Reliability and life evaluation of a DC traction power supply system considering load characteristics

Yilin Chen, Zhongbei Tian, Clive Roberts, Stuart Hillmansen, Minwu Chen

***Abstract*—The traction power supply system is one of the most important parts of a railway system, which is responsible for providing electricity to power the running trains and other operating equipment. The performance of the power supply has a profound impact on the railway system. Therefore, it is necessary to conduct research on the reliability of the power supply system considering traction load and ensure it is highly reliable. This paper introduces some reliability-related indexes based on the Fault Tree Analysis (FTA) method and proposes a method to evaluate the system reliability of a DC-electrified railway. The effect of traction load on power supply system reliability is studied based on IEEE standards. A dynamic reliability and life evaluation model is built up to evaluate the reliability of traction substation and to develop a plan to reduce the operational risk of the power system. Through analysis of a practical example of the Singapore East West line, the system reliability and remaining useful life of each traction substation are obtained. The outcome from this study provides guidance for the maintenance and future operation plan of the power system.**

***Index Terms*—DC power supply; Fault Tree Analysis (FTA); Reliability evaluation; Traction load; Traction power supply system (TPSS)**

I. Introduction

DC traction power systems play an important role in the reliable operation of urban railways. Outage of the power supply will not only cause transportation paralysis, but also cause serious economic losses. It is necessary to conduct research on DC traction power supply system fault analysis and to evaluate the power supply system reliability.

The issue of reliability engineering dates back to around 1920. During this period, the concepts of reliability were first proposed [1]. After 10 years of research, people gradually learned about reliability issues. Then, around 1940, reliability issues were included in engineering disciplines, and they were developed from the losses caused by the unreliability of products [2]. In 1957, the US Advisory Group on Reliability of Electronic Equipment (AGREE) issued a report in which they clearly pointed out the standard specifications and measurement methods for reliability [3]. From then on, reliability science gradually entered research fields. After nearly six decades of development, reliability science has been well developed, and it has gradually become a comprehensive discipline with a wide range of topics and applications [4], such as infrastructure designs [5], computer and communication systems, and rail transportation systems [6, 7].

Research on the reliability of traction power supply systems began in 2004. Sagareli published a typical paper at the annual meeting of ASME (American Society of Mechanical Engineers) and IEEE (Institute of Electronics Engineers) [8]. The paper first proposed the concept of reliability of traction power supply systems. The definition of the reliability of a traction power supply system is clearly stated in this article, but the paper does not give a method for evaluating the reliability. The paper also proposed the establishment of a power reliability organization similar to NERC (North American Electric Reliability Corporation) to ensure the development and improvement of North American power system reliability. The research on the reliability of traction power supply system is still in the initial stage of exploration. Its analysis method mainly relies on the reliability theory of power system, and combined with the characteristics of traction power supply system. There are a few reliability-related studies on electrified railways and their power systems. Most of the existing reliability studies focus on AC-electrified railways, but few focus on DC railway power supply systems. Wang developed an analytical simulation method to evaluate railway catenary systems using credibility theory [9]. Feng et al. applied Failure mode and effects analysis (FMEA) to high-speed railways for reliability evaluation considering relay protection [10], which provides guidance for the maintenance of high-speed railways. Chen et al. used the Fault Tree Analysis method to evaluate the power supply system in AC railways [11]. Ku & Cha used a Minimal Cut Sets Algorithm to assess the reliability of railway substations [12].

Much of the current literature on the reliability of traction power systems pays particular attention to the power grid and its components. Hayashiya evaluated the reliability of each component in a DC power supply system based on 10 years of metro operation data in Japan and conducted quantitative analysis on a redundant system configuration [13]. Li used an improved sequential Monte Carlo method to evaluate the system reliability of a metro traction substation, so as to determine the weakest links of the system [14]. These studies analyze the links and factors that affect the reliability of power supply systems from the perspective of power electronics and systems. Constant failure rate was adopted when conducting reliability assessment, which is not able to reflect the real-time operating conditions of the system. This is the deficiency of current reliability research on railway power supply system. In the process of daily operation, the traction load is affected by station, route, passenger flow and other aspects. Research [15] shows that an impulsive load will not only affect the normal operation of the main output substation, but also have a great impact on adjacent power plant units, reducing their service life

This paper has been partially supported by funding of Chengdu Guojia Electrical Engineering Co., Ltd (No. NEEC-2019-B04). (*Corresponding author: Zhongbei Tian.*)

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and level of quality. However, the current research on railway power system reliability has not taken into consideration of the real-time load. The impact of traction load and the actual operation of the trains on system reliability has not been considered when designing a DC railway power supply system. Previous studies of railway power supply networks usually focused on infrastructure design and capacity, rather than system operation. In many cases, due to the complexity and cost of power supply system equipment, it is impossible to carry out extensive upgrades. Under the condition that the power supply system has been built and the infrastructures are not changed, optimization of the traction load and operation schedules can be considered to maximize the reliability of the system. There is potential to study the influence of traction load on traction power supply systems for better system operations.

This paper presents an approach to evaluating the reliability and life of DC traction power supply systems, considering traction load characteristics. Based on the Fault Tree Analysis (FTA) method, a few reliability-related indexes are introduced to evaluate system reliability. A dynamic multi-train power simulator is developed to study the impact of traction load, which is able to reflect the real-time condition of the power system. The highlights of this paper are as follows:

- The FTA method is applied to the railway DC traction power supply system. The reliability of a typical 750 V DC power supply system is analyzed.
- A TPSS life evaluation model is developed to study the influence of traction load. In this model, the remaining life and failure rate of the device under the influence of dynamic load can be obtained, thus establishing a relationship with the reliability evaluation.
- A multi-train simulator is developed for system evaluation and operation plan decision-making. A case study of Singapore East-West metro line is presented to intuitively show the impact of traction load on TPSS reliability. The real-time operation conditions of TPSS is evaluated.

The paper is organized as follows: Section II studies the structure of a DC substation and its main components, as well as the failure mechanism of the substation. Section III illustrates a reliability evaluation example of a typical railway power supply system. On this basis, the impact of load characteristics on the reliability of the substation system is studied in Section IV and Section IV gives a case study. Section VI concludes.

