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-term rail transportation for passengers grows year after year.

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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:

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

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

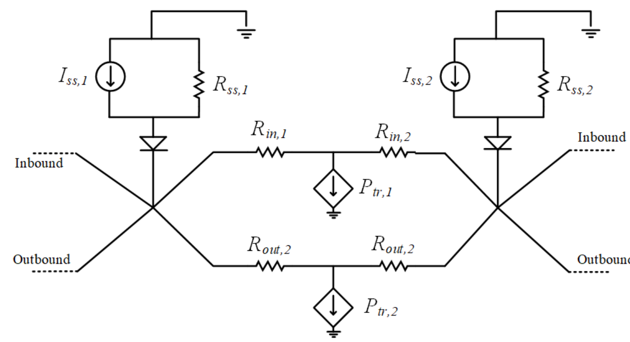

Fig. 1. The equivalent circuit of DC traction power supply.

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).

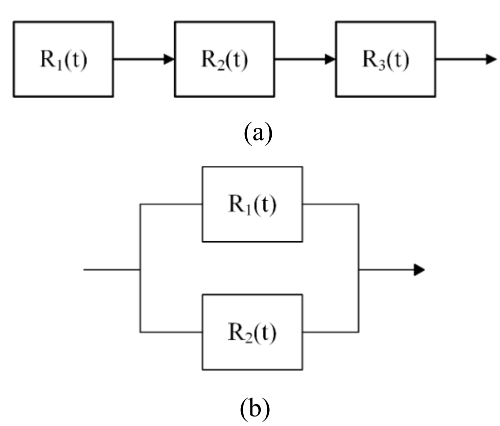

Fig. 2 (a) series connected blocks (b) parallel connected blocks.

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, λ_1, λ_2, λ_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).

$$\begin{aligned} R(t)_{system} &= 1 - (Q(t)_1 Q(t)_2) \\ &= 1 - ((1 - R(t)_1)(1 - R(t)_2)) \\ R(t)_{system} &= R(t)_1 + R(t)_2 - (R(t)_1 R(t)_2) \end{aligned} \tag{10}$$

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

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:

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

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

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].

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

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.

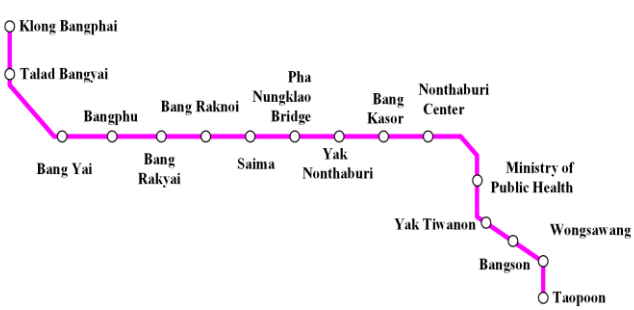

Fig. 3. MRT Purple line service route.

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	-

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	-

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.

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.

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
3^{rd} Rail resistance	0.007	Ω/km

