

**ADDIS ABABA UNIVERSITY**  
**ADDIS ABABA INSTITUTE OF TECHNOLOGY**  
**AFRICAN RAILWAY CENTER OF EXCELLENCE**



**RELIABILITY ANALYSIS OF ADDIS ABABA LIGHT RAIL TRANSIT TRACTION**  
**POWER SUPPLY SYSTEM**

**A Thesis in Electrical Engineering for Railway Systems**

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A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Master of  
Science

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## ABSTRACT

High reliability of railway power systems is one of the essential criteria to ensure quality and cost-effectiveness of railway services. Reliability analysis of traction power supply system (TPSS) is essential for identifying reliability critical components, which causes most of the disruptions, and providing necessary mitigation techniques.

The service quality of Addis Ababa Light Rail Transit Service (AALRTS) has repeatedly been affected by the TPSS component failures that results in part routing, passenger clearing and more severely operation interruption. Thus, analysis and improvement of AALRT TPSS reliability is definitely an important and urgent issue.

The main objective of this thesis is conducting the qualitative and quantitative reliability analysis of AALRT TPSS. Fault mode and effect analysis (FMEA) and fault tree analysis (FTA) accompanied by exponential distribution are selected to model the system and evaluate the reliability indices. The reliability evaluation indexes of AALRT TPSS are then calculated via MATLAB code by applying the exponential distribution equations.

Accordingly, the reliability analysis showed that AALRT TPSS had poor reliability in the mission time of about three years. Hence, reliability mitigation techniques, such as fostering well trained personnel, applying various maintenance approaches, procuring and localizing high quality components, and introducing standby power systems, to improve the poor reliable traction power supply system operation, are suggested.

**Key Words:** traction power supply, failure mode and effect analysis, fault tree analysis, exponential distribution, reliability analysis.

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## TABLE OF CONTENTS

<b>ABSTRACT</b> .....	<b>Error! Bookmark not defined.</b>
<b>ACKNOWLEDGEMENT</b> .....	<b>ii</b>
<b>LIST OF TABLES</b> .....	<b>iv</b>
<b>LIST OF FIGURES</b> .....	<b>iv</b>
<b>1. Introduction</b> .....	<b>1</b>
1.1 Background of Light Rail Transit and its Reliability Study .....	1
1.1.1 Railway Power Supply Feeding Arrangement.....	2
1.1.2 Addis Ababa Light Rail Transit Power Supply System.....	4
1.2 Statement of the Problem.....	17
1.3 Literature Reviews .....	18
1.3.1 Reliability Definitions in Related Works.....	20
1.3.2 Maintenance Strategies for DC Traction Power Supply Systems.....	21
1.3.3 Reliability Study on AALRT TPSS .....	24
1.4 Objectives .....	24
1.4.1 General Objective .....	24
1.4.2 Specific Objectives .....	24
1.5 Research Methods.....	25
1.6 Scope and Limitation of the Thesis.....	27
1.7 Organization of the Thesis .....	27
<b>2. Methodology of AALRT TPSS Reliability Analysis</b> .....	<b>29</b>
2.1 Reliability Evaluation Modeling Method Selection.....	30
2.1.1 Comparison of Reliability Analysis Modeling Techniques .....	33
2.2 Reliability Distribution Method Selection .....	36
2.2.1 Summary of Reliability Distribution Selection.....	37
2.3 Reliability Evaluation Models of AALRT TPSS Using FMEA and FTA.....	38
2.3.1 Establishment of FMEA.....	39
2.3.2 Reliability Analysis Model Using FTA .....	46
2.4 Reliability Importance Measure.....	56
<b>3. Suggestions of Reliability Mitigation Techniques</b> .....	<b>59</b>
4.1 Introduction to Reliability Mitigation Techniques.....	59
4.2 Emergency or Standby Power Supply .....	60
4.3 Redundancy Consideration for AALRT Traction Substation.....	63
4.4 Applying Maintenance Strategies .....	67
4.5 Summary of Reliability Mitigation Techniques.....	71
<b>4. Result and Discussion of Reliability Evaluation</b> .....	<b>73</b>
3.1 Results of Reliability Evaluation Indexes.....	73
3.2 Discussion .....	75
<b>5. Conclusion and Recommendation</b> .....	<b>80</b>
5.1 Conclusion .....	80

5.2 Recommendations for Future Work.....	81
<b>References</b> .....	<b>83</b>
<b>Appendix A</b> .....	<b>85</b>
<b>Appendix B</b> .....	<b>86</b>
<b>Appendix C</b> .....	<b>87</b>

### LIST OF TABLES

Table 1: Comparison of FMEA, FTA, RBD BN and Monte Carlo simulation.....	34
Table 2: Fault mode effect analysis (FMEA) .....	43
Table 3: Calculated reliability parameters for AALRT TPSS components.....	73
Table 4: Calculated reliability parameters of AALRT TPSS subsystems .....	74
Table 5: Calculated reliability parameters of AALRT TPSS .....	74
Table 6: Fault record.....	86

### LIST OF FIGURES

Figure 1: Incoming Power to AALRT Power Supply System [13].....	5
Figure 2: AALRTS Power Feeding Arrangement [24].....	6
Figure 3: Traction Power Supply System Components in Block Diagram .....	7
Figure 4: AALRT Traction Substation (Kality Substation) [24] .....	8
Figure 5: Traction Power Supply System [13] .....	9
Figure 6: Overhead Contact System Structure [13].....	11
Figure 7: Section Insulator and Electrical connection [13] .....	12
Figure 8: Overvoltage protection device (OVPD) [13] .....	13
Figure 9: Kality Depot Power Supply Monitoring Diagram [24].....	15
Figure 10: Block Diagram of the Research Methodologies.....	26
Figure 11: Flow Chart of FMEA to FTA.....	39
Figure 12: Fault Tree Symbols .....	49
Figure 13: Fault Tree .....	51
Figure 14: Availability of AALRT TPSS without Redundancy.....	62
Figure 15: Availability of AALRT TPSS with Standby Power Supply System.....	62
Figure 16: Mainline Railway DC Traction Substation with Uninstalled Redundant system [24] .....	64
Figure 17: Availability of AALRT TPSS with Redundant Circuit Breaker and Transformer Circuits.....	65
Figure 18 : Reliability with Standby Power Supply and Redundant Transformer and Circuit Breaker.....	66
Figure 19: Importance Index of AALRT TPSS Components.....	75

### ABBREVIATIONS AND SYMBOLS

AALRT	Addis Ababa light rail transit
AALRTS	Addis Ababa light rail transit service

AALRT TPSS	Addis Ababa light rail transit traction power supply system
AIS	Air insulated switches
AC	Alternating current
BN	Bayesian network
CT	Current transformer
DC	Direct current
EEU	Ethiopian electric utility
EW	East-west
FMEA	Failure mode and effect analysis
FMECA	Failure mode and effect criticality analysis
FTA	Fault tree analysis
GIS	Gas insulated switches
Hz	Hertz
$I_{xi}^B$	Birnbaum's importance
kV	Kilo volt
MCS	Minimum cut set
MTBF	Mean time between failures
MTTR	Mean time to repair
MV	Medium voltage
M(t)	Maintainability
NS	North-south
OCS	Overhead contact system
OCC	Operation control center
OVPD	Overvoltage protection device
RAMS	Reliability, availability, maintainability and safety
RBD	Reliability block diagram
RTU	Remote terminal unit
R(t)	Reliability
SCADA	Supervisory control and data acquisition

TPLS	Traction power line system
TPSS	Traction power supply system
TPS	Traction power system
TPC	Traction power controller
Us	System unavailability
V	Voltage
VT	Voltage transformer
$x$	Basic event
$\mu$	Repair rate
$\lambda_s$	System failure rate
$\gamma_s$	System mean time to repair

## 1. Introduction

### 1.1 Background of Light Rail Transit and its Reliability Study

Electrified railway has played an important role in modern transportation and social development because of its huge capacity, high efficiency and low pollution. Electric railway system consists of traction power system, rolling stock and track. The traction power supply system (TPSS) is the power source intended to guarantee safe and reliable operation of urban transit. The primary role of traction power systems is to provide reliable and continuous electrical energy to satisfy the traction loads [1].

Traction power supply system mainly consists of two major subsystems; traction substation and traction network. The traction substation transforms the electric power transmitted from an electric power company and supplies it to the railway power system for the operation of traction system. The traction power system has also two major categories: AC (alternative current) and DC (direct current) [2]. AC is mainly used for long distance trains, since transmission and voltage regulation of electrical energy is much more cost effective that way. DC is predominantly used for metro and suburban lines, although; it is used for long distance main lines in some European countries. Nominal voltages for most DC traction power systems are 750V, 1500V and 3000 V, 750 V being most popular for light rail and metro lines [2].

High reliability of railway power systems is one of the essential criteria to ensure quality and cost-effectiveness of railway services [1]. Reliability of railway power system has been defined by different authors; two of them are brought here. According to [2], reliability of a traction power system is defined as its ability to continuously supply electrical power of adequate quality during sudden disturbances, such as a short circuit or loss of system elements, while operating with a normal scheme configuration, or during scheduled maintenance and repairs, without

causing safety hazards, train delays or public nuisance. Besides, European standard EN50126 defined reliability as: The probability that an item can perform required function under given conditions for a given time interval.

The reliability evaluation and analysis of traction power supply systems has been carried out in order to identify the impacts of each component on reliable operation, for scheduling vital maintenance activities and for providing appropriate mitigation techniques [1,3]. Not only is railway system reliability an important influence factor on service quality, but more reliable service quality is also highly desirable by the society. There are many studies in the world, where electrified railways are used, on the reliability analysis and evaluation of electrical components or vehicles but few on railway power supply system [1].

Nowadays, to conduct reliability analysis of TPSS, the traction power reliability analysis methods that are widely used are fault tree analysis (FTA), reliability block diagrams (RBD), Bayesian network (BN) and Monte Carlo simulation [1,3,4]. There are also various power system reliability distribution functions, such as exponential distribution and Weibull distribution, used to calculate the reliability parameters from the models. To show the degree of the impact from the failure rates of the components of the traction power supply system on the failure rate of the system, importance indexes should be evaluated with selected approach [10].

### **1.1.1 Railway Power Supply Feeding Arrangement**

There are lots of arrangements for feeding the substations aiming at increasing the reliable operation of the railway transport system. The most common types of configurations are discussed here. The purpose of the arrangements relies on the principle that states, the traction power should be supplied for all rail traffic loads and its reliability must be guaranteed. Therefore, two independent power supplies should be available for traction substation; in

addition, due to different distribution of power circuits, power supply modes for traction substation are diversified, but they can be divided into the following typical arrangements.

Ring type power supply connection is an arrangement, in which two or more main step-down substations and all traction substations are connected to form a ring topology [16]. This ring type power supply is a very reliable power circuit, reasons: under such case, when one transmission line and one step down substation stop operating simultaneously, if its bus is still powered, normal power supply for any traction substation will not be interrupted. However, its investment is great.

Double-side power supply connection is an arrangement that has two main step-down substations to supply power to traction substation along line, and all transmission lines to traction substation will be connected via its bus; to increase reliability of power supply, two transmission lines are used for power supply, and each line is calculated by transmission power [16]. Reliability of this connection scheme is slightly lower than the ring type connection. When quality is large, many switch devices are required, and investment will also be increased.

Single-side power supply connection is an arrangement, when two power supplies are available only at one side of rail line; single-side power supply mode will be adopted [16]. Reliability of single-side mode is poorer than both ring side and double-side connections; to increase reliability double-circuit power supply shall be adopted. Single-side mode requires less devices and lower investment.

Radial power supply connection is an arrangement, which has two independent transmission lines that are connected to the traction substation and main step-down substation at each traction side [16]. This connection mode is suitable for rail line in an arc. This connection mode is simple, but the whole line will be powered off if the main step-down substation is off.

### 1.1.2 Addis Ababa Light Rail Transit Power Supply System

AALRT is an urban railway implemented at the capital city of Ethiopia, Addis Ababa, which started operation since September 2015. The light rail stretches 16.559km from North to South (NS) and 17.41km from East to West (EW), a total of about 33.3km with common track of 2.627km. It is an electric railway system that consists of traction power system, rolling stock and track.

The power supply system provides power for traction power of the train and other light rail operations, such as lighting, ventilation, air conditioning, drainage, communication, signal, and alarm for preventing disaster, automatic escalator and elevator etc. The power supplied for AALRT is provided by Ethiopian electric utility (EEU) from the dedicated 132kV national grid at four different directions of the two routes, NS and EW. The gas-insulated substation (GIS) under EEU receives 132kV power from the national grid and steps down to 15kV and then transmits to the switching substations (AIS), which are located near to the end of each AALRTS routes as shown in figure 1. Then, switching substations (AIS) supplies 15kV power for Kality depot, Minilik square (NS27), Ayat depot and Torhailoch traction power line systems (TPLSs) with double lines, and the other six TPLSs are supplied from the respective AISs via single supply circuit and the rest are connected to these TPLSs with loop in loop out arrangements.

In AALRT, DC traction power supply system is adopted in which the traction power is being delivered to the rolling stocks at 750V DC via the overhead line system. This traction power supply system mainly consists of two major subsystems; traction substation and traction network. It is intended to guarantee safe and reliable power source for the Addis Ababa light rail transit.

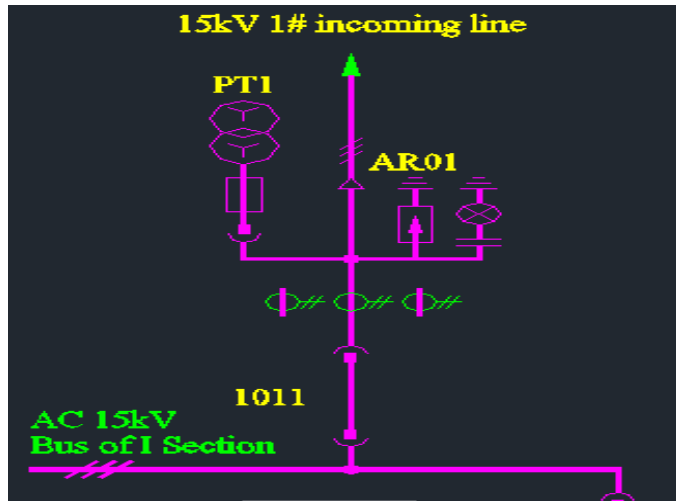


Figure 1: Incoming Power to AALRT Power Supply System [13]

The power system feeding the electric trains relies on the step-down transformer, rectifier, protection equipment, control equipment, compensation equipment and other supporting devices. The other major part of the AALRT power supply system is the communication devices (SCADA) that monitors its operation at each of the TPLSs.

### 1.1.2.1 Traction Substation Power Feeding Arrangement of AALRT

Double-side power supply arrangement is adopted for feeding AALRT TPLSs from the main substation in which there are four 132/15kV GIS substations dedicated from EEU as shown in figure 2. Each 15kV feeder comes directly from the dedicated AIS that provide power for each of the three TPLSs with a total of twelve.

There are twenty substations in AALR TPSS; four of the TPLSs (Kality depot, Ayat depot, Minilik II square and Torhailoch station) are fed by two independent 15kV feeder cables, the other six of the TPLSs (NS6, NS7, NS22, NS25, EW1, EW2, EW18 and EW20) are fed by one 15kV feeder cable and the rest of eight TPLSs are supplied from those TPLSs with the loop in loop out arrangements as shown in figure 2.

Thus, under normal operating conditions; each TPLS feeds its dedicated feeding zone, in an average of about 2km. If one TPLS happens to be out of service, adjacent TPLS feeds the failed TPLS's feeding zones using the loop in loop out configurations and three spare underground 15kV power cables. For communication and signaling equipment and station facilities, there are 0.4kV feeders from all the substations under the scope of AALRT.

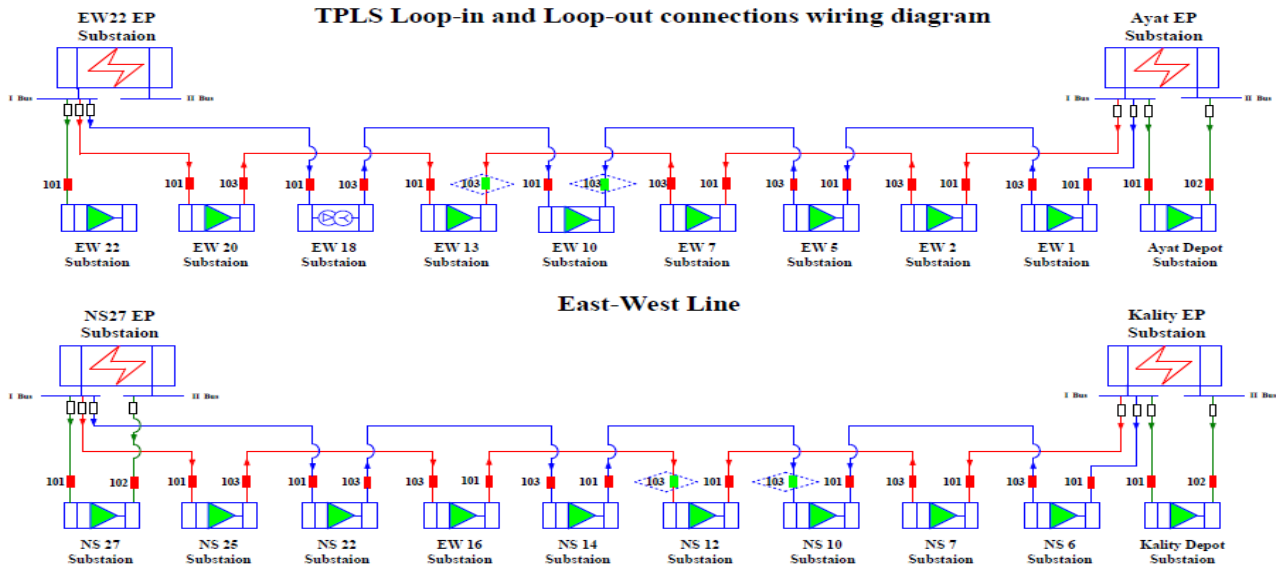


Figure 2: AALRTS Power Feeding Arrangement [24]

### 1.1.2.2 AALRT Traction Power Supply Components

AALRT TPSS is composed of two major subsystems; traction substation and traction network. The sequence of traction power supply circuit consists of the positive busbar of traction substation, feeder line, overhead contact system (OCS), electric bus, the stray current collection cable, the negative return busbar of the traction substation as shown in figure 3.

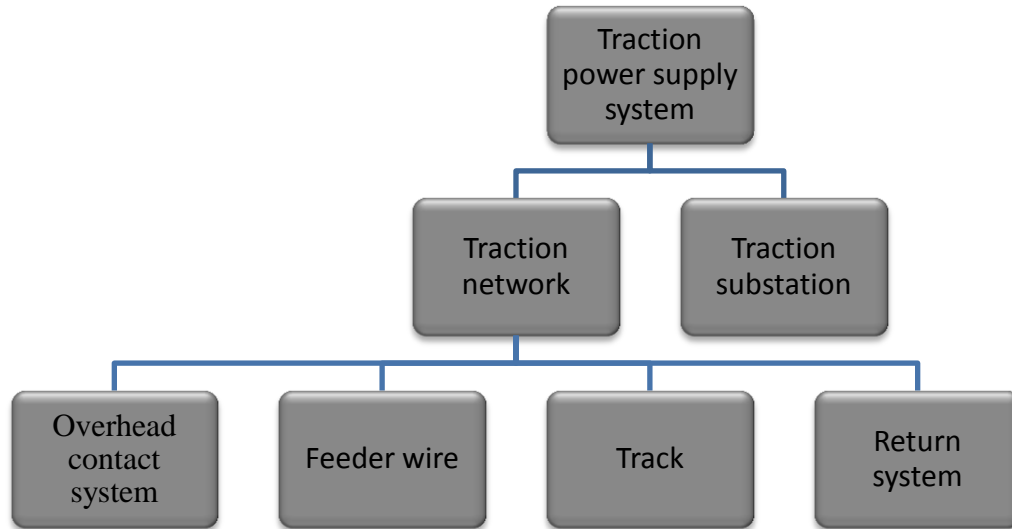


Figure 3: Traction Power Supply System Components in Block Diagram

### **Traction Substation**

Traction substation is the central part of the TPSS, which plays a key role in converting three-phase incoming medium voltage power (15kV) from the AC power system into electric energy suitable for use by locomotives and transferring it to the catenary system. In AALRT TPSS, substations are also called traction power line systems (TPLS). Depending on their function, there are two types of substations; mixed substations which provide power for the rolling stocks and various signaling, communication equipment and other station facilities and only a step-down substation that feeds only to signaling, communication equipment and other station facilities, i.e. EW18.

