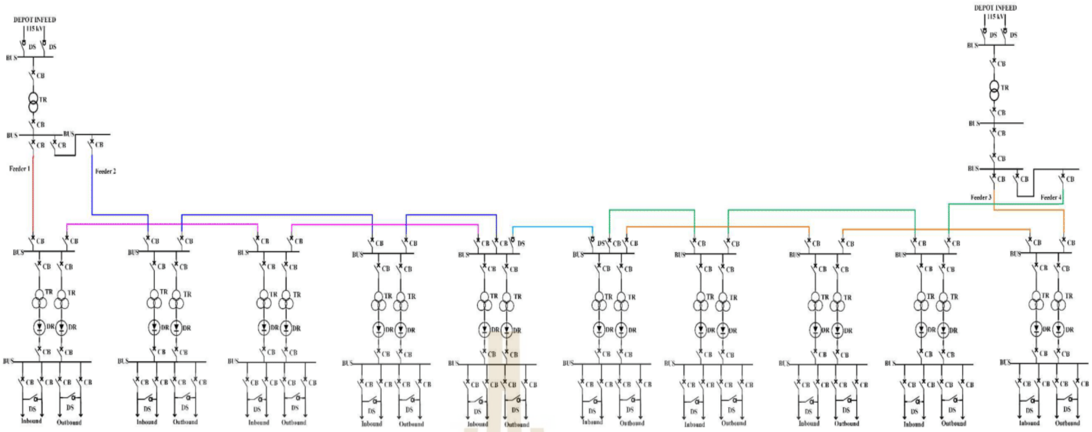

Fig. 4 Single line diagram of traction substation

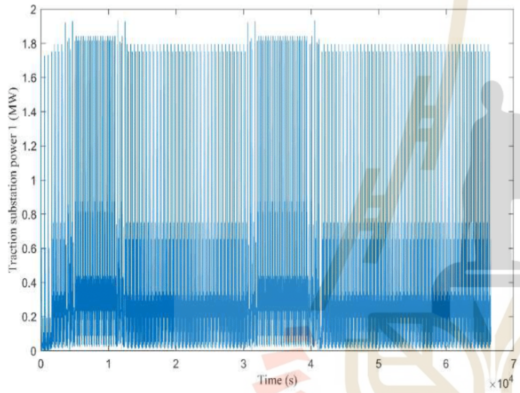

Fig. 5 Load curve of traction substation at Klong Bang Phai

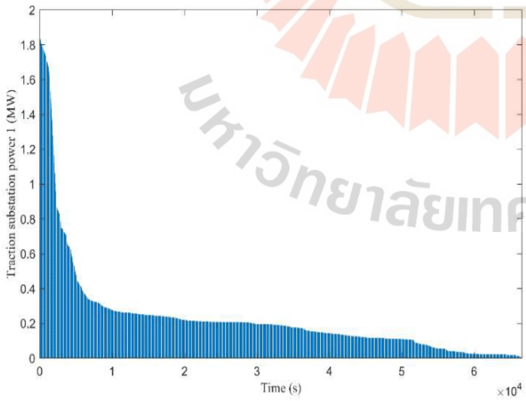

Fig. 6 Load duration curve of traction substation at Klong Bang Phai

3.2. Reliability calculation

Using the single traction substation for RBD method to calculate failure rate, MTTF, MTTR, availability, and unavailability, from Fig. 4 a single line diagram can be created an example (Klong Bang Phai) block diagram for RBD method shown in Fig 7. To calculate RBD of traction substation used component reliability data from literature [17, 23] shown in Table 4. Results of the reliability evaluation are shown in Table 5. According to the results, traction substations close to the distribution substation had a lower failure rate than those further away. Regarding the rate of repair, the results were comparable.

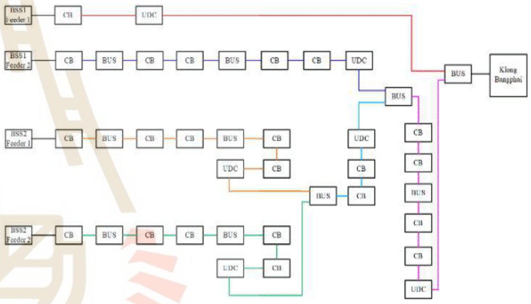

Fig. 7 Reliability block diagram of Klong Bangphai traction substation

Table 4. Component reliability data

Component	Failure rate (Time per year)	MTTR (hours)
DS	0.01	4
DR	0.0131	12.45
CB	0.01	12
TR	0.03	70
BUS	0.01	4
UDC	0.07 (per circuit miles)	10

The results in Table 5 are used to calculate the unavailability values from (15) and after that (16) is used to calculate the availability values for each traction substation shown in Table 6.

Assessing the reliability of the supply system requires load duration data obtained using multi train simulations and system availability data obtained from the reliability assessment Table 6, which results from the past procedure to be used to find the LOLE value from (20). The results for calculating the LOLE of each traction substation are shown in Table 7.