II. Overview of DC Traction Power Supply System

A. *Schematic layout of a 750V DC substation*

In the UK's DC electrified railway system [16], the National Grid or Distribution Network Operator (DNO) first supplies AC high voltage (HV), typically 132, 66 or 33kV to the main substation, then the voltage is stepped down to a medium voltage of 33, 22 or 11kV. After that, the alternating current is stepped down and rectified to 1500 or 750V DC through the traction substation to supply power to the train. The train takes power via the pantograph or the third rail, and finally the current is fed back to the traction substation by the return line. The 750V level is most widely used for metro and urban rail transport. Fig. 1 shows the feeding arrangements and basic components of a typical 750V DC traction power supply system. The power supply system shown in Fig. 1 uses a dual redundant design for the traction power system. All of the electronics are doubled, and if one of the branches is disconnected from the fault and the other is turned on, the entire system can still be powered. Most of the current industrial designs use redundant system design. However, there is a problem with redundant systems. Compared with simple systems, the number of devices in a redundant system increases, and the installation and maintenance costs of the devices also increase.

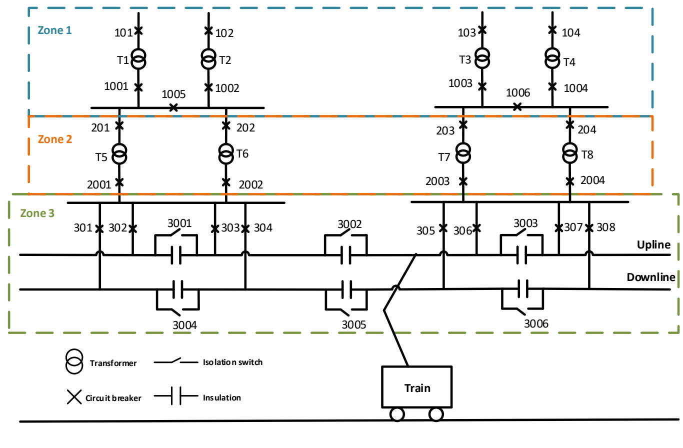


Fig. 1. Main electric wiring diagram of a DC traction power supply system

There are three main components in the whole power system, rectifier transformers, circuit breakers, and isolators. To simplify the evaluation model, the rectifier and transformer are considered as a whole, because rectifier transformers have been widely used in the modern railway industry. Each component is defined and labeled as the bottom event in the FTA, and its corresponding event code is shown in the following Table I. T1-T8 represent the rectifier transformers in the power supply system, 3001-3006 are the isolation switches, and the rest represent the circuit breakers.

TABLE I. Bottom Event and its Corresponding Event Code

Bottom event	Event code	Bottom event	Event code	Bottom event	Event code	Bottom event	Event code
T1	X1	103	X11	305	X21	2001	X31
T2	X2	104	X12	306	X22	2002	X32
T3	X3	201	X13	307	X23	2003	X33
T4	X4	202	X14	308	X24	2004	X34
T5	X5	203	X15	1001	X25	3001	X35
T6	X6	204	X16	1002	X26	3002	X36
T7	X7	301	X17	1003	X27	3003	X37
T8	X8	302	X18	1004	X28	3004	X38
101	X9	303	X19	1005	X29	3005	X39
102	X10	304	X20	1006	X30	3006	X40

Zone 1 is the high-voltage section which gets AC voltage from the National Grid. Zone 2 is called a traction substation, which is used to convert electrical power as supplied by the National Grid to a certain level for providing power to a rail system. Zone 3 connects to the catenary system. There are four core components in the traction substation system, transformers, rectifiers, circuit breakers, and isolators. All the components are in series and function together to enable the system to provide 750V DC power to the train, as shown in Fig. 2 [17, 18]. It is important to note and understand the major components shown in the diagram and to get an overview of how they work together for the entire system. Although the study focuses on a 750V DC traction system, it can be applied to various different installations where the same principles will be used.

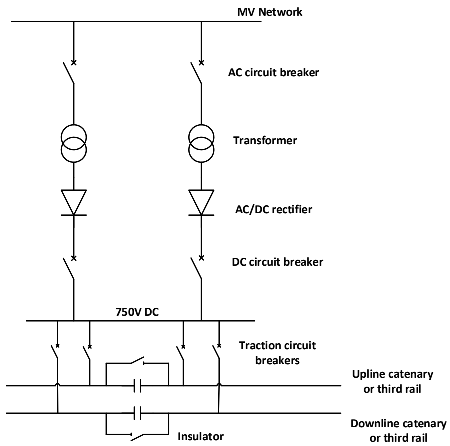


Fig. 2. Schematic layout of a typical DC traction substation

B. Electronic components fault mechanism

The Failure Mode and Effects Analysis, or FMEA, can be defined as "potential failure mode and consequence analysis". In the product design stage and process design stage, FMEA analyzes the various processes that constitute the product, the parts, and the process of the composition, finds out all the potential failure modes, and analyzes the possible consequences, to determine the pre-requisites to improve the quality and reliability of the product. It is important to understand the function of the major components of a traction substation and their fault mechanisms. Table II shows Failure Mode and Effects Analysis (FMEA) summarized from IEEE standards and some papers [19-21].

To summarize, most transformer failures are related to the deterioration of insulation. Most rectifier failures are caused by faulty diodes or faulty circuits. Human error and the external environment such as weather are a big factor in causing failures, which is sometimes inevitable. Note that it is not always possible to completely prevent damage, but the ultimate goal is to have as much control as possible and minimize the risk of failure with existing conditions. In the following sections, the failure mechanism of important components in the substation will be analyzed based on the existing IEEE standards, and the main factors affecting the fault will be obtained.

III. Importance Analysis using Fault Tree

At present, the method of assessing the reliability of traction power supply systems in academia is not perfect. In order to adapt to the development of railway power supply systems, new quantitative evaluation methods and evaluation models should be explored. H. A. Watson at Bell Laboratories first developed the concept of Fault Tree Analysis to evaluate a control system [22]. FTA has since become a comprehensive evaluation method with a wide range of topics and applications [23-25]. It draws a fault tree diagram to determine the various combinations of product failure causes and the probability of their occurrence. In this research, a reliability-related method is introduced and applied to the railway system to identify the factors affecting the reliability of the substation power supply system for fault diagnosis and maintenance. The weakest links of the power system will be determined.