The function of traction substation is to step down or rectify the received 15kV power from AIS, and transmit to OCS through feeder cable at 750V DC, so as to supply power to the subway and light rail train. The nominal DC 750V output has voltage fluctuation ranges of 500V~900V.

The TPLS mainly encompasses; 15kV switchgear, 15kV switchgear protection device, traction transformer, temperature controller, rectifier, negative switchgear, DC switchgear, DC

## RELIABILITY ANALYSIS OF AALRT TRACTION POWER SUPPLY SYSTEM

switchgear protection device, power transformer, SCADA monitoring screen, AC/DC panel, charging module, batteries, AC/DC screen control switch, 400V switchgear, OVPD, cable connection for track, power and communication cables, instrument transformers, and following transformers as shown in figure 4.

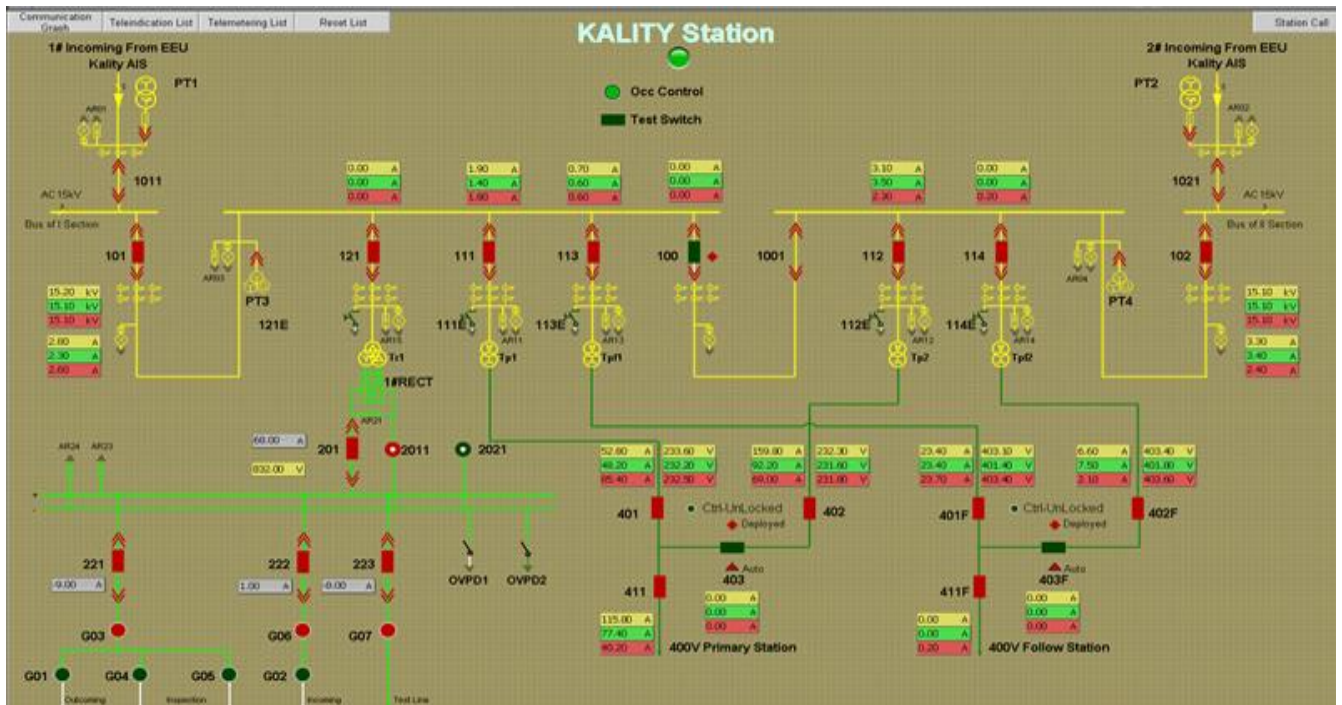


Figure 4: AALRT Traction Substation (Kality Substation) [24]

### Traction Transformer

Traction transformers are used in coordination with rectifiers to ensure the characteristics of a complete set of unit with the following ratings:

- 1) Traction transformer output rated AC voltage: AC 590V.
- 2) Rated DC output voltage: DC 750V
- 3) Rated DC no-load voltage: DC 825V.
- 4) Maximum DC output voltage: DC 900V.

For the rectification purpose, a 12 pulse rectifier is utilized that rectifies the transformer output voltages of 0.59kV in Y and 0.59kV in the  $\Delta$  connections in to DC 750V as shown in figure 5.

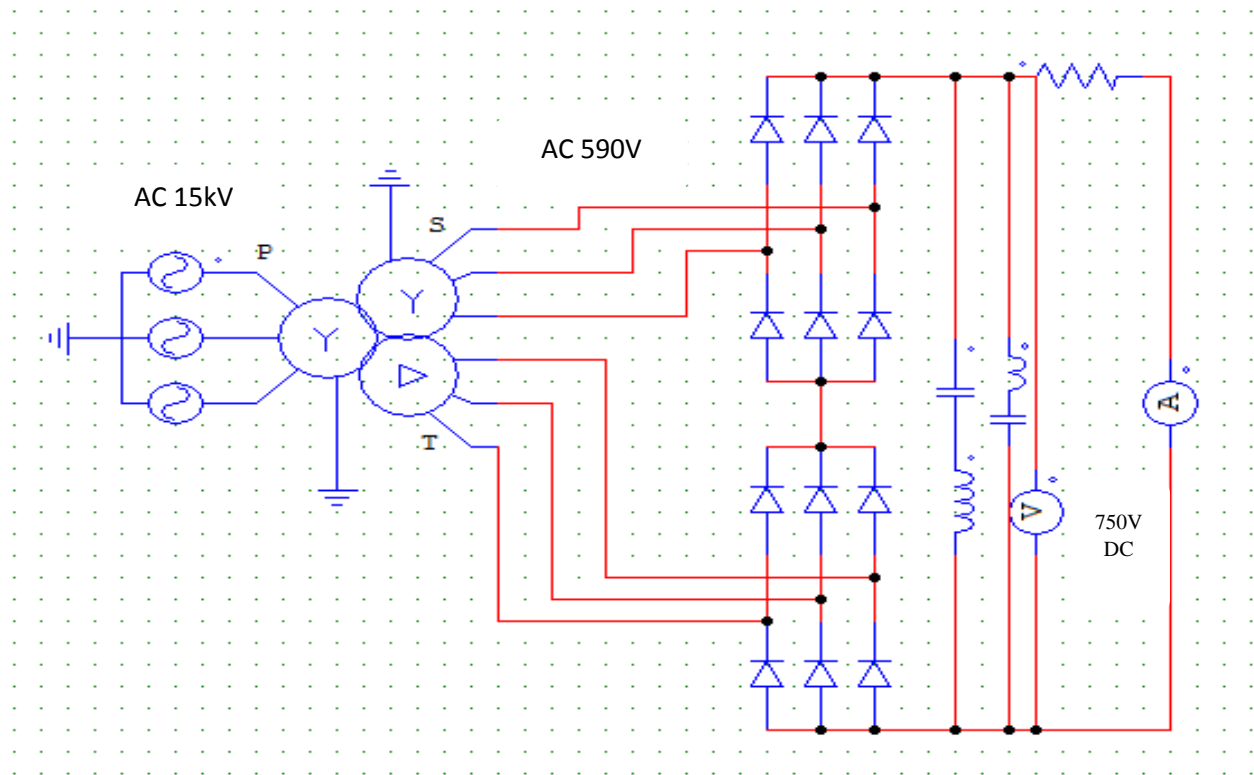


Figure 5: Traction Power Supply System [13]

### Traction Network

Traction network consists of the contact network and the return flow network, such as feeding section, overhead contact system (OCS), contact rail, feeder cables, masts, and the like. It is an electricity grid for the supply of electrified Addis Ababa light rail transit networks. Some of the major components of the traction network are briefed here.

**Feeding section:** is a section from traction substation feeder to the end of the OCS.

**Feeder:** is a wire or cable which connects between traction substation bus and OCS. Power goes through it to railway.

**OCS:** Overhead contact system/line (OCS) hangs above the track along the railway.

**Track:** Current goes through it and returns to substation.

**Return Line:** is a wire which connects between traction substation and track. Current goes through and returns to traction transformer.

### **Overhead Contact System (OCS)**

It is an overhead conductor system that supplies electric power to a locomotive through a pantograph. It mainly consists of foundations, support structures, and contact suspensions. Electric locomotive of AALRTS takes its power for the electric motors, lights, air conditioning, etc., from the overhead line using the pantograph on the roof.

OCS in AALRT TPSS is responsible for the important task to transmit power from the traction substation to electric locomotives. So, the quality and working status of the OCS will directly affect the safe operation of electric trains. As most of the OCS components has no spare locally, and the load on the lines moves and changes along with the OCS, due to the operation of electric locomotives plus the environment, the requirement for the status of OCS equipment is very high.

### **Structure of OCS**

The overhead wire system, which supplies power to electric vehicles through pantograph, consists of foundation, pillar, supporting device, positioning device, contact suspension and additional wire as shown in figure 6.

**Contact suspension:** it is the power transmitting part of the OCS, which is mainly made up of carrier cable and contact wire.

**Carrier wire also known as messenger wire** is the longitudinal cable that suspends single or double contact lines, either directly or indirectly. It directly receives 750V DC electric power from the OCS feeder cable and transmits it to the contact wire via electrical connection wires and droppers.

**Contact wire:** It is the contact line that delivers DC 750V directly to the flow receiver (pantograph) in an overhead contact suspension.

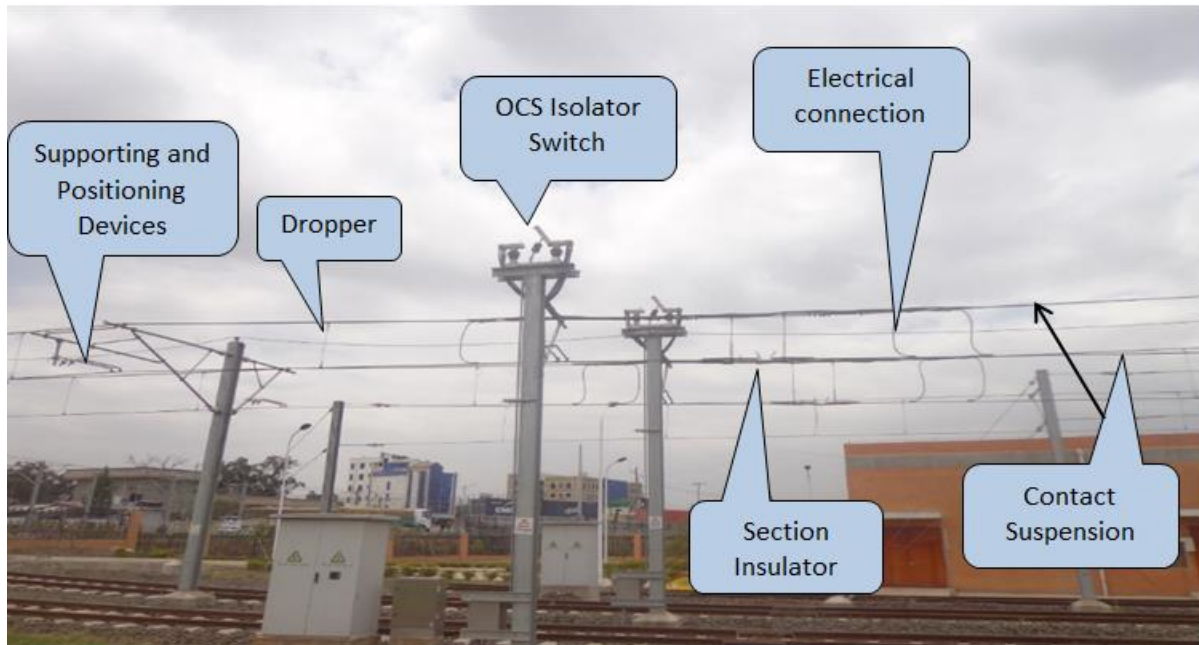


Figure 6: Overhead Contact System Structure [13]

**Additional wire:** The overhead wire besides of contact suspension in the traction wire, including feeders, lightning conductor or overhead ground wire.

**Grounding wire:** The wire connects the pillar, equipment and component of OCS to earth or track, to protect the safety of human and equipment.

**Wire Height:** The vertical distance between the suspension point of the contact wire and the center of the rail connection.

**Support device** also called **cantilever:** is used to support contact suspension, and transfer the load to the pillar or other buildings.

**Isolator Switch:** is used to power isolation or connection of adjacent sections via OCS. It is either manual or motorized depending on its function. Isolator switches can also be classified as on-grid and linked for OCS applications as utilized in AALRT TPSS.

**Section Insulator:** is an OCS component which is connected in series with the contact wire to separate and keep insulation between two adjacent feeding sections, but does not affect the normal sliding of pantograph on the contact line.

It is a kind of insulating device to segment OCS electrically. In normal case, the pantograph passes through it being electrified. In case of a certain OCS section suffering fault or power-off due to construction, open the isolating switch near the sectional insulator to de-energize this section of OCS, but with other section being energized normally. It is mainly composed of the current guiding plate, main insulator anchoring clamp, carrier cable-mounted insulation rods, slings and other accessories. Its structure is shown in figure 7.

**Electrical connection:** provides contact points between the messenger wire and contact wire by being hanged for electrical connection, as shown in figure 7.

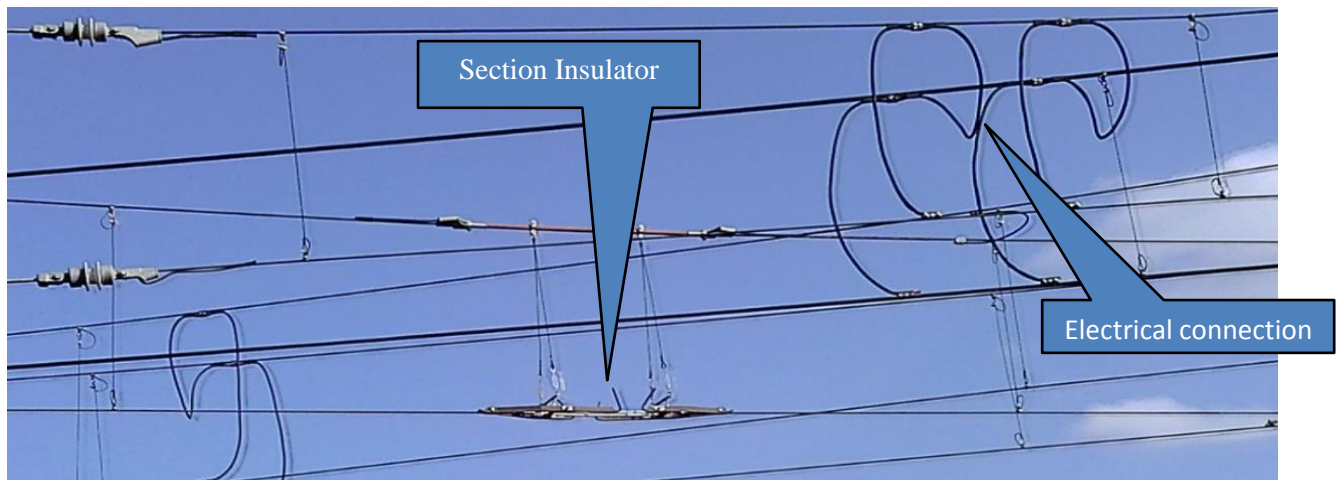


Figure 7: Section Insulator and Electrical connection [13]

### Return System

The return system is part of the traction network other than the OCS. It consists of stray current collection cables, rail track, overvoltage protection device, unidirectional conduction device, etc.

## RELIABILITY ANALYSIS OF AALRT TRACTION POWER SUPPLY SYSTEM

DC current return systems is the DC traction current circuits of AALRT TPSS that consist of rectifier, overhead line, rolling stock, rails, and then return to rectifier via the negative DC 750V cabinet. Stray current is the part of a current which follows paths other than the intended paths (normal return system). The normal current return system includes rails, track cross bonding cables, rail cross bonding cables and return cables, and will ensure normal operation and will be insulated from the earth to avoid unacceptable stray current and so will work at a float potential. Overvoltage Protection Device (OVPD) is part of the return line with the function of overvoltage protection. When the current flows through the track, there is a potential difference between the track and the ground may exceed the safety allowable voltage/ safe permissible voltage and passenger personal safety hazards. For this case, the rail potential limiter or overvoltage protection devices (OVPD) are applied between the rail and the earth. When the OVPD detects that the absolute value of the rail potential exceeds the safe voltage permissible values, 60V inside depots and 90V at the mainline, the rail and earth will be short-circuited by the action of the rail potential limiting device to ensure the safety of the passengers and the staff. A typical OVPD diagram is shown in figure 8.

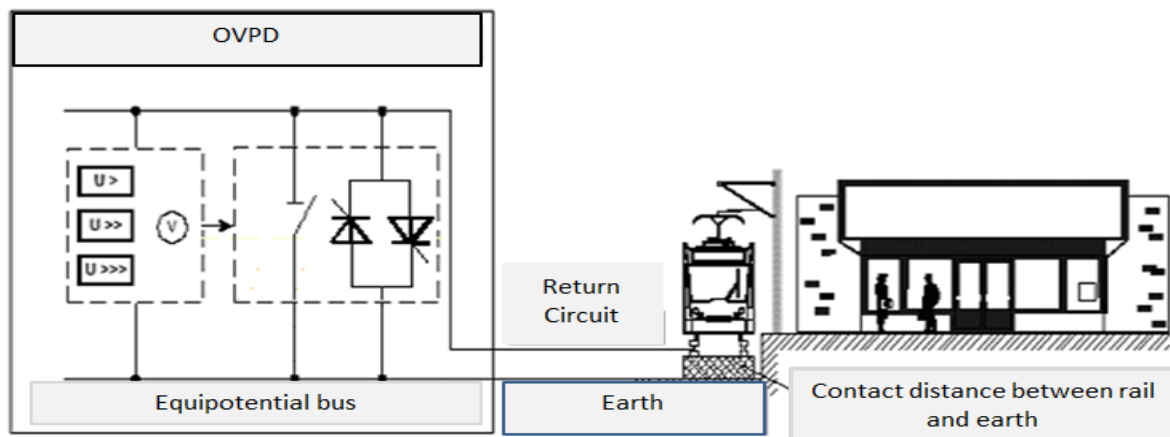


Figure 8: Overvoltage protection device (OVPD) [13]

### 1.1.2.3 AALRT TPSS Control Systems

The power supply system information of AALRTS is stored, transmitted and displayed at SCADA communication device and then the operation control center (OCC) monitors the activities by interchanging information with the SCADA via fiber optics cable.