Table 5. Results of the reliability evaluation

Traction substation	Failure rate (Time per year)	MTTR (hours)	MTTF (hours)
Klong Bang Phai	0.169018	3.049660	51828.71
Talad Bang Yai	0.231219	3.033194	37886.13
Bang Yai	0.285618	2.984382	30670.33
Bang Rak Yai	0.338674	3.362090	25865.58
Sai Ma	0.319514	2.616763	27416.67
Yak Nonthaburi 1	0.333518	2.730568	26265.48
Nonthaburi Civic Center	0.353641	3.454195	24770.87
Yak Tiwanon	0.355466	3.028471	24643.71
Wong Sawang	0.254292	3.079250	34448.60
Bang Son	0.265803	2.731886	32956.76

Table 6. Availability and unavailability of traction substation

Traction substation	Availability	Unavailability
Klong Bang Phai	0.999941	0.000059
Talad Bang Yai	0.999920	0.000080
Bang Yai	0.999903	0.000097
Bang Rak Yai	0.999870	0.000130
Sai Ma	0.999905	0.000095
Yak Nonthaburi 1	0.999896	0.000104
Nonthaburi Civic Center	0.999861	0.000139
Yak Tiwanon	0.999877	0.000123
Wong Sawang	0.999911	0.000089
Bang Son	0.999917	0.000083

Table 7. LOLE of traction substation

Traction substation	LOLE (Second per day)	LOLE (Day per year)
Klong Bang Phai	3.918434	0.016554
Talad Bang Yai	5.331356	0.022523
Bang Yai	6.479622	0.027373
Bang Rak Yai	8.655281	0.036565
Sai Ma	6.355589	0.026849
Yak Nonthaburi 1	6.922758	0.029245
Nonthaburi Civic Center	9.285284	0.039226
Yak Tiwanon	8.183168	0.034570
Wong Sawang	5.952552	0.025147
Bang Son	5.520125	0.023320

The simulation results show that A traction power station with low-reliability results in a high LOLE value. For example, Yak Tiwanon station has the highest failure rate because it is far from the power distribution station. A high failure rate will result in a high LOLE calculation as well, but not the highest LOLE value because, in addition to the failure rate calculation, MTTR is also required. In the same case, the Nonthaburi Civic Center substation with similar failure rates but higher MTTR resulted in higher LOLE calculations than the Yak Tiwanon substation.

The North American Bulk-Power System uses the BAL-502-RF-03 standard based on the LOLE of 0.1 days/year as the reliability target [24]. When comparing the results of the LOLE evaluation of the MRT Purple line with the above standard It is clearly lower than the standard, which indicates that the power efficiency of the designed system is highly reliable. but the standard to be compared is the power system of a region not only the traction power supply. Therefore, it is wise to establish an agreement between the authorities for the mass rapid transit system in each region by reference to the pre-existing standards.

4. CONCLUSIONS

The results of this study indicate that RBD may be utilized to facilitate the dependability assessment of complicated systems. It is not difficult to comprehend the dependability of the traction substation in each area as it is depicted in the form of a block diagram that demonstrates the connection of each component as a single line diagram, with the purpose of enhancing and planning for greater dependability. This not only makes it easier to prepare before beginning a project to evaluate the dependability of the system, but it also makes the whole reliability evaluation simpler. For the purpose of determining COPT, LOLP, and LOLE, the dependability evaluation of the power supply system is applied to traction power substations. The results of the computation indicate that the total tensile substation for LOLE is superior to the standard BAL-502-RF-03. The relevant authorities in each nation will decide whether or not to accept the findings of using this standard. This will determine whether the results will be accepted. The conclusions of this study provide a framework for assessing the degree of dependability inherent in the nation's forthcoming endeavors.

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BIOGHAPHY

Aekkasit Kingmaneerat received his Bachelor of Engineering in Electrical Engineering (Second Class Honors) from Suranaree University of Technology (SUT), Thailand, in 2020. I am currently a graduate student in a Master of Engineering in Electrical Engineering at Suranaree University of Technology (SUT). I am also working as a teaching assistant and research assistant at the School of Electrical Engineering, Institute of Engineering, Suranaree University of Technology. My research interests currently focus on power system analysis, power system reliability, RAMs analysis, railway electrification, electric vehicle, and related fields.

When I was studying for my bachelor's degree at Suranaree University of Technology, I interned at Robert Bosch Automotive (Thailand) Co., Ltd. I have experience in the manufacturing process of ABS brake pump.

After I graduated with a bachelor's degree, I immediately studied for a master's degree at Suranaree University of Technology. I am so proud of my teacher assistant position duty to teach laboratory for students. I also accepted the paper and participated in 2021 International Conference on Power, Energy and Innovations (ICPEI 2021), and accept journal in GMSARN International Journal about reliability research of traction substations for mass rapid transit.

Moreover, I have experience with Intercity electric bus pilot project consulting assistance for Korat Electric City. Assigned responsibilities include supervising the installation of 320 kW electric vehicle charging stations, collecting the results of discharge and charging tests of electric vehicles, and preparing a summary report.