A. FTA modeling

Based on the existing literature using the more mature FTA as the theoretical basis, this paper analyzes the reliability of an electrified railway traction power supply system, the causes of system failure, and proposes measures to improve system reliability. Before analyzing the reliability of the system, two preconditions for the hypothesis are proposed based on the basic characteristics of the traction power supply system:

1. All the pieces of electric equipment involved in the power

TABLE II. Failure Mode and Effects of Major Components

Equipment	Failure modes	Cause	Effects of failure
Transformer (Stepping down the supply voltage to 750V)	Over-temperature	Overload or over-current due to fault in the system	Protection will cause supply to be switched off. If not, there will be major damage to the transformer.
	Short circuit	Isolation materials damaged	High current densities and a rapid increase in winding temperature.
	Open circuit	Loose connection, burnt windings	The fault will cause gas and heat to build up in the transformer. Protection circuit will switch off the supply.
	Low oil level	Leakage at gaskets	If protection circuit operates, the supply will be switched off. Otherwise the transformer will blow up.
Rectifier (AC input to DC output)	Over-temperature	Arcing inside rectifier, loose connection between diode and heat sink, cooling fans not working	Over-temperature protection should switch off the supply. If not, the rectifier may be damaged.
	Short circuit	Faulty diodes, circuit fault	Protection circuit should isolate the rectifier.
	Open circuit	One or more diodes not working, loose connections, circuit fault	No output from the rectifier.
Circuit breaker (Protection switch)	Not opening	Faulty opening relay, protection circuits not working properly	Substation may be damaged because circuit breaker does not open.
	Not closing	Faulty closing relay, protection circuits not working properly	No power supply.
	Current leakage to earth	Dirty porcelain or breakdown of isolating materials	Damage to the circuit breaker and possible trip of substation if leakage is detected by AC earth leakage.
	External damage	Vandalism, lightning, water	Current leakage and possible disintegration.
Isolator (To isolate the substation from supply)	Broken insulators	Vandalism, lightning, water in the base plates causing cracking	Isolator short-circuited.
	Opening mechanism failure	Rust, broken operating handle	No operation will be possible.

system can be statistically considered to be independent of each other during reliability analysis. The failure of one device has limited impact on other devices. To simplify the simulation analysis, the influence of devices on each other is not considered in this study.

2. All the pieces of electric equipment are considered as repairable components in the FTA.

1) Fault tree construction

In the FTA, the basic event is connected to one or more top events by logical symbols such as AND gates and OR gates [26]. Top events generally refer to undesired system failures or events that endanger the system. Bottom events usually refer to a component failure or a human's faulty operation.

The basic steps of the FTA method are as follows:

1. Define the system and system failures and determine the bottom events;

2. Build the fault tree model;

3. Conduct qualitative and quantitative analysis.

2) Reliability evaluation indexes

The reliability index is an important part of reliability theory. In order to quantitatively evaluate the reliability of the power system, four indexes are introduced in this paper:

1. Reliability R(t)

The probability that the system will perform the specified function under the specified conditions and within the specified time t is called the reliability of the system, and is defined as R(t)=P(T>t), t≥0. The reliability of a system at t is the probability that it experiences no failure during time interval [0,t]. Reliability is normally a function of time and can be calculated by the following formula:

$$R(T) = \mathrm{P}(\mathrm{T} > \mathrm{t}) = exp\left[-\int_0^T \lambda(t)dt\right] \quad (1)$$

Where $\lambda(t)$ is the system failure rate.

2. Failure rate/Occurrence $\lambda(t)$

The failure rate is the ratio of the number of components that fail per unit time to the total number of components. The relationship between failure rate and reliability is as follows:

$$\lambda(t) = -\frac{d}{dt}\ln R(t) \quad (2)$$

If the component failure rate obeys an exponential distribution, the reliability R(t) is:

$$R(t) = e^{-\lambda t} \quad (3)$$

3. Repair rate $\mu(t)$.

Repair rate is the probability that a component will be repaired in the next unit time after it has been in operation for a period of time, which is defined as $\mu(t)$.

4. Unavailability

The unavailability of a system at t is the probability that it is not working at t. The calculation formula can be expressed as:

$$Q(t) = qe^{-(\lambda+\mu)t} + \frac{\lambda}{\lambda+\mu}\left(1 - e^{-(\lambda+\mu)t}\right) \quad (4)$$

Average unavailability

$$Q_{Avg}(T) = \frac{1}{T}\int_0^T Q(t)dt \quad (5)$$

Where $\lambda(t)$ is the failure rate, and $\mu(t)$ is the repair rate.

3) Importance factors

Importance analysis is conducted to determine the weakest links/parts of the system from a quantitative point of view. The fault tree formula is used to calculate the probability importance of the bottom event for the top event. By comparing the magnitude of the probability importance, the weakest links can be obtained. Enhancing these weak links can improve system reliability. There are a few importance factors which help evaluate the system:

1. Marginal Importance Factor (MIF)

MIF is often called the Birnbaum Importance Factor. MIF represents the difference between the unavailability when event X occurs and the unavailability when event X does not occur. MIF gives the increase in risk associated with the occurrence of event X. The MIF is defined in (6), where $Q(t)$ is system unavailability, $q_x(t)$ is unavailability of event x, $Q(t)|q_{x=1}$ is unavailability with $q_x = 1$, $Q(t)|q_{x=0}$ is unavailability with $q_x = 0$.

$$MIF(t) = \frac{\partial Q(t)}{\partial q_x(t)} = Q(t)|q_{x=1} - Q(t)|q_{x=0} \quad (6)$$

2. Critical Importance Factor (CIF)

CIF is often called the Fussell-Vesely Importance. CIF indicates the risk associated with a given event, that is, how much occurrence of the event is contributing to system failure. CIF can be calculated using MIF and system unavailability $Q(t)$, as shown in (7).

$$CIF(t) = \frac{q_x(t)MIF(t)}{Q(t)} = \frac{Q(t) - Q(t)|q_{x=0}}{Q(t)} \quad (7)$$

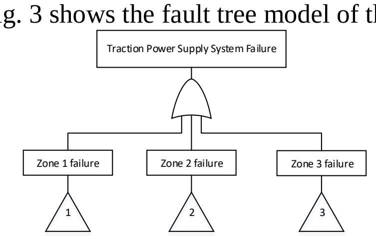
3. Risk Reduction Worth (RRW)

RRW represents the risk that would be reduced by reducing the unavailability of event X to zero. RRW is defined in (8).