#### **Operations Control Centre functionality relating to AALRT TPSS**

In AALRTS, there is always a power dispatcher responsible for the operation of the traction substation and traction network on duty at the operations control center (OCC). The power dispatchers are responsible to monitor the overall traction power supply system mainly via SCADA displays and radio or telephone communication with power supply technicians. An electrical supervisory control and data acquisition (SCADA) system of AALRTS comprising of a master station and remote terminal units (RTUs) is provided to support operations.

#### **Operation Control Center (OCC)**

The operation control center is a center for train operation command, information receiving and dispatching, system equipment monitoring, main track construction ordering. It is also a center for accident and malfunction alarming and emergency processing. It can also control the speed of a train, since the train works by computerized system via automatic train protection (ATP). Generally, the operation of almost the whole TPSS is remotely monitored at one station, Kaliti depot, by the operation control center (OCC).

#### **Supervisory Control and Data Acquisition (SCADA) System**

SCADA systems in AALRT TPSS are employed for simultaneous acquisition of a large amount of data, real time processing, display and supervisory control. It enables the traction power controller (TPC) to be controlled from operation control center (OCC), the switching operations of the equipment at controlled stations i.e. traction substations and switching stations. It also

## RELIABILITY ANALYSIS OF AALRT TRACTION POWER SUPPLY SYSTEM

helps the TPC to achieve real time data acquisition, processing, display and control of data pertaining to the traction power supply to the DC 750V overhead traction systems of AALRTS.

SCADA has a user interface within the main control center with the ability to monitor the entire electrical system and administer controls in real time. The system is configured in such a way that it provides a clear picture of the status of the electrical network and display state changes to the operators via the user interface and log all changes.

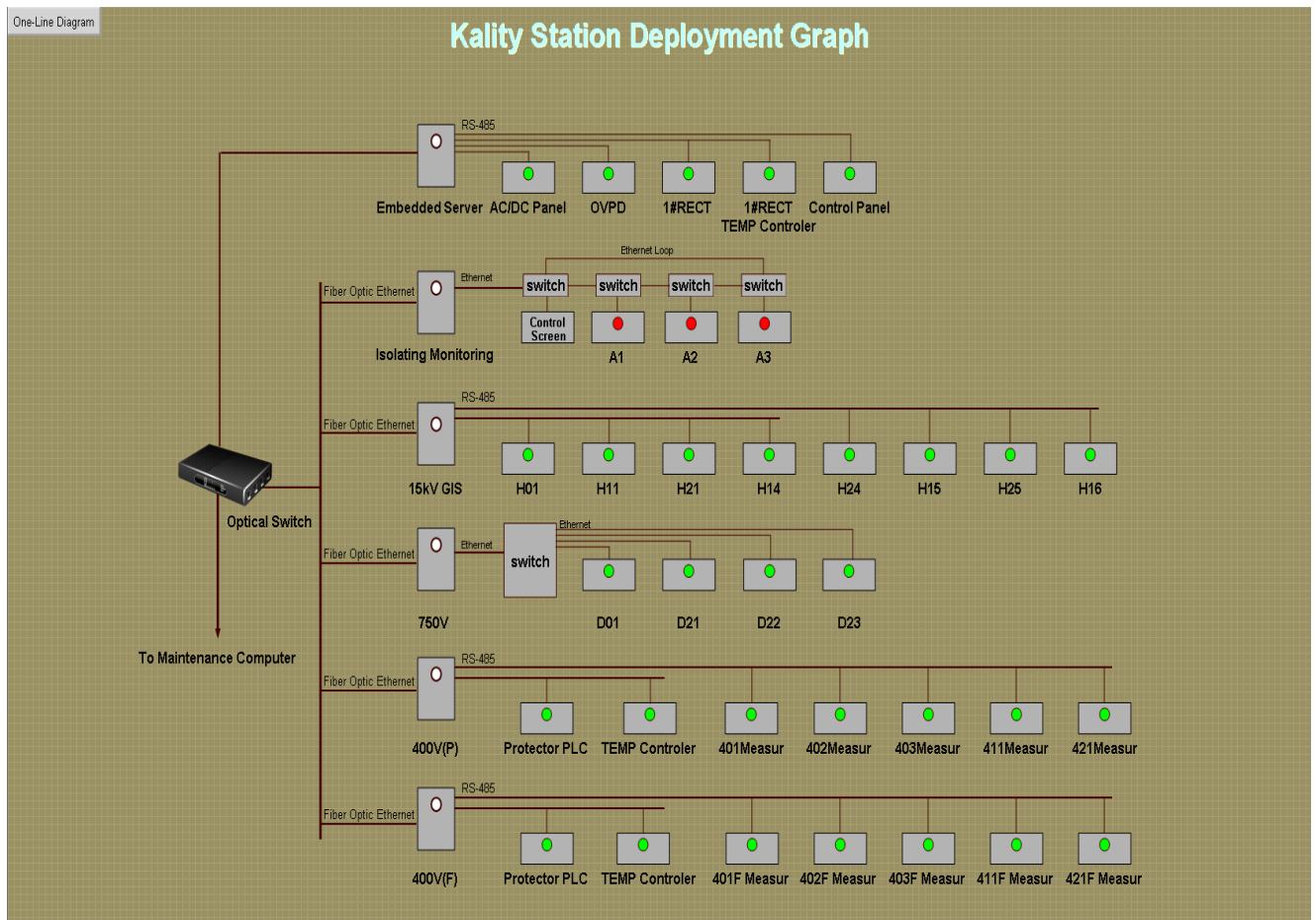


Figure 9: Kality Depot Power Supply Monitoring Diagram [24]

Figure 9 shows how the traction substation equipment's are connected to the central maintenance computer that enables to remotely monitor the operation by the central operation control center (OCC) with the help of SCADA and other related communication devices.

## **RELIABILITY ANALYSIS OF AALRT TRACTION POWER SUPPLY SYSTEM**

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The system provides for monitoring and control of electrical equipment and equipment associated with the electrical system at the following locations:

- Traction power network substations
- Signaling power supply locations
- The OCC

The features of the electrical SCADA software package at AALRT TPSS includes, but not be limited to, the following:

- display analogue and status variables with logical navigation between displays
- Display electrical equipment with appropriate symbols, colors
- display the status of traction power sections
- Alarm management, providing alarm logs
- trending of analogue values
- Facilities for administration and configuration of the SCADA system, including graphics generation allowing preparation of schematic displays
- Manual data entry for data not acquired automatically or not currently acquired due to communication or RTU failure
- Security, to prevent unauthorized access via operator workstations or remote access
- Ability to have different personnel roles with differing access rights for viewing, control and configuration change
- Diagnostics, to allow SCADA system fault detection and rectification
- Communications system monitoring
- Online operator help

### 1.2 Statement of the Problem

DC traction power supply system is preferred for urban railways due to its relatively reliable, cost-effective, and environmentally clean performance [7]. AALRT has implemented 750V DC traction power supply system with loop in loop out configurations and overhead contact system. Since the beginning of operation, the need for improving its power quality especially the reliability concern has been rising due to the frequent traction power supply interruptions related to the failures of its components in traction network, traction substation, and communication devices. Besides, the AALRT TPSS had been disturbed by frequent main substation (AIS or GIS) failures. The failures of those AALRT TPSS components usually resulted in part routing, passenger clearing and more severely total operation interruption.

The frequent failure of underground 15kV power cables, power outages from main substation faults and SCADA communication failures are disturbing the operation. Traction substation of NS10 is not currently working since 2017 due to the 15kV power cable failure that runs from NS6 to NS10. The malfunctioning of NS10 TPLS forces the nearby NS7 TPLS to continuously supply the gap out of its dedicated operation zone. Nowadays, the communication and signaling equipment loads are supplied by the tapped poorly reliable 400V commercial power. Extended abnormal operation of traction power supply equipment may result in shortening the future intended life time of the TPSS component.

The other reliability gap is the absence of standby or emergency power for all traction power supply system, except the 12V batteries, in all TPLSs. These batteries are used only in the AC-DC panel for supplying 220V power for SCADA communication device in cases of power outage. They are deteriorating because of extended operation during power outage due to 15kV power cable failure or main substation failure.

Hence, the reliability evaluation and analysis of AALRT TPSS has to be carried out in order to identify the impacts of each component on reliable operation, for scheduling vital maintenance activities and for providing appropriate mitigation techniques. This thesis work is initiated by those existing problems and emphasizes on evaluating and analyzing the reliability of the system based on the failure data and proposing improvement works to the reliable AALRT TPSS operation.

In making these decisions, reliability concerns are of the utmost importance, since:

- Nobody wants to be part of the chaos created by train delays caused by power interruptions –that will prevent Addis Ababa public from using AALRTS;
- Mass transit service interruptions, like AALRTS, almost always have strong negative effects on business and economy in the regions they serve-Addis Ababa [11];
- In some cases, power failures may cause life threatening situations with catastrophic consequences.

Therefore, this thesis aimed at analyzing the reliability of AALRT traction power supply system based on the selected component failure data that directly or indirectly had been resulting in the power interruption of AALRTS and affecting the service quality. Finally, based on the reliability evaluation results, reliability mitigation techniques will be suggested.

### **1.3 Literature Reviews**

Power system reliability analysis and evaluation was started only after the mid-1960s following an emerging applied science development [2]. There are few studies on the reliability analysis of railway power supply systems. Due to too large and complicated power system structure, usually only power generation, transmission, and distribution electrical systems and interconnected systems were segmented for reliability research [2].

The reliability evaluation and analysis of components or subsystems in traction power supply system had to be carried out in order to identify the impacts on reliable operation and for providing appropriate mitigation techniques [9]. There are many studies in the world where electrified railways are used, on the reliability analysis and evaluation of electrical components or vehicles [9] but few on railway power supply systems. Nowadays, the traction power reliability analysis methods that are widely used are fault tree analysis (FTA), reliability block diagrams (RBD), Bayesian network (BN) and Monte Carlo simulation [3, 4, 9, 22].

As for the studies on reliability evaluation of a railway system and its traction power supply system, there have been some related literatures in the last two decades. Fukuoka developed a network-type reliability evaluation model, type state influence diagram, to denote the complicated dependency among subsystems [3]. Cosulich et al. [3] applied a probabilistic approach based on stochastic reward nets to estimate the vehicle performances including reliability, availability and maintainability, in the Italian high speed railway system. Wang et al. [3] presented an analytical method of reliability of railway catenary system combining radial basis neural networks, finite element analysis with Monte Carlo simulation.

S.K. Chen et al. [9] presented an approach based on fault tree analysis (FTA) to evaluate the overall reliability of a railway power supply system. Through FTA, a railway power supply system was logically expressed by structurally interrelated components and its overall reliability was calculated according to the reliability of individual components and their relationship. The critical components, which more likely lead to failure of the whole system, were also located by specific importance indices. Besides, identifying the critical components to improve the cost-effectiveness of the maintenance activities was done [3, 9]. That sensitivity analysis provided hints for scheduling vital maintenance activities.

In another research, Wei-Lin Chan [15] has studied the reliability of conventional railway overhead contact system (OCS) using FTA and proposed solutions to improve the reliability of the operational phase as the follows: adopting high reliability components, adopting easier-to-replace and modularized components, and fostering trained and experienced maintenance personnel. In this study, FTA is extensively utilized to evaluate both qualitative and quantitative reliability of the overhead catenary system of the Taiwan Railway Administration (TRA) Western Line.

Dezhong Ma et al. [4] used a novel method (FFB (FMEA-FTA-BN)) according to the analysis sequence, from FMEA to FTA to BN. BN was constructed by making full use of the helpful information in the results of FMEA and FTA. The general idea of this method was as follows. Firstly, make a comprehensive analysis on imaginable fault modes, causes and effects in a system by using FMEA. Then, convert FMEA into FTA, deeply analyze the causes of the fault modes whose effects are serious and determine the logical relationships between these factors. Finally, convert FTA into BN; analyze the reliability of the system by using the capacity of BN to deal with uncertainty. Using this method was important for evaluating uncertain reliability parameters rather than the failure status of a system.

In general, from the researches mentioned as references, there are lots of reliability analysis methods which enable to conduct the qualitative and quantitative reliability of any power system. Accordingly, the reliability analysis methods, such as; FMEA, FTA, RBD, BN and Monte Carlo simulation are particularly discussed for the purpose of this thesis work in the next section.

### **1.3.1 Reliability Definitions in Related Works**

According to [20], reliability is defined simply as the probability that a system or product will perform in a satisfactory manner for a given period of time when used under specific

operating conditions. In other words, it was also described as the probability that an item will perform a required function without failure under stated conditions for a stated period of time [20]. European standard EN50126 defined reliability as: "The probability that an item can perform required function under given conditions for a given time interval". The above definitions contain the same elements, namely probability, required function or satisfactory performance, specified operating conditions or stated conditions and time.

Having in mind the above reliability definitions, the most inclusive and appropriate definition of reliability of a traction power system is taken as: the ability to continuously supply electrical power of adequate quality during sudden disturbances such as a short circuit or loss of system elements, while operating with a normal scheme configuration, or during scheduled maintenance and repairs, without causing safety hazards, train delays or public nuisance [2, 23].

### **1.3.2 Maintenance Strategies for DC Traction Power Supply Systems**

According to [23], DC traction power supply system is very cost effective in comparison with other forms of energy, but only if the maintenance cost of this system can be held to the minimum. It is not good practice to cut down on the maintenance itself because of the very high repair cost of DC TPSS components once a catastrophic failure has occurred [20]. It is also not good practice to spend lots of money on maintenance only and not to use the opportunity to improve the overall condition of the assets, resulting in increased life expectancy and reduced life cycle cost [20].

In different literatures, there are lots of maintenance approaches, such as corrective maintenance, preventive maintenance, and predictive maintenance, used for different applications whose purpose is to improve the reliability of system under study [20,23].

The corrective maintenance is failure-driven approach which is a reactive management approach often dominated by unplanned events and it is performed only after the occurrence of failures or breakages of the system [20]. Corrective maintenance actions can recover the malfunctioning part of the system, repairing or replacing the failed component. If the system is not-critical and easily repairable, any potential unplanned crashes will cause a minimum impact related to the availability. There are currently three strategies of corrective maintenance being used in the field of maintenance engineering [20]. These are major breakdown, minor breakdown and routine corrective.

Maintenance during major breakdowns is very expensive and time sensitive. When this strategy comes into play, the system is down and must be repaired as quickly as possible to prevent service losses. Minor breakdowns occur when certain components of the system fail and cause the system to be down. It is easy to replace the components and cost is lower compared to that of major breakdowns. Routine corrective maintenance is a strategy where less critical components are replaced after they failed. The failure of these components does not cause the system to fail entirely. These three strategies are reactive of nature and are the unscheduled repair of failed components to restore its functional capabilities. With certain components it might be feasible to follow this strategy where the failure will not influence the ability of the system to perform at the designed output.

Preventive maintenance is a pro-active maintenance strategy where components are repaired or replaced before they fail using a planned maintenance schedule, which is less costly and time consuming [20]. There is also a time-based maintenance also known as periodic preventive maintenance. These approaches have historically been performed based on recommendations from original component manufactures.

In order to slow down the process of deterioration that leads to a failure, a primary preventive maintenance is performed periodically inspecting and controlling the system through scheduled regular activities [20]. The time-based maintenance assumes that the estimated malfunctioning of the system, i.e. mean time between two functional failures (mean time between failures – MTBF), is statistically or experimentally known for system and device degradation during their normal use. The time-based maintenance involves also scheduled shutdown of the system for revisions or predetermined repair activities on the system still operating. This approach allows preventing functional failures thanks to the replacing of critical components at regular intervals, just shorter than their estimated life cycle. The system revision and the replacement of critical components at determined intervals represent methodologies widely adopted in the maintenance of many modern systems. The maintenance decisions are made by experienced planners, according to the recommendations of the manufacturer of the system, failures history, malfunction data, operational experience, and assessment performed by maintenance staff and technicians [20].

Predictive maintenance is another approach represented by the condition-based maintenance as a method to reduce the uncertainty of maintenance activities [20]. This activity is performed according to the needs indicated by the results of system status monitoring, i.e. condition-monitoring. The predictive condition-based maintenance uses, therefore; the results of condition-monitoring and, according to these, plans the maintenance actions. The goal of condition-monitoring is to delete the failures and extend the preventive maintenance intervals. The condition-based maintenance assumes that the existence of indicative prognostic parameters can be identified and used to quantify potential system failures before they occur. The prognostic parameters provide an indication of potential problems and new issues that may cause the

deviation of the system from its acceptable level of functioning. The condition-based fault diagnosis is triggered by the detection of an evaluated condition of the system, such as the deviation from the expected level, recognizes and analyzes symptomatic information, identifies the causes of the malfunction, obtains the development trend of the fault and predicts the remaining useful life of the system.

### **1.3.3 Reliability Study on AALRT TPSS**

The reliability evaluation and analysis of AALRT TPSS should be carried out in order to identify the impacts on reliable operation, for scheduling vital maintenance activities and for providing appropriate mitigation techniques. As far as the author of this thesis is concerned, there is no research on the reliability analysis or evaluation of AALRT traction power supply system. With this in mind, this thesis work is aimed at focusing on the qualitative and quantitative reliability analysis of AALRT TPSS and then suggesting some mitigation techniques for the reliability improvement.

## **1.4 Objectives**

### **1.4.1 General Objective**

The main objective of this thesis is to analyze AALRT traction power supply system, provide documented findings and suggest mitigation techniques to improve the reliability of the system.

### **1.4.2 Specific Objectives**

- Exploration of AALRT TPSS reliability evaluation, analysis and power feeding arrangements with their impact on reliability.
- Analyzing the likely causes of faults in AALRT TPSS.
- Selection of appropriate methods for reliability evaluation and analysis and then constructing or modeling the system with the selected reliability analysis method (s).