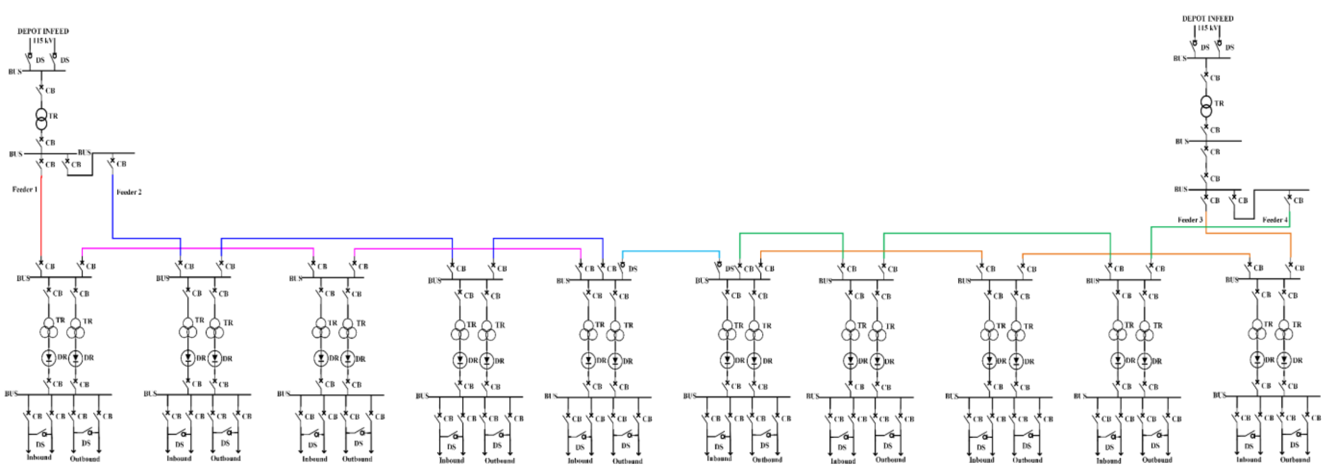

Fig. 4 Single line diagram of traction substation.

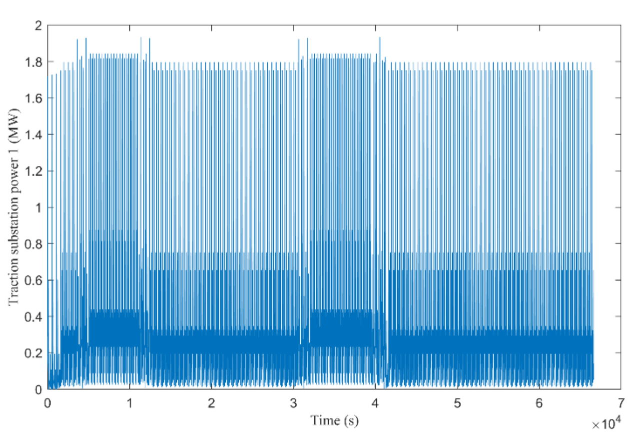

Fig. 5 Load curve of traction substation at Klong Bang Phai.

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.

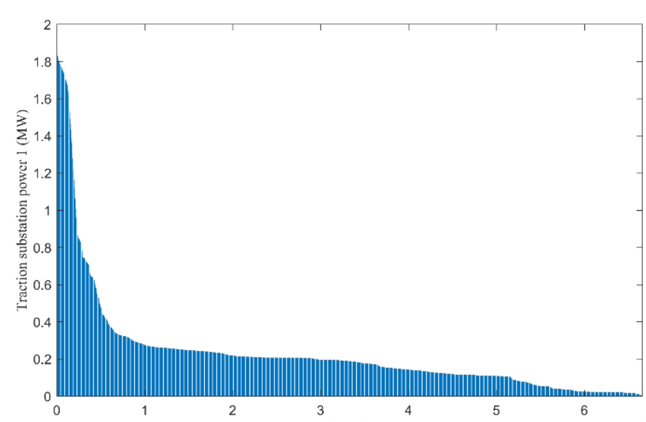

Fig. 6 Load duration curve of traction substation at Klong Bang Phai.

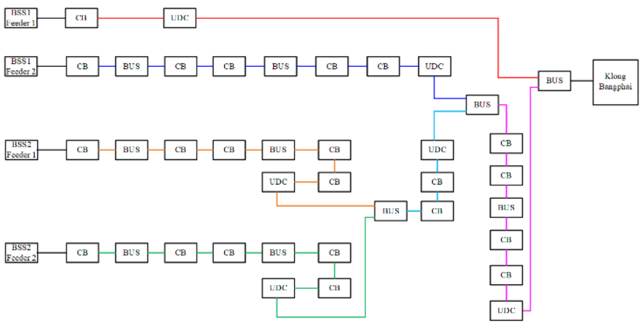

Fig. 7 Reliability block diagram of Klong Bangphai traction substation.

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

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

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.

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 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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