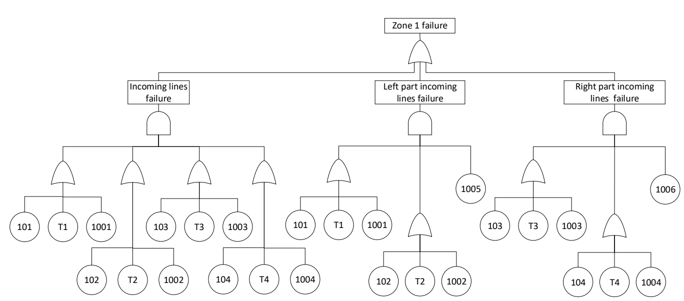
$$RRW(t) = \frac{Q(t)}{Q(t)|q_{x=0}} \quad (8)$$

B. DC power system analysis

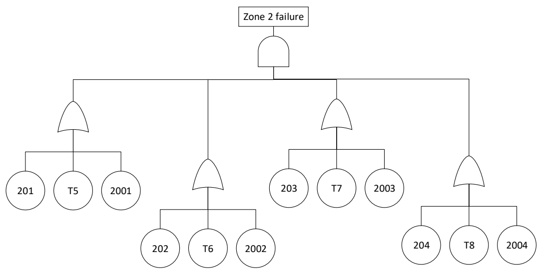
After understanding the structure and basic components of the traction substation, the failure events of the system are determined according to the operation mode of the traction substation. Fig. 3 shows the fault tree model of the system.



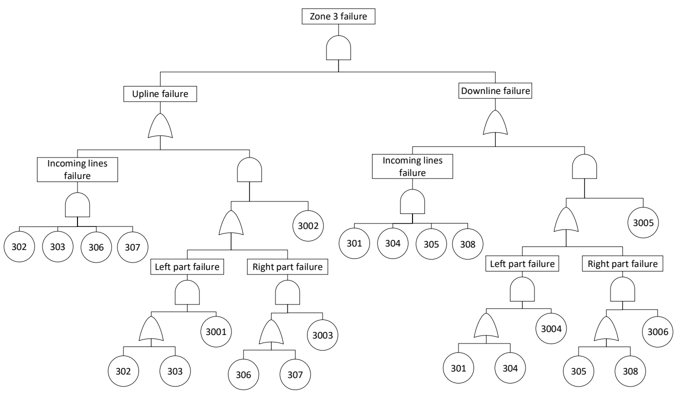
a) DC power system fault tree model



b) Zone 1 fault tree model



c) Zone 2 fault tree model



d) Zone 3 fault tree model

Fig. 3. Fault tree models of a DC traction power supply system

1) Qualitative analysis

Using FTA software and computational algorithms, the fault tree model of the traction substation is qualitatively analyzed to obtain the minimum cut sets. The minimal cut set number is 199, in which there are 12 second-order cut sets, 162 fourth-order cut sets, 16 sixth-order cut sets, 8 seventh-order cut sets, and 1 eighth-order cut set.

The probability of system failure in a cut-set event is inversely proportional to its order. That is, the lower the order of the minimum cut set, the easier it is for the corresponding event to fail the system, so the more important the cut set. It can be summarized from the minimum cut set result obtained that the second-order minimum cut sets {X1, X29}, {X2, X29}, {X3, X30}, {X4, X30}, {X9, X29}, {X10, X29}, {X11, X30}, {X12, X30},that is, the transformers T1, T2, T3, T4, circuit breakers 101, 102, 103, 104, 1005 and 1006 have the greatest influence on the reliability of the system. From a system perspective, it is necessary to avoid problems with the equipment included in the low-order minimum cut set to ensure that the system can function properly. In the actual system design, highly reliable circuit breakers should be used at 1005 and 1006 to minimize the occurrence of minimum cut set events. Transformers T1, T2, T3, T4 are also the weakest links of the power system, which should be enhanced.

2) Quantitative analysis

The devices reliability parameters were tested on a traction substation of Beijing-Shanghai HSR in China using FTA and FMEA method [10, 11]. This study employs the empirical reliability parameters of the electrical components from the field tests in [10, 11] as listed in Table III. The failure rate of each component is a time-related function. These data are used for fault tree simulation and reliability evaluation.

TABLE III. RELIABILITY PARAMETERS OF RELEVANT EQUIPMENT AS REPAIRABLE COMPONENTS

Equipment	**Failure rate**	**Repair rate**
Transformer	$\lambda(t) = (\frac{16.6}{167.25^{16.6}}) \cdot t^{15.6}$	$\mu(t) = 5.15 \times 10^{-2}$
Circuit breaker	$\lambda(t) = (\frac{7.75}{178.67^{7.75}}) \cdot t^{6.75}$	$\mu(t) = 0.10$
Isolator	$\lambda(t) = (\frac{10.88}{175.98^{10.88}}) \cdot t^{9.88}$	$\mu(t) = 0.25$

In the FTA simulation, an assessment of the reliability and unavailability of the substation for 10 years was carried out. As the failure rates of electrical components increase with time, the reliability of the whole system decreases year by year. Fig. 4 depicts the probability of the top events over time, which are the system unavailability and reliability over time (years). After 10 years of operation of the power supply system, its system reliability is 0.962115, and its unavailability is 0.000981057.