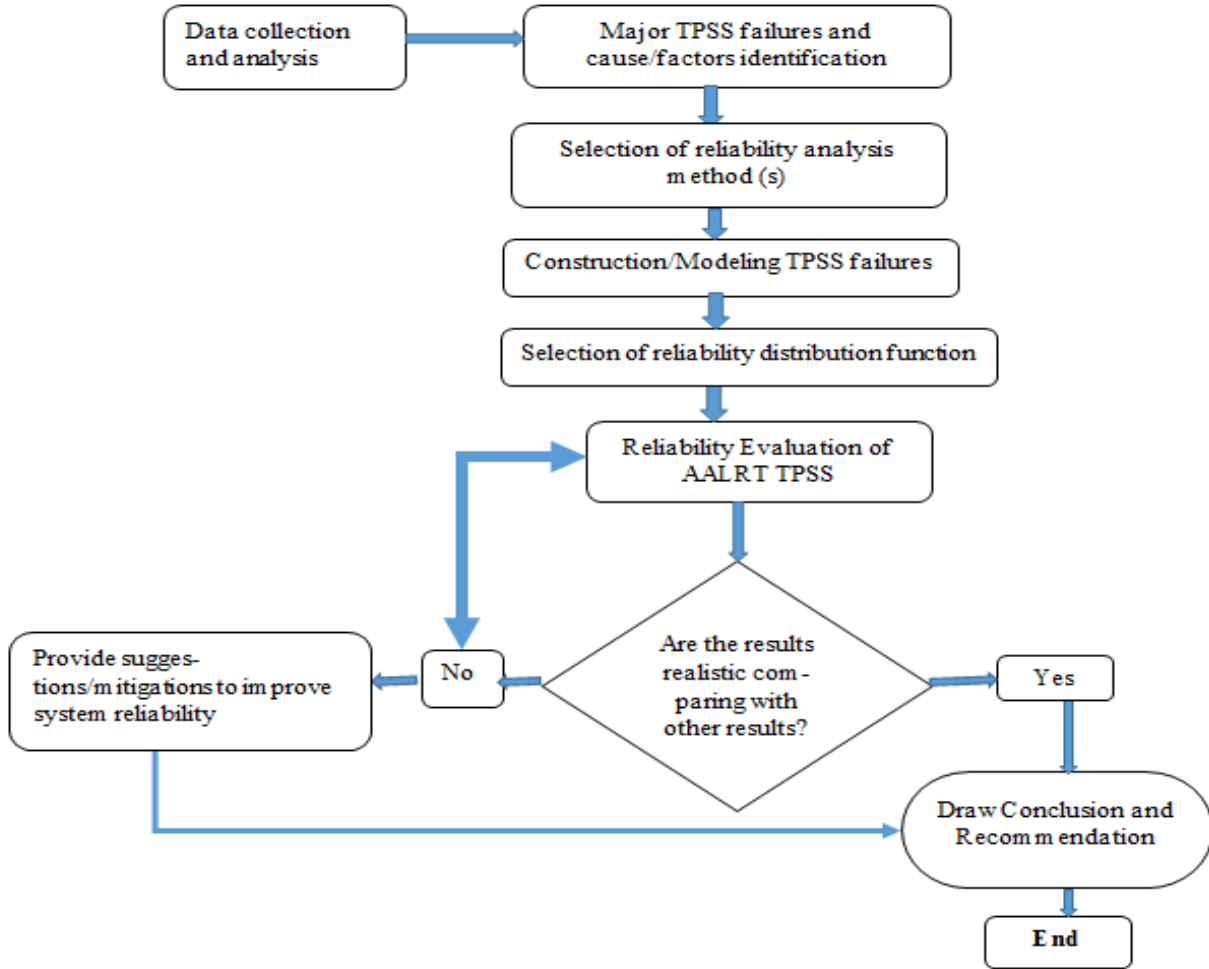
- Selection of appropriate reliability distribution method and calculate reliability evaluation indices using the equations obtained from the selected reliability distribution.
- Discuss and analyze the qualitative and quantitative reliability of AALRT TPSS through the results of reliability indexes by comparing with other related works.
- Suggest mitigation techniques for AALRT TPSS reliability improvement.

### 1.5 Research Methods

To achieve the reliability analysis of AALRT TPSS, various activities are performed. Initially, reviewing different literatures regarding AALRT traction power supply system modeling, evaluating, and analyzing methods are conducted. Different related researches are explored on reliability analysis of traction power systems with various methods and standards. AALRT TPSS theoretical background related to the power provision, power feeding arrangement and configurations are discussed. Having brief understanding of the problem, AALRT TPSS failure data of the number of component failures, corresponding downtimes, the number of equipment, and other relevant data are collected from AALRTS power supply division in the operation duration till October 30, 2018. Accordingly, data analysis is conducted.

Then, selection of appropriate reliability analysis methods and modeling of AALRT TPSS failures are conducted. The calculation of the reliability parameters is performed using a simple MATLAB code, which is developed for this purpose, by applying the equations obtained from the selected reliability distribution, i.e., exponential distribution. Then after, the reliability evaluation results are briefly discussed.

Finally, based on the results and discussions made, some significant mitigation techniques are suggested for the improvement of reliability of AALRT TPSS. The research methodologies are summarized as shown in figure 10.



**Figure 10: Block Diagram of the Research Methodologies**

Generally, the main tasks of this thesis work are arranged as follows:

1. Carefully analyzing the system through the FMEA concerning the failure modes and consequences of TPSS critical power supply equipment and analyzing its qualitative reliability from the perspective of the system with full consideration of system composition;
2. Considering the configuration of TPSS components, establishing the FTA model, which can reflect the impact of components on the reliability of the system;
3. Solving the reliability evaluation indices based on the FTA model of the system with MATLAB code by equations of the selected distribution method and obtaining quantified indexes of reliability on the system to comprehensively reflect the reliability level of the system.

## 1.6 Scope and Limitation of the Thesis

This thesis has aimed at analyzing the traction power supply of the overall AALRTS which covers about 34km in two routes, i.e., NS and EW. So, in this thesis, AALRT TPSS extends from the 15kV AIS supply to the DC 750V output power which delivers power to the locomotives via pantograph. Any power supply unit, out of this range, is not considered as part of AALRT TPSS. AALRT TPSS is assumed to obey exponential distribution by which the calculation results are steady state quantities. The reliability analysis considered the impacts of the failures of its TPSS components on the system operation reliability. However, the study of the underlying faults, such as; electrical, environmental, geographical, weather conditions are not covered.

Reliability analysis of traction power system using FTA has also some limitations. The major drawback is when applying the FTA, assumptions are made that there are only two states in the system, normal and failure and the events in the system are independent of each other.

In addition, in this thesis work, only repairable series compositions of traction power supply system of AALRT are considered for reliability evaluation purpose. However, there are actually non-repairable and parallel arrangements of components that can affect the reliable operation of the system.

## 1.7 Organization of the Thesis

This thesis is organized in six chapters; introduction, methodology of AALRT TPSS reliability analysis, result and discussion, reliability mitigation techniques and conclusion and recommendation for future work.

The first chapter, introduction, provides information about the background of thesis work, clear information about the traction power supply in another countries and that of AALRT, power

feeding systems and configurations, literature reviews of related works, statement of the problem, objectives, research method and scope of the thesis.

The second chapter, methodology of AALRT TPSS reliability analysis; provides the reliability analyzing methods selection, information on qualitative and quantitative reliability analysis of the system.

At the third chapter, result and discussion, the results and the corresponding discussions are provided.

In the fourth chapter, reliability mitigation techniques, some significant reliability mitigation techniques, such as applying different maintenance approaches, introducing standby or emergency power supply and redundancy power supply systems are suggested.

Finally, in the fifth chapter, conclusion and recommendation for future work are provided.

## 2. Methodology of AALRT TPSS Reliability Analysis

### Introduction to AALRT TPSS Operation

The power source for AALRT TPSS is supplied by Ethiopian Electric Utility (EEU) via its four air-insulated switching substations (AIS). For feeding this power, double-side power supply connection is adopted with loop-in loop-out configuration for AALRT TPSS. The loop in loop out configurations is designed to work for ensuring reliable power supply. So, under normal operating conditions; each TPLS feeds its dedicated feeding zone with loop in loop out arrangement and if one TPLS happens to be out of service due to component failure or other faults, adjacent TPLS feeds the failed TPLS's feeding zones via the OCS using the link isolator switches as shown in figure 4. The traction power supply equipment of the AALRT TPSS are designed to maintain full operation services in the event of outage of nearby traction power supply system [13] and allows flexibility for load changeover in any emergency situations using the isolator switches.

Even though, the loop in loop out power supply system arrangement greatly contributes for a relatively reliable operation of AALRT, the frequent failure of underground 15kV power cables, main substation faults and SCADA communication failures are disturbing the operation. The traction substation equipment life time is also being deteriorated due to the resulting abnormal operation.

Therefore, to evaluate the reliability of the TPSS, data collection was conducted at the power supply division of AALRTS. The collected data includes the number of failures, the causes of component failures, the corresponding downtimes, the number of AALRT TPSS system failures due to component faults, TPSS diagrams, the number of active maintenance staffs and so on as shown in Appendix B.

## 2.1 Reliability Evaluation Modeling Method Selection

Nowadays, there are about five reliability analysis methods commonly used for TPSS reliability analysis; FMEA, FTA, RBD, BN and Monte Carlo simulation [1,3,4]. These methods are compared and the appropriate reliability modeling method for AALRT traction power system is selected in this thesis work.

In the last couple of decades, lots of reliability analysis techniques have been developed and refined in order to more accurately represent traction power systems [4, 22]. Qualitative reliability analysis methods have always been used to help identify all possible failures that could occur within a system, and the general risks associated with each of those failures. The most widely used qualitative method is failure modes and effects analysis (FMEA), sometimes also known as failure modes, effects and criticality analysis (FMECA). There are several quantitative reliability analysis techniques with various theories behind them [4]. Nowadays, the traction power reliability analysis methods that are widely used are fault tree analysis (FTA), reliability block diagrams (RBD), Bayesian network (BN) and Monte Carlo simulation [1,3, 4]. These methods are discussed in the following sections.

### **Failure Modes and Effects Analysis (FMEA)**

For qualitative reliability analysis of traction power systems, FMEA is the most commonly used method. It is an inductive method used in the development of products in order to identify and classify fault modes and effects [4]. FMEA's goals are to assess the effects of failure modes of the components in the functions of a system and identify those that affect significantly the aspects of reliability, availability, and maintainability of the system.

The purpose of the FMEA is the definition of the problem and to establish a level of resolution for the analysis. It has 3 objectives set [1]: identify and analyze all potential failures and

assessing the effects; identify actions to eliminate or significantly reduce system failures and consequences associated; document the system from a functional point of view at the design and operating phase.

Further, FMEA helps to determine the levels of analysis, especially the initial and the bottom level which starts from the basic units in bottom level, find the fault modes, fault causes and effects of each unit [4]. In addition, FMEA helps to model FTA fault trees.

### **Fault Tree Analysis (FTA)**

FTA is one of the principal commonly used tools in reliability and risk assessment, analyzing the relationship between components failures and system failures [9]. It is a top down deductive analysis which enables identification of the critical aspects to the possible failures of the systems and provision of qualitative and quantitative system reliability analysis [1,4]. It gives a visual model of how equipment failure, human error and external factors have contributed towards an accident or event [4]. It uses logical gates and small events to present the path of an accident through different steps and hence a fault tree is constructed for the particular event. The technical failures can be represented as basic event while human errors can be represented as intermediate events that may intensify to become a technical failure [1,3,4]. A fault tree analysis can be simply described as an analytical technique, whereby an undesired state of the system is specified, and the system is then analyzed in the context of its operation to find all credible ways in which the undesired event can occur [4].

Reliability analysis of traction power system using FTA has some benefits and limitations. The major drawback is when applying the FTA, assumptions are made that there are only two states in the system, normal and failure and the events in the system are independent of each other [15].

However, in real-world systems, in addition to perfect functionality and complete failure, an element may have several intermediate states.

### **Reliability Block Diagram (RBD)**

The Reliability Block Diagram (RBD) is a useful analysis tool used to evaluate the reliability of traction power systems [22]. By RBD method, the functional components of the system are represented by simple blocks, linking them in serial path or in parallel path respectively if the fault of a single unit affects directly the working of the entire system, or if this fault can be bypassed through an alternative path. The RBD has nothing to do with the functional block diagram of the system behavior: the aim is to represent the reliability relations between components and system.

The structure of a reliability block diagram defines the logical interaction of failures within a system and not necessary their logical or physical connection together. The diagram can represent an entire system or any subset or combination of that system which requires failure, reliability or availability analysis.

### **Bayesian Network (BN)**

Bayesian network (BN), also called the reliability network, is a kind of probability network, it is based on probabilistic graphical network [4]. BN is a kind of uncertainty expression and bidirectional reasoning model based on probability theory and graph theory, which is more suitable to solve uncertain problems than FMEA, FTA and RBD [4]. It is a directed acyclic graph; it is represented by variables of nodes and connecting the nodes of directed arcs. After years of development and perfection, it has become an effective evaluation of reliability [4].

BN uses nodes to represent variables and directed arcs between nodes represent the relationship between variables, through the graphical expression of uncertain knowledge, through annotations

of the conditional probability distribution [5]. It is more powerful to deal with uncertainty, but more difficult to construct than FMEA and FTA. So, it is less preferable than the FTA as it works for uncertainty than the analyzing the failure, like the one in this thesis.

### **Monte Carlo simulation**

Monte Carlo simulation is the most versatile modeling methodology available [21]. The methodology can be implemented in many forms from simple models in a spreadsheet environment to complex models that are “handcrafted” in a programming language of choice.

The Monte Carlo simulator operates on an iterative process where each of the “iteration” represents a description of what the system could experience through a set mission life. For instance, if we consider the past experience of a system, including what really failed, that experience was only one of infinite possible outcomes that depended on the failure characteristics of that system.

Thus, Monte Carlo simulation looks forward by considering possible scenarios that could occur in the future and those scenarios, with their associated likelihoods, is dependent on the failure characteristics applied to the system components. However, it has some modeling limitations due the need for variety of data [21] that leads it not be a perfect choice for traction power system reliability analysis, of course for the purpose of reliability analysis of AALRT TPSS.

#### **2.1.1 Comparison of Reliability Analysis Modeling Techniques**

To analyze the reliability of AALRT TPSS, appropriate methods have to be selected based on some characteristics, such as; analysis direction or appropriateness, expression form, analysis capability, function and modeling difficulty [4, 23]. The criterion for using these characteristics is to help select the appropriate methods. In doing so, bi-directional, visually ease, relatively easier to model, ability to analyze both qualitative and quantitative reliability and the ability to

## **RELIABILITY ANALYSIS OF AALRT TRACTION POWER SUPPLY SYSTEM**

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analyze the failure causes, modes and effects comprehensively in a simple logical order are considered. The characteristics of the five methods, FMEA, FTA, BN and Monte Carlo simulation are compared as shown in table 1.

Table 1: Comparison of FMEA, FTA, RBD BN and Monte Carlo simulation

Characteristic	FMEA	FTA	RDB	BN	Monte Carlo Simulation
Analysis direction	From bottom to top	From top to bottom	From bottom to top	Bidirectional analysis	Bidirectional analysis
Expression form	In the form of tables	In the form of trees	In the form of blocks	In the form of networks	In the form of blocks and software codes
Function	Qualitative analysis	Qualitative and quantitative analysis	Qualitative and quantitative analysis	Qualitative and quantitative analysis	Qualitative and quantitative analysis
Analysis capabilities	Can analyze failure modes comprehensively, can't reflect the combined effect of failure.	Can analyze failure causes comprehensively and represent simple logical relationship by AND gate and OR gate.	Can represent an entire system or combination of that system but can't analyze their logical or physical connection together.	Can reflect uncertain characteristics of complex system, e.g. multi-state, failure correlation and uncertain logical relationship.	Can analyze failure causes comprehensively and represents a description of what the system could experience through a set mission life.
Modeling difficulty	Easy	Difficult	Difficult	More Difficult	Most Difficult

As shown in table 1, reliability analysis methods characteristics are compared. All of them have their own importance for reliability analysis of traction power supply system. In terms of function all except FMEA enables to analyze both qualitative and quantitative reliability. One of the important characteristics, which help to differentiate the methods, is the analysis capacity. In

this case, the requirement of this thesis work is the ability to analyze the failure causes, modes and effects comprehensively in a simple logical order. Thus, FMEA and FTA can fulfil these criteria by complementing to each other. To achieve qualitative reliability analysis, FMEA can be used. The rest of the methods; FTA, RBD, BN and Monte Carlo simulation can be used for quantitative reliability analysis of TPSS.

One of the benefits of the fault tree is the inherent organization that comes with the creation of a fault tree. The process of creating such a top-down approach model helps to organize all of the events much more than if the same model is created in a bottom-up approach such as RBD. It becomes much easier to find a specific event in a model, or trace the effects of a given event when the model has been broken down from a system level all the way to the component level [22]. Moreover, the selection of FTA for reliability analysis has lots of benefits, such as deductive failure identification, highlight the important elements related to system failure, provides an alternative way to analyze the system, focuses on one fault at a time, expose system behavior and possible interactions, and amount for human error. However, in RBD and BN the subsystems are not necessarily identified, and since it is merely the accumulation of all of the basic events, in order to get the failure probability of a subsystem, one would need to create a new model to obtain this value.

Even though, Monte Carlo simulation has become the most versatile reliability analysis method, it has got some limitations, such as large network size, the requirement of smart distribution function, modeling hurdles and modeling solutions with sophisticated software are found to be inappropriate for reliability analysis of AALRT TPSS.

In summary, there are of course advantages and disadvantages to all methods being considered. There is no one reliability analysis technique that is superior to all others for every case, and

decisions on which technique is to be used to analyze a given system should always be made on a case by case basis. Since the FMEA and FTA can complement each other to a certain extent, they can be used for qualitative and quantitative TPSS reliability modeling and analysis respectively [4, 9]. Therefore, integrating Failure Mode and Effect Analysis (FMEA) and Fault Tree Analysis (FTA) is found to be significant to model and analyze AALRT TPSS reliability based on the failure data collection.

### 2.2 Reliability Distribution Method Selection

In this section, different reliability distributions, which are commonly used for traction power supply system reliability analysis, are briefly discussed and the appropriate one is then selected.

There are many reliability distribution methods commonly used for reliability analysis of traction power supply system [23]. Exponential distribution and Weibull distribution are the most commonly used reliability evaluating techniques.

**Weibull distribution:** It owes its name to Prof. Waloddi Weibull who created a versatile function that allows modelling and evaluation of reliability. The function has three calibration parameters:  $\gamma$ ,  $\beta$  and  $\alpha$ . These are adjustment parameters that allow the function to produce reliability and MTBF results from test values. The parameter  $\gamma$  is normally known as the location parameter. Parameters  $\beta$  and  $\alpha$  are known as shape and scale parameters respectively. The special case of  $\beta=1$  and  $\gamma=0$  is a simplification of the Weibull function which yields the exponential distribution.

It is used for evaluating reliability parameters of power systems in the case of a non-constant failure rate, especially in mechanical components [21]. The reliability of TPSS can be mathematically expressed as:

$$R(t) = \exp\left[-\left(\frac{t - \gamma}{\alpha}\right)^\beta\right] \dots\dots\dots (1)$$

The function of failure rate with parameter t is given by the Weibull function expression shown below [21]:

$$\lambda(t) = \frac{\beta}{\alpha} \left(\frac{t - \gamma}{\alpha}\right)^{\beta-1} \dots\dots\dots (2)$$

**Exponential distribution:** The exponential distribution is a simple distribution with only one parameter and is commonly used to model reliability data [23]. The exponential distribution is actually a special case of the Weibull distribution with  $\beta = 1$ . For a system that obeys an exponential distribution, the reliability (R(t)) is mathematically expressed as shown below.

$$R(t) = \exp(-(\lambda t)) \dots\dots\dots (3)$$

If exponential distribution is selected, it is not necessary to know the time to failure for each failure, instead the total time and number of failures. An important property of the exponential distribution is that it is memoryless. The memoryless property indicates that the remaining life of a component is independent of its current age. Hence, this distribution is used when the failure rate is assumed constant during the mission times of the equipment.

### 2.2.1 Summary of Reliability Distribution Selection

From the discussions above, it is important to understand that the selection of distribution function for reliability analysis relies on the failure rate of the system under study. The failure rate can be considered either constant or non-constant depending on the number of failure data, types of system component and so on.

For the reliability analysis of traction power supply systems of a large number of failure data, constant failure rate is usually assumed [21]. According to the above discussions and researches

[15, 18, 21] with large numbers of data for different types of component failures, a component during the effective life cycle, the failure rate  $\lambda(t)$  is taken to be nearly a constant.

The reasons for making the constant failure rate assumptions are many. One of the reasons is that the aging process of components involved in a system seldom is clear. However, even if the process is clear, there are still a couple of obstacles, for example components in a system might work in different environments and they might be utilized differently. A related problem is to keep track of the age for all components. Ease of calculation and data assessment is another motive, exponentially distributed failure and repair times result in constant failure and repair rates, which is a property that makes the modeling easier. The other assumption of constant failure rate is that preventive maintenance becomes virtually unnecessary. As the implementation of the preventive maintenance strategy for AALRT TPSS is observed to be poor, assuming a constant failure rate for components will be reasonable. When the failure rate is assumed to be constant, exponential distribution will be used.

Based on the above reasons, exponential distribution is selected to be applied to calculate the reliability evaluation indexes of AALRT TPSS in this thesis work. Hence, for the quantitative reliability evaluation of AALRT TPSS, exponential distribution equations are used for calculating the reliability parameters by being applied in to the developed MATLAB code.

### **2.3 Reliability Evaluation Models of AALRT TPSS Using FMEA and FTA**

In the previous chapter, reliability analysis methods; FMEA and FTA, are selected based on their benefit to determine the qualitative and quantitative reliability of AALRT TPSS by complementing to each other. FMEA and FTA are used for evaluating the qualitative and quantitative reliability via FMEA tables and fault tree respectively accompanied by the exponential distribution.

The general idea of this method is as follows. First, AALRT TPSS failure modes and consequences are analyzed and FMEA tables are established according to the actual system composition, including traction substation equipment, catenary system equipment, communication device and AC main substation. Based on the FMEA table, the FTA model of the AALRT TPSS is then constructed. At last, the system reliability indexes and other derived parameters are calculated applying exponential distribution equations in to the MATLAB code.

In general, the reliability modeling procedures are shown in figure below.

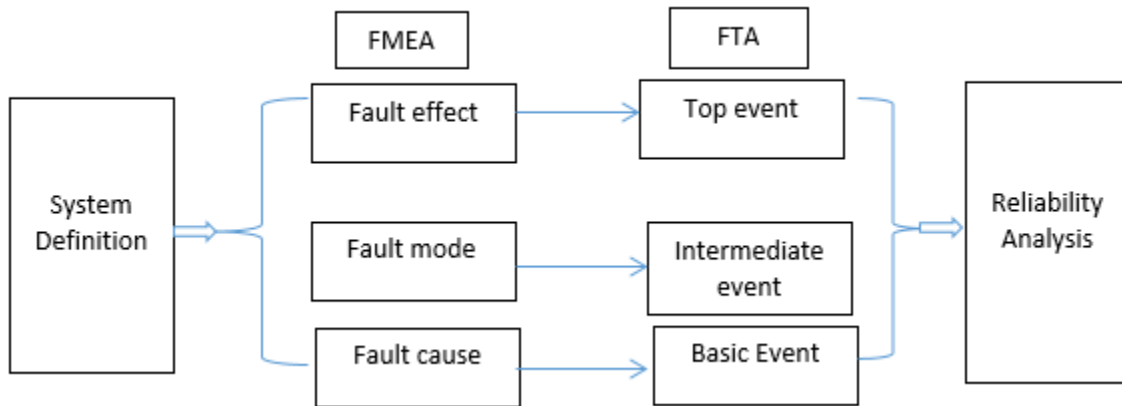


Figure 11: Flow Chart of FMEA to FTA

### 2.3.1 Establishment of FMEA

FMEA allows evaluating the behavior of a system via hierarchically decomposing into levels of detail, to understand the failure modes and all the causes that lead to the crisis of a component or the whole system. It enables the bottom-up approach, from small details to the higher levels, which is normally the practice for conducting reliability analysis. To establish FMEA table, the critical failure of AALRT TPSS system are briefly analyzed in the following section.

### Failure Analysis of AALRT TPSS

A traction power supply system is composed of traction substation and traction network. In addition to these subsystems, the operation of AALRT TPSS relies on the main substation and

SCADA communication operating status. Thus, the major factors that determines the normal operation of the system can be categorized in to four subsystems; traction substation, traction network, main substation, and SCADA communication for the study of the reliability of AALRT TPSS. Accordingly, the functions and the power outage contributions of those subsystems for the operation of AALRT TPSS are briefed hereafter.

**Traction substation:** It converts 15kV power incoming from the nearby AIS to traction used energy. Electric equipment in AALRT traction substation can be divided into four categories; transformation equipment, control equipment, protection equipment and compensation equipment.

Transformation equipment is the equipment used to convert voltage or current, such as rectifier transformer, rectifier, VT, CT and so on. Control equipment is used to turn on/off control circuit, such as high and low voltage switch devices. From the collected data, in AALRT TPSS operation, the AC 15kV circuit breaker closing coil had been damaged seven times which prevented the TPLS power not to be able to automatically recover after outage due to some other faults. Protection equipment is used to protect circuit from over voltage or overcurrent, such as high/low voltage fuse and lightning or surge arrester. From, the collected data, the transformer surge arrester had been failed three times that forced the traction substation operation to be stopped for safety. Compensation equipment is used to compensate reactive power of the circuit and thus increase power factor, such as high/low voltage capacitors and static compensator. Generally, the fault in one of its components resulted in the failure of the traction substation.

**Traction network:** is an electricity grid for the supply of electrified light rail networks of AALRTS. It consists of a series composition of power supply components, such as feeding section, 15kV power cable, OCS feeder cable, Overhead contact system (OCS), track, stray

current collection cables, overvoltage protection devices (OVPD) and the like. The failure of one of the above components had been resulting in the failure of the traction network, if not, the failure of the overall AALRT TPSS. Till October 2018, most of faults occurred in AALRT TPSS are due to failures of 15kV power cable, OCS, track and return system as shown in Appendix B. There are lots of reasons for the 15kV power cable failure which includes under voltage, overcurrent, rodent attack, and the like, but the root case needs further investigation with scientific experiments. The recorded OCS failures are cantilever failures due to lightening, catenary failures due to sparking by pantograph to contact wire interaction, and on-grid isolator switches failures. The return system failures are caused from the over voltage protection device (OVPD) failure due to various electrical and mechanical problems, stray current collection cable failures due to construction work at the rails, theft and so on and track failures are due to mechanical damage to the rail.

**Main substation:** its main function is to receive high voltage power from the dedicated EEU power grid of 132/15kV for AALRTS, turns into switching substations (AIS) after step-down. AIS supplies middle voltage power (15kV) to the traction substations, also called TPLS.

The recorded factors of the occurrence of faults at the main substation are different, such as incompatibility due to relay setting variation between AIS and TPLS and technical errors or blackouts at the GIS or AIS. The author of this thesis observed that the relay setting variation needs coordination work between AALRTS and EEU, but the root cause of technical errors or blackouts need further detail investigation.

**Supervisory control and data acquisition (SCADA) communication:** SCADA systems are employed for simultaneous acquisition of a large amount of data, real time processing, display and supervisory control. The failure of SCADA at a traction substation means that OCC cannot

get information about the power supply status which leads the operation interruption for that specific area where the TPLS supplies. The SCADA fault that has been recorded so far is dead halt. This failure has been temporarily solved by resetting it and reporting for the manufacturer for further action.

According to [18], SCADA dead halt occurs when it locks up and does not allow the processing of further commands. This event is more commonly referred to as a freeze or lockup of the SCADA. When a dead halt occurs, the only way to recover the SCADA is to reboot or reset.

The causes for SCADA dead halt may be hardware or software errors which needs detail study to provide long term solutions for the problem by local professionals.

**Traction Power System Interruption:** AALRT TPSS operation disruption has been occurred due to the faults at one or more of the components and subsystems of the traction power system. The failure data record shows that 59.8% of the faults are due to traction network equipment of which about 74% is due to 15kV power cable faults. About 24.5% of the faults are due to SCADA dead halts at TPLSs. The rest of the failures are due to main substation (13.3%) and traction substation (2.4%) failures. Moreover, about 90% of the operation interruption has been caused by traction power system failures, as of the operation statistics reports in AALRTS by OCC on September, 2018. The collected failure data are placed in table shown in Appendix B.

### **Constructing FMEA Table**

In the previous section, AALRT TPSS description and failure analysis are briefed. Based on the theoretical failure analysis, it is easier to determine the basic units in bottom level, find the fault modes, fault causes and effects of each unit. Then, from bottom to top, analyze the effects from the faults in lower level to the system in upper level step by step and form the FMEA table.

Then, FMEA table helps to determine the levels of analysis, especially the initial and the bottom level for qualitative reliability analysis. It also enables to construct FTA fault tree taking the fault of a basic unit as the top event, the fault modes as the intermediate events, the fault causes as the basic events. The terms used in FMEA are described as follows:

**Failure cause:** Defects in requirements, process, quality control, handling or part application, which are the underlying cause or sequence of causes that initiate a process that leads to a failure mode over a certain time. In other words, failure cause is a component fault or failure that leads the failure of a system. In AALRT TPSS the fault causes are 15kV power cable failure, OCS isolator switch failure, cantilever failure, contact suspension failure, OVPD failure, stray current cable failure, track failure, circuit breaker closing coil failure and transformer surge arrester failure. Additionally, SCADA dead halt fault and AIS failure are taken as failure causes.

**Failure mode:** The specific manner or way by which a failure occurs in terms of failure of the component function under investigation; it may generally describe the way the failure occurs. In this thesis, traction network failure, OCS failure, return system failure, traction substation, communication failure and main substation failures are taken as failure modes. In other words, they are subsystem failures of AALRT TPSS.

**Failure effect:** Immediate consequences of a failure on operation, function or functionality, or status of some item. The failure effect of AALRT TPSS is taken to be the traction power supply system interruption or failure.

Table 2: Fault mode effect analysis (FMEA)

## **RELIABILITY ANALYSIS OF AALRT TRACTION POWER SUPPLY SYSTEM**

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Basic Unit	Fault Cause	Fault Mode	Fault Effect	Response measures
Traction Power Supply System	<ul style="list-style-type: none"> <li>▪ 15kV power cable failure</li> <li>▪ OCS Isolator Switch failure</li> <li>▪ Cantilever failure</li> <li>▪ Contact suspension failure</li> <li>▪ OVPD failure</li> <li>▪ Stray current cable failure</li> <li>▪ Track failure</li> </ul>	<ul style="list-style-type: none"> <li>▪ Traction network failure; OCS failure and return system failure</li> </ul>	<ul style="list-style-type: none"> <li>▪ Power outage;</li> <li>▪ TPSS loses power</li> <li>▪ Operation interruption</li> </ul>	<ul style="list-style-type: none"> <li>▪ Prompt repair and replacement</li> </ul>
	<ul style="list-style-type: none"> <li>▪ Transformer Surge Arrestor failure</li> <li>▪ CB (Closing coil) failure</li> </ul>	<ul style="list-style-type: none"> <li>▪ Traction substation failure</li> </ul>	<ul style="list-style-type: none"> <li>▪ Power outage, operation interruption</li> </ul>	<ul style="list-style-type: none"> <li>▪ Switch to the other power supply line</li> <li>▪ conduct prompt repair</li> </ul>
	<ul style="list-style-type: none"> <li>▪ SCADA failure</li> </ul>	<ul style="list-style-type: none"> <li>▪ Communication interruption</li> </ul>	<ul style="list-style-type: none"> <li>▪ Operation disruption</li> </ul>	<ul style="list-style-type: none"> <li>▪ Reset the system and report to the manufacturer</li> </ul>
	<ul style="list-style-type: none"> <li>▪ AIS failure</li> </ul>	<ul style="list-style-type: none"> <li>▪ Main substation (AIS or GIS) failure</li> </ul>	<ul style="list-style-type: none"> <li>▪ Operation disruption</li> </ul>	<ul style="list-style-type: none"> <li>▪ Prompt repair and replacement</li> </ul>

### **Reliability Analysis Based on FMEA Table**

As shown in figure 2, the failure causes are the factors for the failure mode that in turn results the failure effect. The responses for the failure effects are provided to be prompting repair and replacement.

The failure modes of AALRT TPSS can be categorized as traction network failure and traction substation failure. The other failure modes are communication device (SCADA) failures and AC main substation failures that resulted in the power outage or operation interruption of the system. Traction network failure is nothing but the failures of one of its components; such as, 15kV power cable, OCS equipment, and return system or track failure. The 15kV power cable failure was led by ageing, application unsuitability, mechanical failure, and degradation of the cable sheath, moisture in the insulation, heating of cable, electrical overloading, rodent attack and etc. OCS failures were caused by vehicle crash, sparking burns between contact wire and pantograph interaction, isolator switches failure are caused by various electrical, mechanical problems and aging.

Traction substation equipment failure was caused from mechanical and electrical faults such as; overloading, over and under voltage or current, equipment outage, disconnection, wear overrun, electrical burns, wear, break, disconnection, electrical burns, fatigue overrun, rail potential rise and the like. Main substation (AIS/GIS) failures were caused by EEU technical error or blackout, and incompatibility of systems; like relay setting mismatch. SCADA failures were due to dead halt problems in which the root causes are not clearly known by the responsible department and the maintenance was being outsourced for the manufacturer.

Generally, the failures of the TPSS system can be classified as factors of material, operational use, operational environment, and electricity, etc. The reliability of the system can be increased by means of using components with higher reliability and by means of strengthening maintenance.

With analysis of causes of system failures, specific arrangements to improve the reliability of the system can be obtained as listed below:

1. For the components that are easily failed during operational process should be listed as key items for preventive maintenance and patrolling frequency should be increased. Based on the failure data collection as shown in appendix B; 15kV power cable, OCS isolator switch, catenary system components, stray current collection cables, SCADA and the like need serious concerns of mitigation actions.
2. For the OCS components that are easily failed by electrical factors during operational use, the lightning arrester facilities should be strengthened to prevent short circuits caused by lightning from happening, and highly quality insulation equipment should be used.
3. The basic events of cantilever and contact suspension system damages are caused by lightening, vehicle crashes, and sparking due to the rough interaction of contact wire and pantograph. These faults can be reduced by regular patrolling, maintenance, and cleaning.
4. The rest of the undeveloped events need further detail study for the root causes of the faults so that appropriate long term mitigation techniques will be provided.
5. For the frequent faults of the AC network, main substation, the concerned department should work with the power supplier, EEU.
6. The SCADA dead halt faults underlying cause investigation should be done with skilled personnel.

### **2.3.2 Reliability Analysis Model Using FTA**

In this section, using Fault Tree Analysis (FTA), the quantitative reliability analysis model of AALRT TPSS is constructed, to identify fault paths with low reliability index. The quantitative reliability of the system is conducted on the basis of the operation of AALRT TPSS in both NS and EW lines of the railway line. The operation failure data are collected for the statistical failure analysis of the system in the mission time of 27,360 hours. As it is already selected, FTA is used

for modeling the system to help analyze the failure causes comprehensively and to represent its logical relationship using gates.

### **Fault Tree Analysis**

Fault tree analysis, FTA, is a top down deductive analysis in which the causes of an event are deduced. It gives a visual model of how equipment failure, human error and external factors have contributed towards an accident or event. It uses logical gates and small events to present the path of an accident through different steps and hence a fault tree is constructed for the particular event [3, 4].

The AALRT TPSS can be considered as a series composition formed by two major categories; traction substation and traction network and its operation is monitored by the operation control center (OCC) with the help of SCADA communication.

The reliability of the traction power supply system is relevant not only to every single component, but also to the way they are composed or how they match each other. Thus, every single component failure will affect the normal operation of the TPSS [15]. The most unwanted system failure state is taken in FTA as the target for the fault analysis, and the selected system failure state is called the top event [4,15]. The analysis is then taken place to find all the possible factors that lead to a failed state. The tracing ends at the factors that are not necessary for any analysis, called basic events [3,4,15]. The general hypotheses are that the basic events are independent from each other, and only two states are considered for the top events and the basic events, normal or fault.

### **Construction of Fault Tree**

The fault tree is a model reflecting the causal relationship among the system faults [15]. To identify the causes for the TPSS failures, the study summed up the key failure factors leading to

the power supply failures based on data of a total of 421 AALRT TPSS faults during the period of operation in the mission time of this thesis work.

Based the FMEA table, to model FTA, take the fault causes as basic events, fault modes as intermediate events and fault effects as top events as shown in figure 11. Accordingly, as the top event, intermediate events and the basic events are identified, the fault tree can be constructed using FTA symbols with the help of FMEA table. Hence, the traction power supply system interruption is taken to be the top event of the fault tree that is the most unwanted system failure state.

The basic principles of constructing the TPSS fault tree is as follows: only the system's critical components were considered; the events with lesser impact on the system were not considered to simplify the model; the events that had not been investigated were taken as basic events.

When building a fault tree, the following steps are followed [3, 4]:

- Identify the top event; i.e., traction power supply failure
- Identify the first-level events; i.e., failure modes; traction network failure, traction substation failure, communication interruption, and main substation failure.
- Link these first-level events to the top event using gates; use OR-gate
- Identify the second-level events; i.e., OCS failure and return system failure.
- Link these second-level events to the top event using gates; use OR-gate
- Identify the second-level events; i.e., the basic events; 15kV power failure, OCS isolator switch failure, cantilever damage, contact suspension failure, OVPD failure, return current collection cable failure, track failure, transformer surge arrester failure, circuit breaker failure, AIS failure, and SCADA dead halt.
- Link these second-level events to the top event using gates; use OR-gate

### Definitions of FTA Symbols

The symbols used in the fault tree represent specific types of faults and normal events in FTA [3]. The circle (oval) stands for the basic initiating fault event that requires no further development. The undeveloped event, the diamond-shaped symbol, represents an event that is not examined further because information is unavailable that will be open for further detail study for the root causes of their failure. AND-gate indicates that the output event occurs only if all the input faults occur at the same time. The OR-gate indicates that the output event occurs only if one or more of the input events occur.

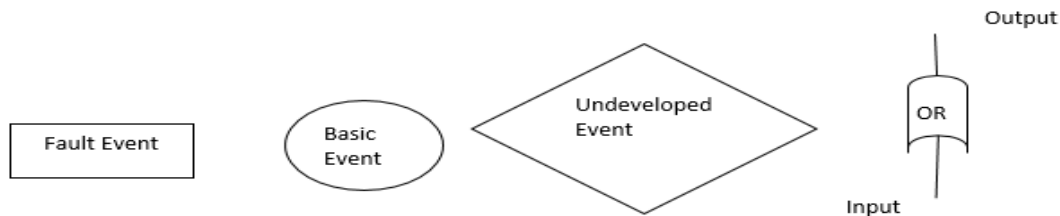


Figure 12: Fault Tree Symbols

**Top event:** The top event is the foreseeable and undesirable event of the system under analysis. A fault tree uses rectangular to symbolize both the top event and intermediate events. The intermediate event is a fault event that occurs because of one or more antecedents causes acting through logic gates. Since AALRT TPSS is considered to be series composition of components, only OR-gate is utilized for linking the events.

Generally, traction power supply interruption is considered as the top event which is the most undesirable event by which the overall system fails to operate. The intermediate events are the failures modes of FMEA table that are main substations failure and the communication interruption, traction network failures, and traction substation failure. The basic events and undeveloped events are the failure cases of FMEA table that are placed at the end or leaf of the fault tree. There are four basic events of AALRT TPSS fault tree whose fault or damage reasons

are clearly defined; i.e., cantilever failure, contact suspension damages, track failure and stray current collection failure. Cantilevers were damaged due to lightening and vehicle crash. Contact suspension wires were damaged by vehicle crash and sparking burns between contact wire and pantograph interaction. Rail tracks were damaged by sliding movements of wheels or intentional construction. The stray current collection cables were damaged due to rail gap adjustment or theft or ageing or wear out. The rest seven are undeveloped events that are taken as basic events because of the need for further detail scientific investigation for the underlying cause of the faults; though, some of the possible causes are listed in the qualitative reliability analysis section. According to the above principles, the TPSS fault trees can be built as shown in figure 13. The top of the fault tree is the overall TPSS failure.