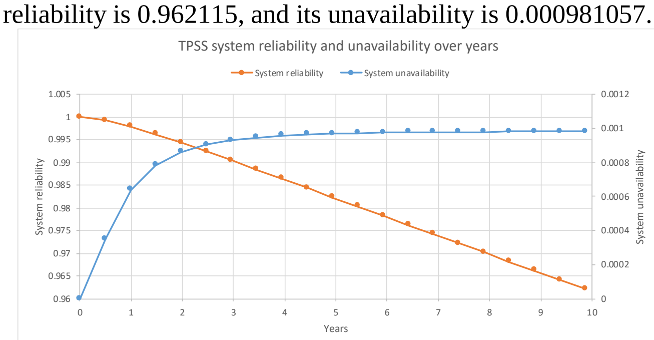


Fig. 4. Traction power supply system reliability and unavailability over time

3) Importance factors analysis

From the fault tree software and the calculation formulas listed in Section II, the importance indicators of each component to system failure are calculated, shown in Table IV.

TABLE IV. IMPORTANCE FACTOR RESULTS OF RELEVANT COMPONENTS

Bottom events	Unavai lability	Marginal Importance	Critical Importance	Risk Reduction Worth
X29, X30	0.0056	0.0869	0.4959	1.9837
X1, X2, X3, X4	0.0287	0.0534	0.1563	1.3852
X9, X10, X11, X12	0.0107	0.0053	0.0573	1.0025
X25, X27, X28, X26	0.0056	0.0052	0.0298	1.0608
X13, X14, X15, X16	0.0287	8.65E-05	0.0025	1.0307
X18, X19, X22, X23, X17, X20, X21, X24	0.0287	2.28E-10	6.66E-09	1.0000
X5, X6, X7, X8	0.0107	8.49E-05	9.27E-04	1.0009
X31, X32, X33, X34	0.0056	8.45E-05	4.81E-04	1.0005
X36, X39	0.0056	2.67E-09	1.52E-08	1.0000
X35, X37, X38, X40	0.0056	1.33E-09	7.91E-09	1.0000

It can be seen from the simulation results that bottom events X29, X30, X1, X2, X3 and X4 are of most importance to the system. They have the greatest impact on the reliability of the traction power supply system. Fig. 5 lists the Marginal and Critical Importance of major components, sorted by the degree of importance. X29 and X30 have the largest Risk Reduction

Worth numerical value for RRW of 1.9837. If the probability of failure of the bottom events X29 and X30 is reduced, the probability of occurrence of the top event can be quickly reduced, that is, the probability of failure of the traction power supply system, which is more effective than reducing the probability of occurrence of any other bottom events by the same value.

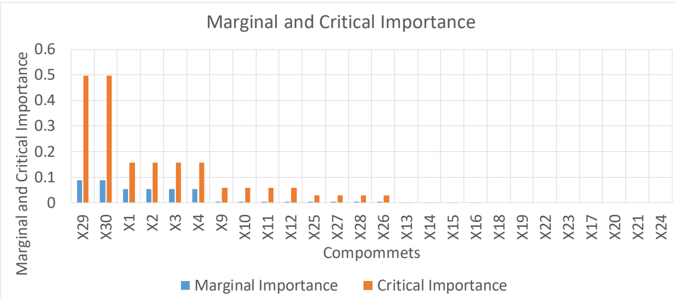


Fig. 5. Order of Marginal and Critical Importance of major components in the DC traction power supply system

Through quantitative analysis of the traction power supply system (TPSS), it can be seen that the results are consistent with the analysis results of the minimum cut set of the qualitative analysis. To ensure a highly reliable system, the key components should be monitored and should be repaired and replaced in time.

IV. TPSS Life Evaluation

A. Life of components

There are four major components in a TPSS system, transformers, rectifiers, circuit breakers and isolators. In this section, the failure mechanisms of these major components will be described separately, and the reliability model of the traction substation will be derived.

1) Transformers (IEEE Std C57.91-2011 [20])

The transformer is one of the key pieces of equipment for the normal operation of a traction power system. The load capacity of an oil-immersed transformer is closely related to its top-oil temperature and hot spot temperature. There are several factors affecting the transformer's overall life expectancy and overload capability, however the hottest-spot temperature is the most critical parameter for determining the transformer's life expectancy. A higher winding hot-spot temperature will cause degradation of the winding insulation and increase the potential for transformer failure. An inordinate temperature rise in an oil-immersed transformer is featured by hot-spot temperature. It is an important parameter to determine the optimum load ability of a transformer.

IEEE C57.91-2011 [20] presents a commonly used thermal model (Clause 7) for calculating the transformer hot-spot temperature and top oil temperature. The specific formulas are not detailed in this paper. For details, please refer to the IEEE standard and other related papers [27-29]. The theoretical basis of the model is that an increase in the loading current of the transformer will result in transformer losses and then cause an overall temperature rise. The mechanism of hot-spot temperature change can be explained by formula (9), which has been verified by IEEE C57.91-2011 standard [20].

$$T_{HS} = T_A + \Delta T_{TO} + T_G \tag{9}$$

Where, T_A is the ambient temperature, ΔT_{TO} is the top-oil temperature rise over the ambient temperature, T_G is the winding hottest-spot temperature rise over top-oil temperature.

2) Diode rectifiers (IEEE P1653.2-2009 [19])

A traction rectifier is used to convert AC power to DC power. A controlled rectifier means that the DC output voltage can be controlled or adjusted in value based on demand, whereas an uncontrolled rectifier will produce a fixed DC output. Traction rectifiers are either 6, 12 or 24 pulse. The six-phase full-wave uncontrolled diode rectifier is the basic design on most 750V DC traction substations.

The standard rating of a rectifier unit for heavy traction service is as follows [19]: one hundred percent rated load amperes continuously until constant temperatures have been reached by all parts of the rectifier unit, followed by either 1) 150% current for 2 h, or 2) 300% current for 1 min. Most modern rectifiers have been designed with proper circuits to indicate the condition of the diodes, protect the rectifier against over-temperature and monitor the cooling fan.

The diode can withstand short periods of overload. After returning to the normal load after overloading, the temperature and leakage current of the diode will return to the normal values, so it will not have a great impact on its life. Studying the effect of dynamic load-time characteristics on diode life does not make much sense, as it has little influence on diode failure.

3) Circuit breakers (IEEE Std C37.14 [21])

The circuit breakers form a very important part of the protection circuits in the substation. They will switch off the supply when a fault occurs inside the substation. The circuit breaker tripping mechanism is operated by protection relays which protect the substation from overloading and high fault currents.