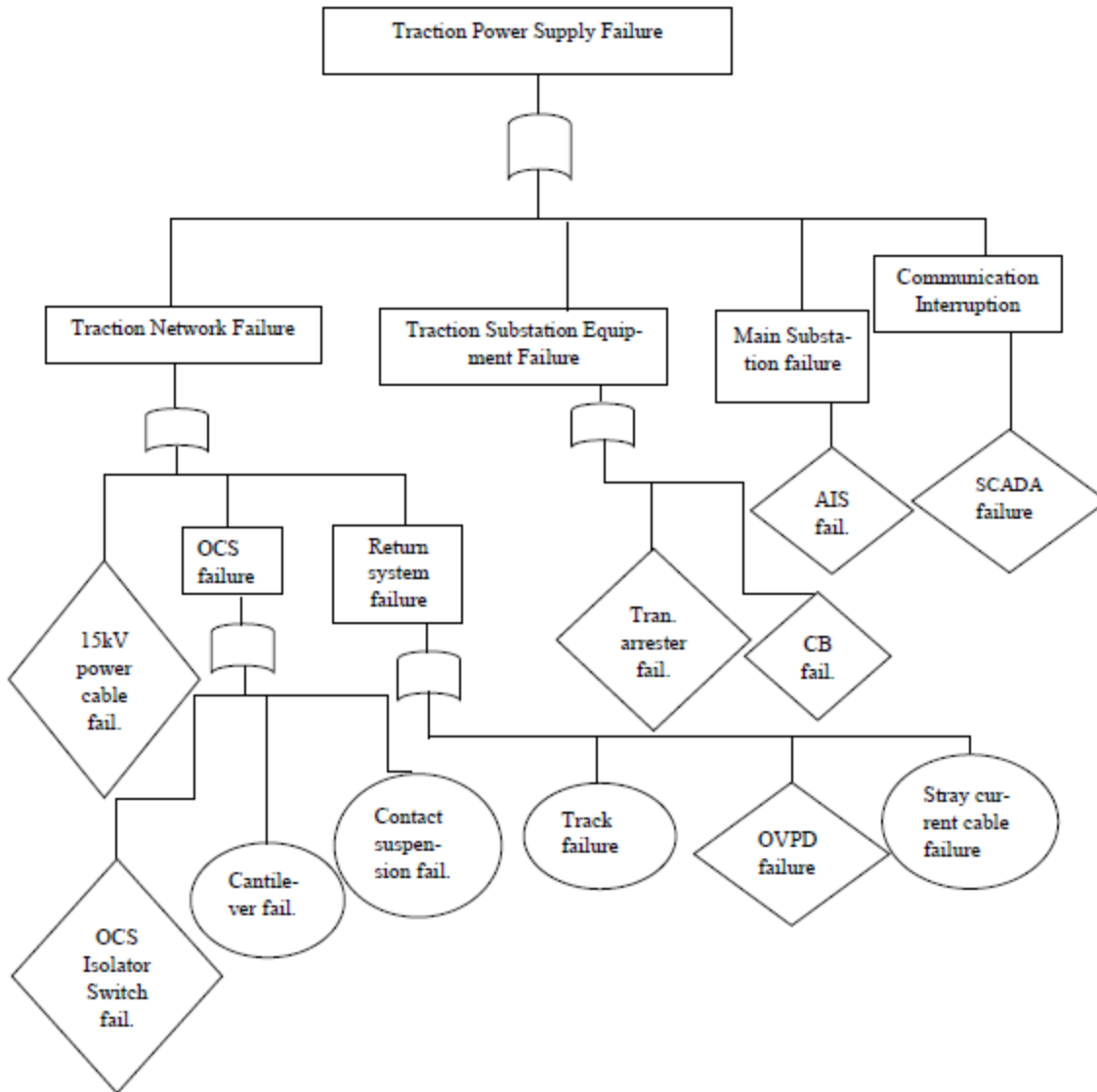


Figure 13: Fault Tree

Figure 13 show that traction power supply failure is the top event that occurs when one of the intermediate events, such as traction network or traction substation or main substation or the communication devices, fails. Similarly, the intermediate events fail when one of its components or subsystems fails. In other words, the fault tree vividly shows how the failures of the TPSS components or FTA basic events affect the overall operation. Hence, based on the FTA model of the above fault tree, the reliability evaluation indices can be calculated using the selected distribution methods.

### 2.3.2.1 Statistical Reliability Analysis Using Reliability Evaluation Indexes of TPSS

In the FTA fault tree, AALRT TPSS is decomposed from top to bottom that helps to clearly understand the fault paths and easily calculate the numerical values of the reliability parameters of the components and the overall system.

As discussed in the previous chapter, AALRT TPSS is assumed to obey exponential distribution for calculating the reliability evaluation indices. In order to comprehensively evaluate the reliability of the TPSS, this thesis adopts five evaluation indexes, such as failure rate, MTTR, MTBF, repair rate and unavailability or availability. Additionally, referencing to the existing importance indexes [10]; two importance indexes are defined to characterize the weakness and importance degree of components. They are described in the following section.

To make the calculation results of the reliability analysis of AALRT TPSS precise, MATLAB code is developed by applying the reliability parameter calculating equations of the exponential distribution as shown in Appendix C.

#### Exponential Distribution Equations

The reliability function mathematically defines the probability over the duration. It is a function of time that provides the probability of success or surviving till a time of interest. The exponential distribution of reliability function has only one parameter, lambda or its inverse, i.e.,  $\lambda$  or MTBF.

The hypothesis that failure rate  $\lambda(t)$  for each component of the AALRT TPSS obeys the exponential distribution is given in the thesis. The reliability function ( $R(t)$ ) in an exponential distribution is as shown in the equation (3):

#### Reliability Evaluation Indexes for TPSS

It has been noted that reliability is the ability of a product to perform without failure, a specified function, under given condition and for a given period of time. In many cases, it is convenient to specify the reliability of the system by some parameters which indicate the failure rate of such a system or equipment and also independent upon the operating time. The parameters made it possible compare performance between different systems with various operating periods.

Commonly used parameters include:

- Mean time between failures (MTBF)
- Mean time to repair (MTTR)

**Mean time between failures (MTBF):** The concern of system operators is usually the length of time that a system will run without failure. This is regarded as the measure of its reliability. For repairable system, the time between failures is the critical characteristics.

MTBF can be obtained by running equipment for predetermined length of time under specified conditions and calculating the average length of time between failures is exponential, thus, MTBF is the mean or average time between consecutive failures. Low MTBF could either indicate poor handling of the component by its operators or a poorly-executed repair job in the past. Mathematically, MTBF is expressed as:

$$MTBF = \frac{\text{Total Operating Hours}}{\text{Number of Failures}} \dots\dots\dots (4)$$

For N identical systems;  $MTBF = \frac{N \cdot T_{up}}{F}$ , where N is the total number of equipment,  $T_{up}$  is the total operating time and F is the total number of failures.

**Mean Time to Repair (MTTR):** refers to the amount of time required to repair a system and restore it to full functionality. The MTTR clock starts ticking when the repairs start and it goes on until operations are restored. This includes repair time, testing period, and return to the normal operating condition. For a constant failure rate ( $\mu$ ), it is mathematically expressed as:

$$MTTR = \frac{\text{Total Maintenance time}}{\text{Total number of repairs/failures}} \dots\dots\dots (5)$$

For many identical systems;  $MTTR = \frac{N \cdot T_d}{F}$ , where N is the total number of equipment, Td is the total maintenance time and F is the total number of failures.

**Availability:** The availability of equipment is the ease by which the equipment can perform within a planned period of time. Adequate reliability in the power system and equipment is a sine-qua-non since it ensures efficient and effective operation of electrical equipment and electro-technical components eliminate or reduce high failure rate and maintenance.

The equipment availability is determined by its maintainability and reliability. In particular, when equipment failures and repairs obey exponential distribution, the availability A ( $\infty$ ) converges to a constant that is not related to time (t), i.e. the steady-state availability, A. Hence, the operational availability of the TPSS component can be expressed as follows:

$$A = \frac{MTBF}{MTBF+MTTR} \dots\dots\dots (6)$$

Correspondingly, the steady-state unavailability U is expressed as:

**Maintainability:** deals with duration of maintenance outages or how long it takes to achieve (ease and speed) the maintenance actions compared to a datum. The datum includes maintenance (all actions necessary for retaining an item in, or restoring an item to, a specified, good condition) is performed by personnel having specified skill levels, using prescribed procedures and resources, at each prescribed level of maintenance.

**Reliability of Component System Configurations**

AALRT TPSS is composed of components that work together to form a configuration and execute a goal of delivering reliable power. The following are possible system configurations.

**Series System:** A system in which all the components are arranged in series. A series system fails whenever one of the components fails. If a series system consists of reliability R1, R2, R3, R4...Rn. The system reliability Rs, will be:

$$R_s = e^{-\lambda_1 t} * e^{-\lambda_2 t} * e^{-\lambda_3 t} * e^{-\lambda_4 t} * \dots e^{-\lambda_n t} \dots \dots \dots (7)$$

Where,  $\lambda_1, \lambda_2, \lambda_3, \lambda_4 \dots \lambda_n$  are the failure rates of the component.

Similarly, availability for series x and y components will be:

$$A = A_x * A_y \dots \dots \dots (8)$$

**Parallel System:** is a system in which constituent components are connected in parallel. A parallel system fails when all the components have failed. In parallel system, the system reliability is expressed as:

$$R_s = 1 - e^{-\lambda t} \dots \dots \dots (9)$$

Similarly, availability for parallel x and y components will be:

$$A_s = 1 - \text{Unavailability}$$

If x and y are similar power supply components connected in parallel with availability Ax, then the operational availability will be:

$$A_s = A_x^2 + 2A_x(1 - A_x) \dots \dots \dots (10)$$

Generally, AALRT TPSS is considered as a series composition of traction substation, voltage reducing substation, feeder line, contact network, running track, return line, stray current flow protection system. For series repairable system, the reliability index data of the failure rate  $\lambda_s$ , the mean time to repair  $\gamma_s$ , and the unavailability  $U_s$  of the traction power supply system can be obtained by summing the individual reliability indexes of the components or subsystems. Hence, the TPSS failure rate is the sum of the failure rates of traction network, traction substation, and main-substation and SCADA communication as shown in equation [9] below.

$$\lambda_{system} = \lambda_{Tr} + \lambda_{ss} + \lambda_{SCADA} + \lambda_{AIS} \dots\dots\dots (11)$$

The unavailability  $U_s$  of the TPSS can be calculated as follows:

$$U_{System} = U_{Tr} + U_{SS} + U_{SCADA} + U_{AIS} \dots\dots\dots (12)$$

The mean time to repair ( $\gamma_s$ ) of the TPSS can be calculated as follows:

$$\gamma_s = \frac{U_s}{\lambda_s} \dots\dots\dots (13)$$

For such series and repairable TPSS reliability analysis, there are three commonly used important indices, namely, the failure rate  $\lambda$ , the mean time to repair  $\gamma$ , and the unavailability  $U$ , where  $U$  is the product of the failure rate  $\lambda$ , and the mean time to repair,  $r$  [15].

The reliability indices of a series system are shown in the equations (14) to (16) as follows:

$$\lambda_s = \sum_{i=1}^n \lambda_i \dots\dots\dots (14)$$

$$\gamma_s = \frac{\sum_{i=1}^n \lambda_i \gamma_i}{\sum_{i=1}^n \lambda_i} \dots\dots\dots (15)$$

$$U_s = \sum_{i=1}^n \lambda_i \gamma_i \dots\dots\dots (16)$$

Generally, to calculate reliability parameters, exponential distribution function equations listed from (1) to (15) are applied to develop the MATLAB code shown Appendix C. The results of the reliability indexes of TPSS components, subsystems, and the overall system are provided in the form of tables and charts in the result section.

**2.4 Reliability Importance Measure**

The importance measure is the focus of fault tree analysis. The main purpose is to determine weak links of the system in order to improve the design, or as an important reference for

maintenance. Calculation of the importance measure of the TPSS components has two major advantages. First, the critical component can be easily identified and hence the overall reliability can be improved with minimum cost. Secondly, efficient ways to diagnose system failure are provided by a maintenance order check list.

Due to the influences from each basic event of the fault tree on the system failures being different, an importance measure method must be used to measure the degree of importance affecting the occurrence of the fault tree top events. There are various approaches or formulae used by different researchers for evaluating the importance measure of equipment on the system. Birnbaum's structural importance defines component importance as the component's number of occurrences in critical paths, normalized by the total number of system states. One drawback with this method is that it does not take probabilities into account, though; the author claimed that this is the whole idea with such an index. Such a method is interesting in the case of sparse reliability data and could moreover be used for identifying critical component positions in new designs. Another reliability importance index approach that enables to identify the impact of TPSS components on the overall system is used in [10] and it is adopted for this thesis as follows.

**Importance index**

**a. Importance of Basic Unit**

The basic unit importance  $I_i$  refers to the ratio of the number of system failures  $z_i$  caused by the failure of the equipment  $i$  to the number of failures  $Z_i$  of the equipment  $i$  itself. It indicates the weakness of the equipment itself, which can reflect the impact of failures in equipment on the system. The calculation formula is expressed as:

$$I_i = \frac{z_i}{Z_i} \dots\dots\dots (17)$$

**b. Mode Importance of Basic Unit**

The basic unit mode importance  $M_i$  refers to the ratio of the number of system failures  $z_i$  caused by the failure of the equipment  $i$  to the total number of failures  $Z$  of the system. The basic unit mode importance is related to the failure rate of equipment, indicating the possibility of system failure caused by the equipment, which reflects the importance of the equipment to the system. The calculation formula is expressed as:

$$M_i = \frac{z_i}{Z} \dots\dots\dots (18)$$

From the above two approaches, importance index is adopted to determine the weak links or importance measure of the components of AALRT TPSS in this thesis. Hence, the basic unit importance ( $I_i$ ) and the mode importance of the basic unit ( $M_i$ ) results are calculated via MATLAB applying the above equations.

### 3. Suggestions of Reliability Mitigation Techniques

In this chapter, different reliability mitigation techniques are proposed based on the results of the reliability evaluation indices of AALRT TPSS.

#### 4.1 Introduction to Reliability Mitigation Techniques

In this thesis work, the main focus was evaluating and analyzing the reliability of the AALRT TPSS based on the collected failure data of power supply components that led to the interruption of the operation. The reliability evaluation was achieved by calculating the reliability parameters, such as failure rate, MTTR, MTBF and availability or unavailability.

The qualitative and quantitative reliability evaluation result of AALRT TPSS indicated that the need for applying different mitigation techniques to improve its poor reliable operation. Based on the quantitative reliability results, emphasis for the frequently failing system components, such as; 15kV power cable, OCS isolator switches, catenary failures, SCADA communication and main substation (15kV AIS), is provided in the development of reliability mitigation techniques.

Reliability of traction power supply systems is usually provided by the redundancy of elements and circuits in the substation and beyond it [23]. A typical DC traction substation has two high voltage feeders, two transformers and rectifiers, two sections of distribution bus; each section of catenary is fed by two breakers from the two adjacent substations [23]. Automatic recloses, using closing coils, are used on distribution breakers to restore power as quickly as possible in case of self-clearing short circuits or other power outages due to feeder cable faults or any other. The emergency back-up power system (EBPS) should provide standby power for communication and

signaling devices that are remotely controlled by operation control center (OCC), for 24 hours of operation during an extended system-wide power outage [23].

In general, to improve the poor reliable operation of AALRT TPSS, applying the following mitigation techniques are suggested for reducing the downtimes and the number of failures of the system. Firstly, introducing emergency or standby power is considered for AALRT TPSS operation. Secondly, suggesting some selected redundant traction substation equipment to improve the low MTBF and high MTTR values considering the available of space for the second set of equipment. Finally, to improve the operational reliability of the system, the need for applying various approaches of maintenance activities are assessed.

### **4.2 Emergency or Standby Power Supply**

Achieving the necessary degree of reliability of the traction power supply in utilization equipment that, for a variety of reasons, cannot tolerate outages and quality problems experienced with the normal power supply, often leads to application of emergency or standby power supplies. These power supplies can provide necessary acceptable power during the times the normal power supply is not acceptable or is not available.

Though, railway power supply must be as such strictly reliable, the reliability evaluation result of AALRT TPSS indicated poor reliability of the system with high failure rates of the components. One of the reasons for this poor reliability is the absence of emergency or standby power supplies in AALRT TPSS. Hence, introducing standby or emergency supplies into the TPLSs to improve its reliable operation, after a detail load analysis of the selected loads is proposed. For instance, some of the necessary loads that require backup power are OCC, communication, signaling and water supply loads.

There are only battery system back-up power supplies in AALRT TPSS substations which are primarily provided for the purpose of feeding power to the communication devices in case of failure of the main power supply fault. The TPLSs and step down substation of AALRT TPSS do not have a reliable backup power supply for a duration lasting two hours except the small scale 18 batteries of about 12 to 14V capacities. The frequent power outages result in the frequent discharging of those backup batteries for a long time. They are also being deteriorating so fast and such lead-acid batteries are considered to be dead when their capacity drops to 80% of their original design [22].

The standby power supply type to be used might be automatically switching diesel generators or any alternative. To quantitatively illustrate the importance of introducing standby power supply systems, a typical circuit that enables to evaluate its effect on the availability of the system is shown in figure 15.

The calculation results of MTBF, MTTR and availabilities of each component are summarized in table 4 and also the availabilities of each TPSS component are provided in the same table. Here, let's consider a typical circuit that represents the mainline TPLS to analyze the combined reliabilities of the AC power supply (R), traction substation and DC supply systems, and then the availability of AALRT TPSS is assessed. The life time of the equipment are assumed to be 30 years.



As shown in figure 16, another alternative power source is added which represents a standby power supply. Accordingly, AALRT TPSS availability is calculated as;

$$A = R_p * T * D = 0.99999996 * 0.9997002 * 0.99.90 = 0.99870028 = 99.87\%$$

Where,  $R_p$  represents the receiving circuit with the added standby power supply to the existing single line system of the mainline AALRT TPLS.

The difference between the availability after introducing standby power supply system and that of the existing system is 0.01997001% and, assuming 30 years as an average life time of the equipment, it corresponds to be 52 hours and 29 minutes operation stop during the 30 years of AALRT TPSS. Hence, to enhance the reliability of AALRT TPSS operation, introducing reliable backup supplies is essential.

### 4.3 Redundancy Consideration for AALRT Traction Substation

Redundancy should be considered in design when establishing railway substation ratings and locations. A transit property may require that train operations be maintained, either at normal full load, or at some prescribed reduced operating capacity, in the event of the loss of any one piece of traction power substation equipment, or loss of multiple equipment units, or complete loss of one or more traction power substations. These criteria will result in increased loads on remaining in-service traction power equipment or adjacent in-service substations, and will have significant impact on determination of substation location(s) and rating(s).

In the design of AALRT TPSS, the redundant TPLS equipment have been considered though it is not applied but left with spaces for the second set of equipment for future installation as shown in figure 16. The results of MTTR is 54.07hour or about 2 days, which shows the repair time for failed components is too high and the corresponding maintenance cost for system operation is obviously increasing due to its operation disruption and poor reliability for a long period of time.

## RELIABILITY ANALYSIS OF AALRT TRACTION POWER SUPPLY SYSTEM

This is resulting passenger dissatisfaction and revenue loss so that the need for installing the redundant systems should be considered now. Though, implementing these redundant systems at selected TPLSs, such as Kality depot, Ayat depot, EW16, NS10, NS12, EW7, and EW5 will increase the installation cost of the system, in the long term operation it will be compensated by the high maintenance cost incurred, with the current MTBF value of around 29 days.

Therefore, installing the necessary redundant components in to the existing the design as shown in figure 17 for the TPLSs are suggested.