The Consumer Product Safety Commission (CPSC) estimates the life expectancy of a circuit breaker to be around 30 to 40 years. Short circuits, power surges and spikes are the main cause of circuit breaker failure. Circuit breakers are not used frequently under the normal operating conditions of a substation. Under normal operating conditions, the reliability and life of the circuit breaker have little to do with the load. Therefore, in this study, the impact of dynamic load on the circuit breaker is ignored.

4) Isolators

Isolator switches, also called disconnectors, in particular, are used in power grids and substations to isolate very high voltage apparatus such as transformers and circuit breakers when they are due for maintenance or when there is a fault. When a fault occurs, the isolator will cut out a portion of the substation.

B. Loss-of-life calculation

1) Loss of life

The Acceleration Aging Factor F_{aa} (also called the Accelerated Aging Rate or Acceleration Factor) is defined as the ratio of the real-world lifetime to the test duration. The higher the F_{aa} , the less reliable the test is. In the IEEE C57.91-2011 guide, the relationship between the Acceleration Aging Factor F_{aa} and the hot-spot temperature θ_h is presented as:

$$F_{aa} = e^{\frac{15000}{110+273}-\frac{15000}{\theta_h+273}} \quad (10)$$

This equation is an adaption of the Arrhenius reaction rate theory. It indicates that the aging of the transformer is a function of hot-spot temperature because of the load current. F_{aa} is a per-unit quantity for a reference temperature of 110°C.

The equivalent aging factor (F_{eqa}) of the transformer with respect to the reference temperature 110°C over a given period of time (T) is calculated as:

$$F_{eqa} = \frac{\int_{t=0}^{t=T} F_{aa}dt}{T} \quad (11)$$

The loss-of-life percentage is the ratio of the loss-of-life over a period of time T and its normal insulation life, as shown in (12). Normal insulation life is generally an empirical fixed value, which could be found in the device user manual.

$$Loss\ of\ Life\ \% = \frac{F_{eqa} \times T}{Normal\ Insulation\ Life} \times 100 \quad (12)$$

The remaining useful life (RUL) is an estimate of the number of years remaining for a component or system to operate without failure before replacement. In this study, the system's remaining useful life can be calculated as:

$$RUL = Normal\ Insulation\ Life - (F_{eqa} \times T) \quad (13)$$

2) Failure rate

According to the definition of conditional probability, the probability of failure during time interval Δt after T equivalent operation time can be calculated:

$$\lambda(t) = P(T \le t \le T + \Delta t \mid t > T, \theta_0)$$
$$= \frac{F_{eqa}(T + \Delta t|\theta_0) - F_{eqa}(T|\theta_0)}{1 - F_{eqa}(T|\theta_0)} \quad (14)$$

Where θ_0 is the hot-spot temperature at time t. Here, the failure rate is a function related to time and temperature, rather than an empirical fixed value.

V. TPSS Reliability and Life Evaluation Considering Load Characteristics

A. Simulation structure

Different to the substation in a general power system, the TPSS has a single load, and the impact on the traction transformer is very large, while the load of a general power system is mostly industrial or household load, and the transformer is relatively more stable. After understanding the operating modes and failure modes of the main components, the load-time characteristics of a DC traction substation can be determined by Matlab simulation. According to the fault mechanism of the rectifier and isolator, only transient high currents can damage the life of the rectifier and isolator. In general, during normal operation, the current does not exceed the maximum allowable threshold of the rectifier and isolator. The load current-time characteristics have a greater impact on the life of the transformer than the other components. The influence of instant load on the rectifier and isolators can be ignored. Therefore, this research focuses on the impact of load characteristics on the traction transformer.

A dynamic model of single train simulation and power supply system was established in Matlab to study the influence of traction load. The simulator was developed for the use of railway energy evaluation [30-33]. It is based on a discrete time operation at which the power and energy consumption are calculated over 0.1s time period. The train route is divided into segments with equal length to calculate the dynamic parameters at different locations. In this study, the purpose is to explore the impact of traction load on the power system reliability, and whether there is a way to maximize system reliability without affecting the normal operation of the power supply system. The proposed simulation framework is shown in Fig.6. The dynamic inputs are train driving strategies and timetables, the outputs are reliability-related system reliability and remaining useful life.

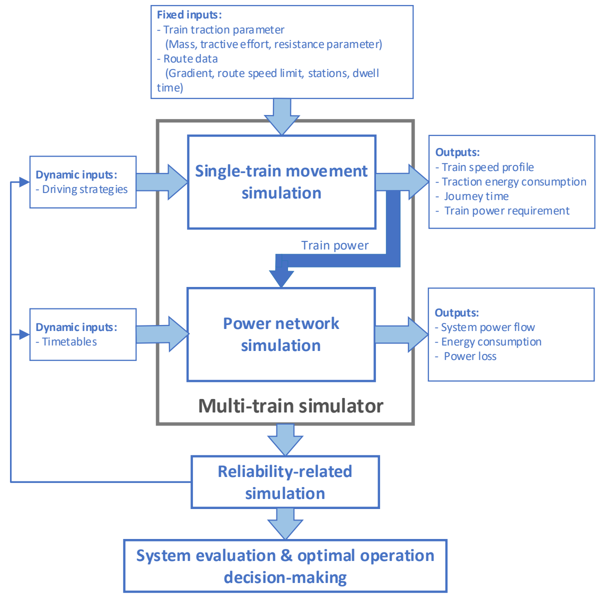


Fig. 6. Diagram of the overall simulation structure

B. Load parameters and timetable

In this paper, the Singapore East West line is used as a simulation example. It is a high-capacity metro line operated by SMRT, which is 49.46km in length with 27 substations, 8 tie stations and 2 stations without a DC-link connection. Fig. 7 shows the Singapore line's altitude and TPSS locations.

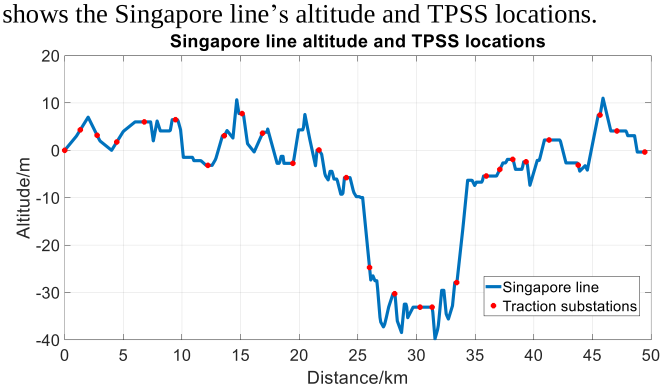


Fig. 7. Line altitude and station locations of the Singapore line

C. Results and analysis

The normal lifespan of a distribution transformer is 20.55 years, which is 180,000 h. Suppose the power system is at its first day of operation. The rated power of the TPSS is 4MW. The ambient temperature is held constant at 25°C. A full day's timetable is adopted in this simulation. For more accurate results, the simulation runs every 120s and repeats to reach a full day's timetable.

1） Scenario 1 (No. 1 TPSS)

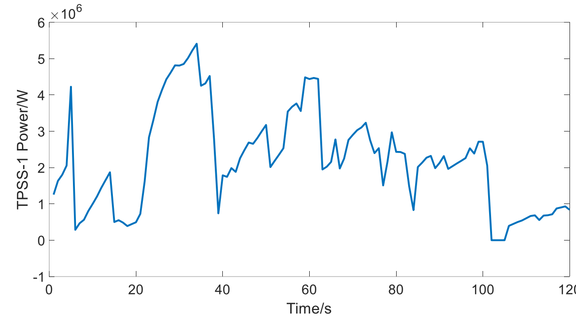


Fig. 8. No. 1 TPSS power vs. time

A distribution of power usage for traction substation Tuas Link (No. 1 TPSS) is shown in Fig. 8. These data are for a single train journey of 120s and show the amount of power that is drawn from the substation. There is a peak between 20 s and 40 s where the load is higher. The power system experiences an overload for a short period of time. The hot-spot temperature of the traction transformer changes with time, as shown in Fig. 9.

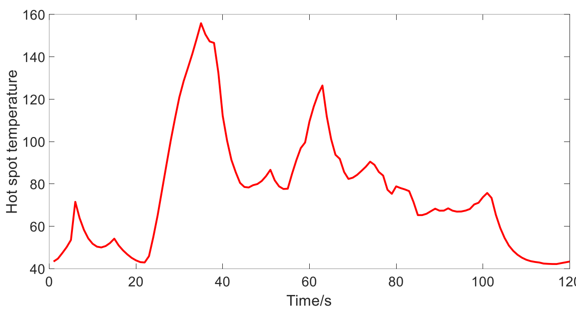


Fig. 9. No. 1 TPSS hot-spot temperature vs. time

At the maximum load of the substation, between 30 s and 40 s, the Aging Acceleration Factor of the transformer is highest, meaning that the system is most likely to fail at this point of time.

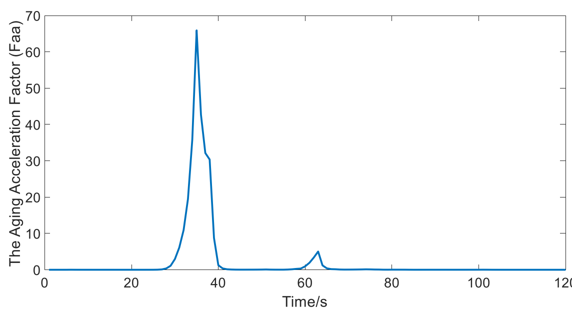


Fig. 10. No.1 TPSS Faa vs. time

Fig.11 shows the loss-of-life percentage over given periods of time compared to the system's normal life. From the simulation results, it can be seen that the total loss of life over a single run of 120 s (2 min) is 5.2156× 10^{-6} years, which is equivalent to 0.0457 h (2.74 min).

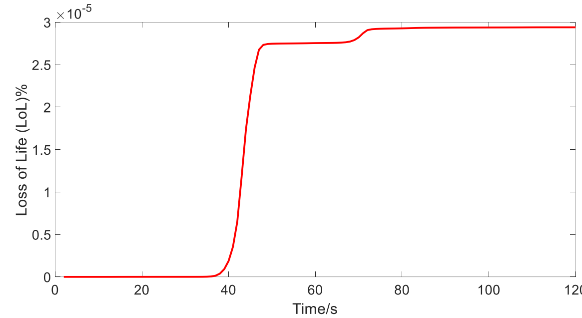


Fig. 11. No. 1 TPSS loss-of-life vs. time

2） Scenario 2 (No. 7 TPSS)

Under the premise that the entire metro line runs on the same schedule, the reliability and life loss of different substations are different due to the different output power and load cycle of each substation. Scenario 2 gives the simulation results from traction substation Lakeside (No. 7 TPSS), in which the system is under normal operation and experiences no overload.

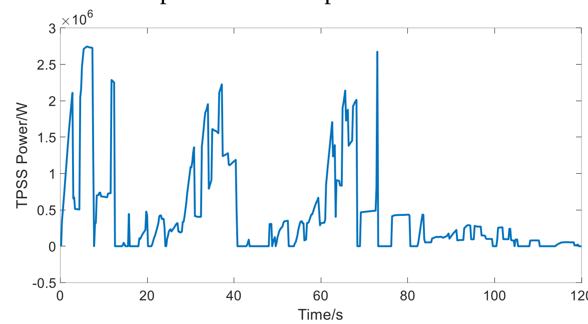


Fig. 12. No.7 TPSS power vs. time

The Aging Acceleration Factor, as shown in Fig. 13, is less than 1 when the hot-spot temperature is lower than 110 °C, meaning there is little loss of life.