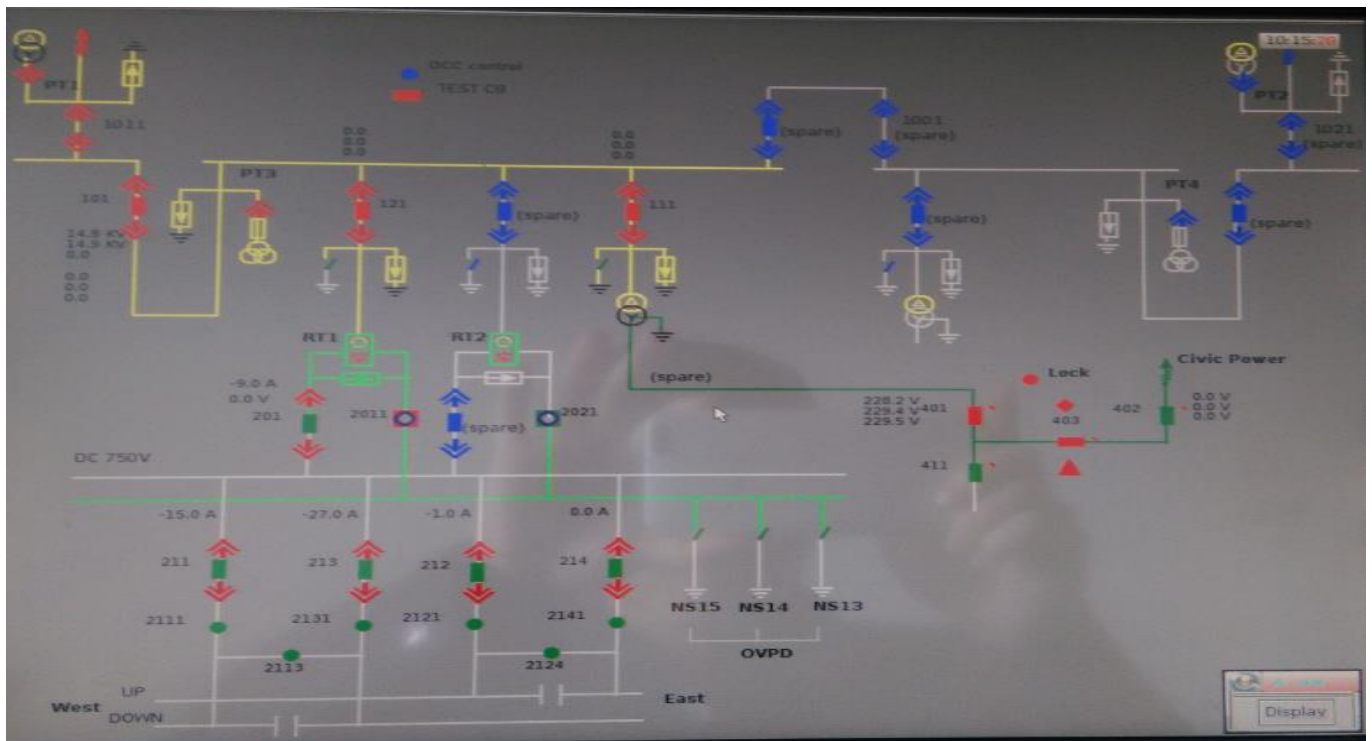


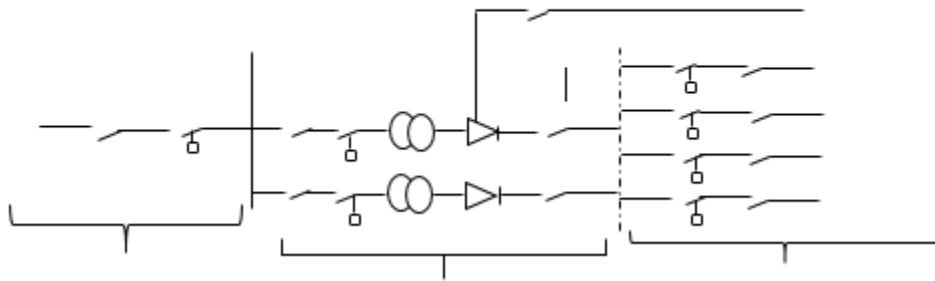
Figure 16: Mainline Railway DC Traction Substation with Uninstalled Redundant system [24]

Figure 17 shows the design for main line AALRT TPSS that is not actually implemented with reasons not clear yet. But, there is a space for each cabinets of the traction substation equipment, like traction transformer, rectifier, 15 kV circuit breakers, and other protection equipment that can be part of the switchgear.

To quantitatively illustrate the importance of redundant equipment, such as traction transformer and AC circuit breaker, a typical circuit that has already been used above is considered here again.

**Effect of Redundant Transformer and Circuit Breaker**

Figure 18 shows the availabilities of total traction substation with redundant transformer and circuit breaker circuit. Different from the case shown in figure 15, it is supposed that single circuit breaker and transformer circuit is enough in the mainline TPLSs of AALRT and the additional circuit breaker and transformer circuit is redundant in figure 18.



Receiving Circuit	Transformer Circuit (with return circuit)	DC Circuit
$R = DS * CB$	$T_p = (T^2 + 2T(1-T))$	$D = HSCB * DS$
$= 1 * 99.98 = 99.98\%$	$= 0.9997^2 + 2 * 0.9997(1 - 0.9997)$	$= 1 * 0.9990 = 99.90\%$
	$= 0.99999991 = 99.999991\%$	

Figure 17: Availability of AALRT TPSS with Redundant Circuit Breaker and Transformer Circuits

In this case, an additional transformer, circuit breaker and rectifier circuits are added to the existing system. Based on this, AALRT TPSS availability can be calculated as:

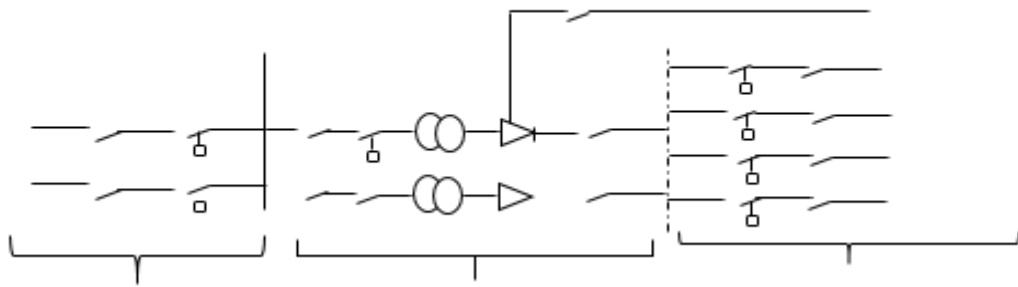
$$A = R * T_p * D = 0.9998 * 0.99999991 * 0.9990,$$

## RELIABILITY ANALYSIS OF AALRT TRACTION POWER SUPPLY SYSTEM

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$= 0.9988001101 = 99.88\%$ , where  $T_p$  is the availability of transformer circuit with redundant transformer, circuit breaker and rectifier, in which the availability of the rectifier is taken to be 1. The difference between the availability of the redundant transformer and AC circuit breaker system to that of the existing system is  $0.03\%$  which corresponds to about 78 hours and 50 minutes operation stop during 30 years expected operation of AALRT TPSS.

### Effect of Redundant Standby Power Supply and Transformer and the AC Circuit Breaker



Receiving Circuit

Transformer Circuit (with return circuit)

DC Circuit

$$R_p = (R^2 + 2R(1-R))$$

$$T_p = (T^2 + 2T(1-T))$$

$$D = HSCB * DS$$

$$0.9998^2 + 2 * 0.9998(1 - 0.9998^2)$$

$$= 0.9997^2 + 2 * 0.9997(1 - 0.9997)$$

$$= 1 * 0.9990 = 99.90\%$$

$$= 0.99999996 = 99.999996\%$$

$$= 0.99999991 = 99.999991\%$$

Figure 18 : Reliability with Standby Power Supply and Redundant Transformer and Circuit Breaker

In this circuit, both the standby power supply and the redundant transformer and AC circuit breaker are considered. Accordingly, the availability of AALRT TPSS can be calculated as:

$$A = R_p * T_p * D = 0.99999996 * 0.99999991 * 0.9990$$

$$= 0.9989998701 = 99.89998701\%$$

The difference between the availability after introducing standby power supply system and redundant circuits of transformer and circuit breaker to that of the existing system is  $0.04993\%$

which corresponds to about 131hours and 13minutes of operation stop during 30 years expected operation of AALRT TPSS.

### **4.4 Applying Maintenance Strategies**

It is obvious that every efficient maintenance system always needs to look at how to reduce MTTR as much as possible. Low MTBF could either indicate poor handling of the asset by its operators or a poorly-executed repair job in the past. Having in mind these, appropriate maintenance activities are proposed after identifying the real gaps; as part of the reliability mitigation techniques for AALRT TPSS.

The average maintenance time (MTTR) value of AALRT TPSS is found to be 54.1h which corresponds to about 2 days of average repairing duration. It is too long. Besides, the MTBF value of the system is found to be 695.2 hours that corresponds to about 29 days. This means, the TPSS component failures had been occurred in average of 28 days and had been interrupting the overall operation.

Though, for such high failure rate and the requirement of highly sustainable power supply system for a railway service, the executions of maintenance by power supply division has been slow relying almost on corrective approach.

### **Maintenance Activities in AALRTS Power Supply Division**

Power supply division, in AALRTS, is a maintenance department entitled for maintenance works of TPLSs, 750V DC and low voltage supplying equipment. The TPLSs and OCS accompanied by the dedicated AC power supply network from EEU form an integral part of the entire AALRT TPSS that must be maintained. For the execution of maintenance activities in AALRTS power supply division had about 50 technicians and only two engineers deployed by October, 2018. The engineers were responsible for managing the maintenance activities by which one of them is

entitled for planning and controlling the maintenance actions and the other one is the division manager, for two sub-divisions so called OCS sub-division and substation sub-division.

The major maintenance activities were performed by senior Ethiopian technicians with the supervision of the Chinese technicians, who were responsible to participate and transfer knowledge for locals till their commissioning time ends in late 2019. The number of those senior technicians is small in which only four OCS and three substation technicians were trained in China with the help of Chinese to English translator. The rest of the technicians are trained and being trained in AALRTS by those senior technicians.

All, five of the Chinese technicians, speak only Chinese and one translator was assigned to help the communications between them and the Ethiopian side, especially in major incidents and trainings. So, language barrier can be taken as one of the challenges for poor knowledge transfer. The other challenge is unavailability of adequate well-trained technicians, who directly involve in maintenance work. In addition, most of the internal TPLS equipment failures like circuit breaker failure, DMR330 relay protection failure, and communication device faults had been maintained by the Chinese technicians while the Ethiopians were acting as assistant though the end of the commissioning time were about to end.

Furthermore, there are lots of reasons for low maintenance actions in AALRT TPSS, the author of this thesis has observed some of them, such as absence of enough well-trained planning and maintenance engineers, well-prepared standard documents and procedures, well-organized working environment and management are the major ones. Hence, to properly improve the reliability of the system, the maintenance team should be equipped and well-organized.

Since the objective of this thesis work involves suggesting mitigation techniques for improving the existing reliability of AALRT TPSS, maintenance is discussed here as one of the major

factors of reliability improvement methods. In different literatures, there are lots of maintenance approaches used for different applications whose purpose is to improve the reliability of system under study. From those strategies, three of the well-known approaches are selected to be applied for AALRT TPSS, which are corrective maintenance, preventive maintenance, and predictive maintenance.

Preventive maintenance is a pro-active maintenance strategy where components are repaired or replaced before they fail using a planned maintenance schedule, which is less costly and time consuming [20]. There is also a time-based maintenance also known as periodic preventive maintenance. These approaches have historically been performed based on recommendations from original component manufactures.

Corrective maintenance actions can recover the malfunctioning part of the system, repairing or replacing the failed component. If the system is not-critical and easily repairable, any potential unplanned crashes will cause a minimum impact related to the availability.

In AALRT TPSS, most of the maintenance activities are failure driven targeting the recovery of the functionality of the system. It may be due to this approach that the failure rate of the system was such too high.

In order to slow down the process of deterioration that leads to a failure, a primary preventive maintenance is performed periodically inspecting and controlling the system through scheduled regular activities [20]. The maintenance decisions are made by experienced planners, according to the recommendations of the manufacturer of the system, failures history, mal-function data, operational experience, and assessment performed by maintenance staff and technicians.

This approach was not often applied in AALRT TPSS maintenance division, however; it is time to apply it seriously to reduce the number of failures so that to improve system reliability.

Predictive maintenance is another approach represented by the condition-based maintenance as a method to reduce the uncertainty of maintenance activities [20]. This activity is performed according to the needs indicated by the results of system status monitoring, i.e. condition-monitoring. The predictive condition-based maintenance uses, therefore; the results of condition-monitoring and, according to these, plans the maintenance actions. The goal of condition-monitoring is to delete the failures and extend the preventive maintenance intervals. This maintenance approach has not been applied, but as the reliability analysis result is worsened AALRTS should have to consider applying it by fostering dedicated well-trained and experienced engineering team.

### **Implementation of Maintenance Program**

The mentioned three approaches of maintenances can be applied in AALRT TPSS to improve its reliability. The implementation should be done step by step, starting at prioritizing the works of high probability of failure and frequent downtime or weak links of the reliability analysis as shown in the importance index results. From the importance index table, the weakest links of AALRT TPSS are the 15kV power cable, SCADA and AIS substation..

As previously discussed, AALRTS power supply division focuses on corrective maintenance. To enable the proper implementation of preventive and predictable approaches, the power supply division maintenance teams must be set up with two distinct responsibilities. One will react on faults and the other will focus on preventing these faults from occurring. Then, if the scheduling is strictly implemented and maintained over a period of time, the number of faults would decrease, allowing for more time to do proper maintenance. Besides, the issue of staff competence and adequacy must be addressed in AALRTS power supply division with periodic refreshment training and tests.

Moreover, considering cooperation with universities and other technical institutions for training and knowledge transfer will be helpful. Emphasis should also be given for localizing and modifications of spare parts with the local experts and institutions. The identification of tasks that can be performed by people with general electrical skills will enable outsourcing of those skills and reduce the staff risk inside the company. Only those specialized maintenance task will be performed by skilled personnel trained specifically for that.

### **4.5 Summary of Reliability Mitigation Techniques**

The reliability analysis of the AALRT TPSS indicated that the reliability of the system is rapidly decreasing as time increases as shown in the reliability probability equation (17). It is suggested that effective improvement techniques should be applied to increase the reliability of the system based on the reliability evaluation indices, and to reduce the impact on operational interruptions caused by system failures. Generally, specific suggestions are proposed as follows:

- (1) Organizing well-trained engineering staffs who can work on reliability and failure prediction, maintenance scheduling and planning, equipment upgrading, modification and localization of spare parts and the like.
- (2) Fostering well-trained and experienced maintenance technicians to shorten the time needed for equipment checkup, maintenance, and replacement.
- (3) Adopting predictive and preventive maintenance approaches in parallel with the corrective maintenance activity by prioritizing the weak links of the system. Using stricter maintenance strategy and more advanced inspection of equipment that will enable to discover failures in time before they occur for a prompt process.

(4) Planning short term and long term goals to minimize the frequent failures by prioritizing the weak links which directly results in AALRT TPSS interruption, such as; 15kV power cables, OCS isolator switches, catenary failures, and SCADA communication.

(5) Procuring components with higher reliability to minimize the probability of failures to ensure the system safety.

(6) Using components that are easier to be replaced and modulated, so that the maintenance time can be reduced at failures, which means the condition of operational interruption can be reduced; using failure positioning devices, with the use of advanced high-performance maintenance equipment, to shorten the maintenance time as much as possible.

**4. Result and Discussion of Reliability Evaluation**

**3.1 Results of Reliability Evaluation Indexes**

The reliability evaluation indexes of AALRT power supply components and the overall system are calculated using the developed MATLAB code applying the equations of exponential distribution as shown in appendix C. The result comprises of the reliability indices, such as failure rate, mean time between failure, mean time to repair, repair rate, and unavailability.

Those results are brought here in the form of tables.

Table 3: Calculated reliability parameters for AALRT TPSS components

Component type	Number of Failures	Total downtimes (h)	Failure rate $\lambda$ (1/h)	MTTR (h)	MTBF (h)	Availability (%)
15kV power cable failure	186	1671.30	$0.0862 \times 10^{-3}$	754.7806	$1.1601 \times 10^4$	93.8914
OCS isolator switch failure	25	27.05	$0.0457 \times 10^{-3}$	21.6400	$2.1866 \times 10^4$	99.9011
Cantilever failure	1	3.40	$0.0366 \times 10^{-3}$	3.4000	$2.7357 \times 10^4$	99.9876
Contact Suspension failure	15	26.27	$0.0366 \times 10^{-3}$	26.2700	$2.7334 \times 10^4$	99.9040
OVPD failure	9	13.57	$0.0366 \times 10^{-3}$	13.5700	$2.7346 \times 10^4$	99.9504
Stray current cable failure	10	5.50	$0.0366 \times 10^{-3}$	5.5000	$2.7355 \times 10^4$	99.9799
Track failure	6	8.20	$0.0366 \times 10^{-3}$	8.2000	$2.7352 \times 10^4$	99.9700
Transformer arrester fault	3	3.34	$0.0366 \times 10^{-3}$	3.3400	$2.7357 \times 10^4$	99.9879
Circuit breaker failure	7	4.39	$0.0366 \times 10^{-3}$	4.3900	$2.7356 \times 10^4$	99.9840
SCADA failure	103	200.50	$0.9481 \times 10^{-3}$	7.7864	$0.1055 \times 10^4$	99.2672

**RELIABILITY ANALYSIS OF AALRT TRACTION POWER SUPPLY SYSTEM**

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AIS Failure	56	54.20	$0.1025 \times 10^{-3}$	19.3571	$0.9752 \times 10^4$	99.8019
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Note: - The collected data is taken from the AALRT TPSS expected operation time, also called mission time, of about 27,360 hours that started from September 17<sup>th</sup> 2015, to October 30<sup>th</sup> 2018.

Table 4: Calculated reliability parameters of AALRT TPSS subsystems

Subsystem	Failure rate $\lambda$ (1/h)	Mean time to repair r(h)	MTBF (h)	Unavailability, U
Traction Network	$0.3148 \times 10^{-3}$	216.4607	$0.3177 \times 10^4$	0.0681
Traction Substation	$0.0731 \times 10^{-3}$	3.8650	$1.3678 \times 10^4$	0.0003
Main Substation (AIS/GIS)	$0.1025 \times 10^{-3}$	19.3571	$0.0975 \times 10^4$	0.0020
SCADA	$0.9481 \times 10^{-3}$	7.7864	$0.0105 \times 10^4$	0.0074

Table 5: Calculated reliability parameters of AALRT TPSS

System	Failure rate $\lambda$ (1/h)	MTTR(h)	Repair rate, $\mu_s$ (1/h)	MTBF (h)	Unavailability, $U_s$
AALRT TPSS	0.00144	54.0710	0.0185	695.1643	0.0778

**Reliability Probability**

Substituting the value of the system failure rate shown in table 6 in to the reliability function with the obeyed exponential distribution, the reliability probability will become:

$$R(t) = e^{-0.0014t} \dots\dots\dots (19)$$

If it is assumed that AALRT TPSS will be failure free for two months. The time t will be two months that corresponds to 1440 hours. Thus, the reliability of the system will be:

$$R(1440) = e^{-0.00144 \times 1440} = 0.8127 = 81.3\%$$

**Importance Measure**

To evaluate the importance measure and to determine the weak links of AALRT TPSS, importance index formulae are applied in developing the MATLAB code.

The calculation results of importance of basic unit (Ii) and mode importance of basic unit are shown in figure 14, in chart.