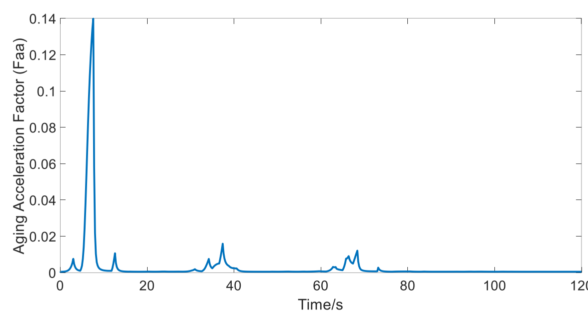


Fig. 13. No. 7 TPSS Faa vs. time

In this case, the total loss of life over a single run of 120 s (2 min) is 3.5× 10^{-6} years, which is equivalent to 0.03066 h (1.839 min). Compared to scenario 1, in which the loads are slightly over the rated power, the total loss of life of the system in this simulation is very small. There will be a slight extension of lifespan compared to its normal life under rated power operation. It can be seen that operating below the rated load of the transformer has a negligible impact on its life and reliability; overloading has a great influence on the system, which will reduce the life of the transformer.

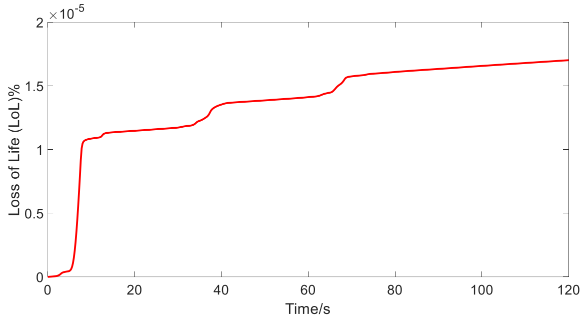


Fig. 14. No. 7 TPSS Loss of Life vs. time

3）Scenario 3 – Full year operation

The daily average failure rate and reliability of each TPSS are predicted using the reliability evaluation indexes listed in Section III. The remaining useful life of the substations is also calculated, as illustrated in Table V. According to the simulation data listed, under the condition that the same timetable is operated on the whole line for 1 year, the third substation Tuas Crescent will bear the largest load, and the estimated remaining service life is 14.215 years, which is much shorter than for other substations. Based on the FTA results in Section III, the simulation results can more accurately reflect the real-time operation conditions of TPSS. When developing a maintenance and replacement plan, emphasis should be placed on this substation. It can be concluded that due to the influence of dynamic traction load, each substation on the same line has different life effects. Predictive maintenance could be carried out when necessary.

In this way, running a 24 h timetable and analyzing the simulation results, we can find out which time slot for each TPSS is the most risky and which substation is most likely to fail. During this time period, it is important to monitor substations that have the highest risk of failure. If the utilization rate and reliability of the current power supply system can be improved, it can not only save the operation cost for railway utilities, but also optimize the allocation of power resources and make contributions to energy conservation. Theoretically, by optimizing the timetable and train running diagram, the impact of the traction load on the system can be reduced without compromising energy consumption and travel time. It can also provide guidance for future power supply system design and optimal operation of the system once it is built.

TABLE V. SUBSTATION DATA FOR EAST WEST LINE

Platform	Maximum Faa	Failure rate	Average reliability	Remaining useful life (years)
Tuas Link	65.91	4.15×10^{-3}	0.995	14.599
Tuas West Road	3.75	5.39×10^{-4}	0.999	19.312
Tuas Crescent	67.84	4.32×10^{-3}	0.995	14.215
Gul Circle	55.58	9.89×10^{-4}	0.997	16.943
Joo Koon station	25.36	7.34×10^{-4}	0.997	17.874
Pioneer Station	24.54	7.29×10^{-4}	0.998	17.925
Lakeside	0.14	8.36×10^{-5}	0.999	21.754
Chinese Garden	1.59	5.30×10^{-4}	0.999	19.578
Jurong East	0.87	7.48×10^{-5}	0.999	20.146
Sungei Uiu Pandan Online	20.42	4.46×10^{-4}	0.998	19.024
Commonwealth	34.87	6.65×10^{-4}	0.998	18.344
Buona Vista	55.36	8.87×10^{-4}	0.997	17.036
Queenstown	49.87	8.25×10^{-4}	0.997	17.874
Delta Online	44.69	8.17×10^{-4}	0.997	17.364
Outram Park	50.74	8.32×10^{-4}	0.997	17.567
Raffles Place	20.15	4.67×10^{-4}	0.998	19.176
City Hall	10.81	6.47×10^{-4}	0.998	18.674
Lavender	25.87	1.25×10^{-3}	0.997	16.368
Aljunied	14.35	7.02×10^{-4}	0.998	18.341
Paya Lebar	10.69	5.27×10^{-4}	0.999	19.394
Eunos	29.36	7.75×10^{-4}	0.998	17.964
Kembangan	28.65	6.83×10^{-4}	0.998	18.156
Bedok	44.58	8.06×10^{-4}	0.998	17.440
Sungei Bedok Online	30.58	6.19×10^{-4}	0.998	18.343
Simei	1.87	3.65×10^{-4}	0.999	19.890
Tampines	0.56	8.04×10^{-5}	0.999	20.694
Pasir Ris	0.19	8.96×10^{-5}	0.999	21.866

VI. CONCLUSION

This paper proposes a method to investigate the influence of traction load on TPSS reliability and life. A comprehensive evaluation and simulation model of a DC traction power system is proposed. In this paper, the reliability of a typical 750 V DC traction power supply system is evaluated by using fault tree model and a series of reliability indices. According to the fault mechanism of the electrical components, the thermal model of transformer and simulation model of traction load are established. The model is used for evaluating the railway power system and for optimal operational plan decision-making. The impact of traction load on system reliability is clearly shown. The weakest links and time slot of the system is found. Through the actual case analysis of Singapore metro line, it is found that although the same timetable is operated on the same line, the impact of dynamic load on substation life is different. Overload will reduce the life span of devices of traction substation. Due to the large random fluctuation and non-linear characteristics of traction load, the change of load will have a certain impact on the reliability of the system and equipment.

This experimental method can be used for simulation verification when designing a new power supply system. The developed simulator can be used to verify whether the location and sizing of the traction substations are reasonable. Similarly, this method can be used to upgrade the existing power supply systems and the capacity of substations to cope with overload. If the utilization rate and reliability of the current power supply system can be improved, it can not only save the operation cost for railway utilities, but also optimize the allocation of power resources. The study of TPSS reliability considering load characteristics provides a way to pre-diagnose a system and make predictions. It can help determine when to maintain or replace certain components based on present load, future growth and ambient operation conditions.

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