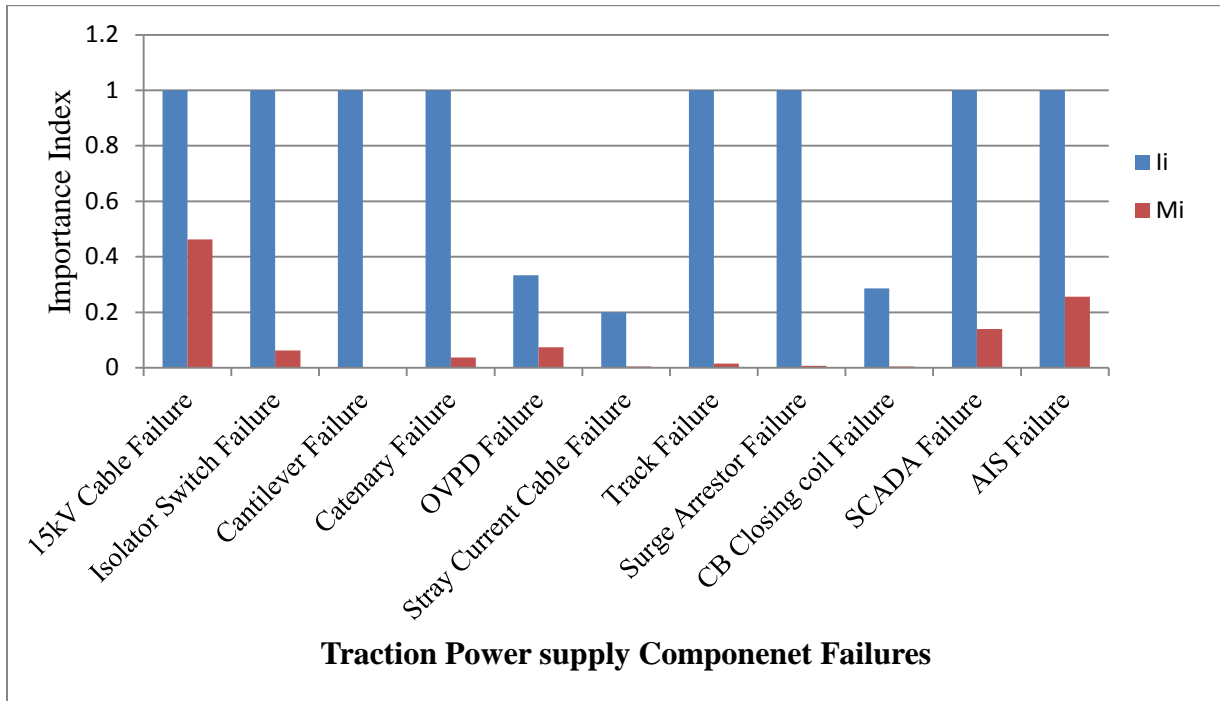


Figure 19: Importance Index of AALRT TPSS Components

### 3.2 Discussion

The qualitative reliability analysis was conducted on the system by fault mode and effect analysis (FMEA). Based on the FMEA table and failure analysis, the failures of the system were classified as factors of material, operational use, operational environment, mechanical damage and electricity, etc. The reliability of the system could be increased by means of using components with higher reliability, introducing standby power supply and strengthening maintenance activities. Besides, in the long term, all TPLSs should have two circuits of 15kV power sources. For substations with two circuits of power sources, the probability of TPSS interruption due to power source failure will be minimized. So, the two independent incoming power sources will enhance the reliable AALRT TPSS operation.

## **RELIABILITY ANALYSIS OF AALRT TRACTION POWER SUPPLY SYSTEM**

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Based on the statistical evaluation of the AALRT TPSS reliability using FTA and exponential distribution, the results obtained are discussed herewith. In the calculation, various component faults that directly or indirectly resulted in the interruptions of the AALRT TPSS are used to quantify the reliability of the system in terms of reliability indices, such as MTBF and MTTR.

In table 3, the results of the reliability evaluation indices of AALRT TPSS component failures or basic events of FTA are shown. Under this category, the TPSS components with MTTR values highest to lowest are 15kV power cable failure, contact suspension, OCS isolator switches failure, AIS faults, overvoltage protection device (OVPD) failure, rail track failure, SCADA failures, stray current collection cables failure, 15kV circuit breaker failure, traction cantilever failure, and transformer surge arrester failure. That means the power cable failure (15kV) had been taking the highest average maintenance time per failures, which is about 755 hours during the three-year operation of the system. This is too long for recovering the equipment. The second and third TPSS components with high MTTR values are contact suspension and OCS isolator switch with 26 hours and 22 hours during the mission time respectively. The components or systems with high failure rate values are SCADA, AIS failure, 15kV power cable, OCS isolator switch, contact suspension, OVPD, track, stray current collection cable, circuit breaker closing coil, transformer surge arrester, and cantilever in decreasing order as shown in the third columns of table 3. This means, the communication device (SCADA) had the highest number of faults per operation time or the lowest average duration between two consecutive failures of 1055 hours that corresponds to 44 days. Contrarily, cantilever had the highest average gap between two consecutive failures with MTBF value of 27,357 hours which corresponds to 1,140 days. Of all the components, 15kV power cable had the lowest steady state availability of 93.8914%, which indicates it had the lowest performance time within the expected operation time, which requires a

serious concern for a mitigation action to improve the reliable operation of the equipment and at large the AALR TPSS.

In table 4, the results of the reliability evaluation indices of AALRT TPSS subsystem failures or FTA intermediate events, which are the consequences of the failures of one or more of component failures, are shown. The subsystem failures are traction network failure and traction substation failure; besides, main substation (AIS/GIS) failure and communication device (SCADA) failures are considered as subsystem failures. The failure of one of those subsystems immediately resulted in operation disruption of the overall AALRT TPSS. From these subsystems, SCADA and traction network had lower MTBF values of 1,055 and 3,177 hours respectively which indicates either poor handling of the asset by its operators or a poorly-executed repair job in the past. In addition, the traction network had the highest unavailability of 6.81% or the lowest availability of 93.19% which shows the low performance availability of the system in the expected operation time.

Furthermore, the overall quantitative reliability analysis of AALRT TPSS using FTA accompanied by exponential distribution is conducted. The results of the important reliability evaluation indices of the system showed that its MTBF were 695.2 h, MTTR were 54.1 h, and unavailability (Us) were 7.78%. That means, for reliability analysis of AALRT TPSS, which obeyed the exponential distribution, the average time between two consecutive failures had been about 695 hours, the average amount of time required to restore the system, just after a fault happened, was 54 hours which is too long. Further, the steady state operational availability of AALRT TPSS was 92.22%.

As it can be observed from the quantitative reliability evaluation of the AALRT TPSS indices, in the specified operation time, the results show poor reliability of the system. In order to

understand how worse, the results of the reliability evaluation indexes of TPSS are; the results of some researches with the same reliability parameters are brought here for the sake of comparison.

As shown in table 3, the AC circuit breaker MTBF value is found to be  $2.7356 \times 10^4$  hours, but, according to [7], the MTBF values of AC circuit breaker of DC TPSS was found  $4.7 \times 10^6$  hours that is higher by  $4.67 \times 10^6$  hours. This means, the AC 15kV circuit breaker in DC traction power supply system of Tokyo area of East Japan Railway [7] have about 194,583 more average days to fail than the one in AALRT TPSS. In table 4, the MTTR value of the traction network is found to be 216.5 hours, whereas in [10], its value for the same subsystem of DC TPSS was found as 35 hours that is 181.5 hours lesser. In addition, the operational availability of AALRT TPSS is found to be 92.22%, but the operational availability of the DC TPSS in Tokyo area of East Japan Railway [7] was found as 99.998%. Further, comparing the failure rates of the results of AALRT TPSS with those similar works, the results show that the failure rate of AALRT TPSS is too high. The average maintenance time taken for a failure was also higher.

The lower MTTR and higher MTBF values of other DC TPSS railways in the mentioned papers, are resulted due to different factors, such as the availability of well-organized maintenance procedures and personnel, redundant power supplies and traction substation equipment that helps to have lower average maintenance or repair time and higher average gap between two consecutive failures. Hence, it is found necessary to check the presence of those conditions as part of reliability mitigation in the reliability analysis of AALRT TPSS.

Based on the impact of the operation interruption on AALRT TPSS, the reliability importance measure of the components is evaluated using two importance index equations as shown in figure 14. From this chart, it can be observed that the weakest links of AALRT TPSS is the 15kV

power cable with the highest mode importance of basic unit value of 0.4627. In other words, the 15kV power cable had the greatest impact in determining the reliability of the operation of AALRT TPSS. Thus, detailed investigation for the frequent failure of this underground power cable should be done and the improvement works should also be done.

Generally, AALRT TPSS reliability evaluation result indicated that the need for serious improvement actions. Based on the reliability evaluation indices, some reliability mitigation techniques are suggested in the next chapter.

Hence, the quantitative availability evaluations with the redundant equipment show that the following system availability improvements:

- If the redundant transformer and AC circuit breaker is added in to the existing AALRT TPLSs, the system availability would be improved from 92.22% to 99.88%.
- If the standby power supply system is added in to the existing AALRT TPLSs, the system availability would be improved from 92.22% to 99.87%.
- If the standby powers supply system and redundant transformer and AC circuit breaker is added in to the existing AALRT TPLSs, the system availability would be improved from 92.22% to 99.9%.

## 5. Conclusion and Recommendation

### 5.1 Conclusion

Reliability of the traction power supply system is one of the keys to high level of service quality in railway transit system. The main objective of this thesis work was to conduct reliability analysis of AALRTS TPSS and provide helpful proposal for reliability improvement to reduce the disturbance of train service and excessive maintenance costs incurred due to traction power supply system faults.

The reliability analysis of AALRT TPSS was conducted using FMEA and FTA accompanied by the exponential distribution. Using FMEA, the failure causes, failure modes and effects were identified and then the qualitative reliability analysis of the system was conducted. In the qualitative reliability analysis via FMEA, the failures of the system were classified as factors of material quality, operational use, operational environment, and electricity, etc. Thus, the reliability of the system can be increased by means of using components with higher reliability or by means of strengthening maintenance. Based on the FMEA analysis, FTA tree was constructed and the visual model of the system failure using logical gates is provided in a deductive way.

Applying the exponential distribution equations, the MATLAB code was developed that enabled the calculation of the reliability evaluation indexes. Hence, based on the three years experiences, the reliability of equipment of traction substation, traction network, communication device and the main substations were quantitatively evaluated and the total availability of traction power supply system of AALRT TPSS was also calculated.

At the component level, 15kV power cable, contact suspension, and OCS isolator switches are found to have the highest average maintenance time taken for a failure. Similarly; SCADA, AIS

substation and 15kV power cables are found to be with the highest failure rates. Traction substation is found to have the highest mean time to repair and the lowest mean time between failures that makes it to be the critical subsystem of AALRT TPSS. Finally, the overall system reliability indices are also calculated; so, the failure rate is found to 0.0014 (1/h), the mean time to repair is found to be 54.1 hours, and the unavailability is found to be 7.78%. Similarly, the mean time between failures of the AALRT TPSS is found to be 695.2 hours, which is about 29 days. In comparison with other similar works, the numerical results showed that AALRTS have poorer TPSS reliability.

Then, based on the reliability analysis, to improve the reliability of the system, adopting regular maintenance, introducing redundant traction substation equipment and emergency or standby power supply systems to the existing system are suggested.

The redundancy of traction substation equipment configuration was evaluated using the calculated reliability indicators to make the suggestions quantitatively reasonable. It was calculated that redundant AC breaker circuit and transformer circuit can avoid 79 hours, introduction of standby power supply can avoid 52 hours, and both the redundant AC breaker circuit and transformer circuit and power supply circuits can avoid about 131 hours' operation influence for an assumed 30-year life time, respectively.

### **5.2 Recommendations for Future Work**

For reliability analysis, FMEA, FTA and exponential distribution, are selected based on their ability to analyze the existing system and the available data collected for the operation duration of about three years. Using these methods, the dynamic property of the system reliability cannot be achieved. The actual system is time-dependent that needs dynamic reliability analysis. Hence,

any further study should consider the dynamic reliability analysis of the system using dynamic reliability analysis methods, such as; Monte-Carlo simulation.

This thesis is conducted on the overall TPSS, but, reliability analysis on the selected components has to be done in the future. The component selection can take the important index results of this thesis. Moreover, the next study should focus on emphasizing the weak links of AALRT TPSS that are identified in this thesis, such as 15kV power cable, SCADA communication, and other traction network and traction substation power supply components. The root causes of the faults should also be investigated through experiments.

Further, in this thesis constant failure rate is assumed depending on the unavailability of adequate data in which exponential distribution is utilized. However, the actual failure rates of the traction power supply components cannot be constant so that using other dynamic reliability distribution functions, like Weibull distribution, is recommended.

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### Appendix A

#### Reliability Parameters

**Fault:** is an identifiable condition in which one element of a redundant system has failed (no longer available) without impact on the required function output of the system.

**Failure:** is departure of a component's functionality targets from specification. Alternatively, the other definition is "termination of the ability of an entity to perform a required function under specified conditions".

**Failure rate ( $\lambda$ ):** It is the probability of occurrence of a failure at a specific component age, defined in terms of failures per time, load cycle, or cumulative load. It can be useful in almost every component. It is used in the RAMS life cycle to compute values of component/system failure and unavailability. At system level, it is normally assumed that the failure rate is constant, but at component level this might not be the case.

**Mean time between failures (MTBF):** It is a measure of total uptime of the components(s) divided by the total number of failures. Whilst  $\lambda$  is the number of failures in a certain span of time or load, MTBF is the time or load span between two failures. The higher the value, the less maintenance actions are needed in the same time span and vice versa.

**MTTR (Mean Time to Repair):** is the expected value of all the repair times experienced by a component.

**Repair rate:** is the ratio of the conditional probability that the corrective maintenance action ends in a time interval,  $[t, t+\Delta t]$  over the length of this time interval,  $\Delta t$ , when  $\Delta t$  tends to zero, given that the entity is faulty at time  $t=0$  [21]. It is also represented by  $\mu(t)$ .

**Availability/Unavailability:** Unavailability is the Probability of Failure on Demand, extremely useful when assessing safety aspects, such as the behavior of hazard mitigation components which must remain ready to work in standby while waiting to be triggered.

**Appendix B**

**Failure Data**

Table 6: Fault record

No.	Fault Type	Failures in operation years				Total number of component faults	Number of failed equipment	System (TPSS) failures	Total downtime (hour)
		2015	2016	2017	2018				
		Quantity	Quantity	Quantity	Quantity				
1.	15kV power cable	2	52	57	75	186	84	186	1671.30
2.	OCS isolator switch failure	2	5	8	10	25	20	25	27.05
3.	Cantilever failure	0	0	1	0	1	1	1	3.40
4.	Contact suspension failure	0	4	4	7	15	15	15	26.27
5.	OVPD failure	2	3	2	2	9	9	3	13.57
6.	Stray current cable failure	2	3	3	2	10	10	2	5.50
7.	Track failure	3	2	0	1	6	6	6	8.20
8.	Transformer arrester failure	0	0	2	1	3	3	3	3.34
9.	CB Closing coil failure	2	1	1	3	7	7	2	4.39
10.	SCADA dead halt	31	39	23	10	103	20	103	200.50
11.	AIS failure	8	12	17	19	56	4	56	54.20
Grand Total						421		402	2020.08

**Appendix C****MATLAB Code****1. Matlab Code for AALRT TPSS Component's Reliability Parameter Calculation**

```
clear all;
clc
N=[84;20;1; 15; 9; 10; 6; 3; 7; 20; 4]; %Number of failed equipment
F= [186; 25; 1; 15; 9; 10; 6; 3; 7; 56; 103]; %Number of failures in 27,360hrs.
D= [1671.3; 27.05; 3.4; 26.27; 13.57; 5.5; 8.2; 3.34; 4.39; 54.2; 200.5];
% Total downtimes of TPSS components in 27,360hrs.
T = 27360; %Total operation time (h) for more than three years
Tup =T-D; % Total operating hours
Zi = [186;25;1;15;9;10;6;3;7;103;56]; % TPSS Component Failures
zi = [186;25;1;15;3;2;6;3;2;103;56]; % TPSS Failures due to Zi
Z =sum(zi); %Sum of TPSS failures due to Zi

[r1,c1] =size(F);
[r2,c2] =size(D);
if c1~=c2
    input('Matrices cannot be divided!');
else if c1==c2
    for i=1:c1;
        for j=1:c2;
% AALRT TPSS Components reliability parameter calculation
        K1 =Tup.*N;
        MTBF=K1./F; % Mean time between failure
        K2=D.*N;
        MTTR=K2./F; % Mean time to repair
        m = MTBF + MTTR;
        A = (MTBF./m); % Availability
        %% Importance Index Calculation
        Ii =zi./Zi; % Basic Unit Importance Index
        Mi =zi./Z; % Mode Importance of Basic unit
        end
end
```

```
end
K=[MTTR,MTBF,A];
I=[Ii,Mi];
disp('AALRT Traction Power Supply Components Reliability Parameters ')
VarNames1={'MTTR','MTBF','Availability'};
fprintf(1, '%s\t%s\t%s\t%s\t%s\t\n', VarNames1{:})
fprintf(1, '\n')
disp('Importance Index ')
fprintf(1, '\t')
VarNames2={'Ii'};
fprintf(1, '\t')
VarNames3={'Mi'};
fprintf(1, '%s\t%s\t%s\t%s\t%s\t\n', VarNames2{:}, VarNames3{:})
fprintf(1, '\n')
disp(I)
end
end
```

### Result

```
AALRT Traction Power Supply Components Reliability Parameters
MTTR    MTBF    Availability
          1.0e+04 *
754.7806  1.1601  0.9389
 21.6400  2.1866  0.9990
   3.4000  2.7357  0.9999
 26.2700  2.7334  0.9990
 13.5700  2.7346  0.9995
   5.5000  2.7355  0.9998
   8.2000  2.7352  0.9997
   3.3400  2.7357  0.9999
   4.3900  2.7356  0.9998
 19.3571  0.9752  0.9980
   7.7864  0.1055  0.9927
```

**Importance Index**

<b>Ii</b>	<b>Mi</b>
1.0000	0.4627
1.0000	0.0622
1.0000	0.0025
1.0000	0.0373
0.3333	0.0075
0.2000	0.0050
1.0000	0.0149
1.0000	0.0075
0.2857	0.0050
1.0000	0.2562
1.0000	0.1393

**2. Matlab Code for AALRT TPSS Subsystem's Reliability Parameter Calculation**

```
clear all;
clc
N = [84;20;1; 15; 9; 10; 6; 3; 7; 20; 4]; %Number of failed equipment
F= [186; 25; 1; 15; 9; 10; 6; 3; 7; 56; 103]; %Number of failures in 27,360hrs.
D= [1671.3; 27.05; 3.4; 26.27; 13.57; 5.5; 8.2; 3.34; 4.39; 54.2; 200.5];
% Total downtimes of TPSS components in 27,360hrs.
T = 27360; %Total operation time (hrs.) for more than three years
Tup =T-D; % Total operating hours
[r1,c1] =size(F);
[r2,c2] =size(D);

if c1~=c2
    input('Matrices cannot be divided!');
else if c1==c2
    for i=1:c1;
        for j=1:c2;
% AALRT TPSS Components reliability parameter calculation
            K1 =Tup.*N;
            L=(F./(K1)); %Failure rate
            MTBF=K1./F; %Mean time between failure
            K2=D.*N;
            MTTR=K2./F; % Mean time to repair
% AALRT TPSS Subsystems reliability parameters
```

```
Ltr_n =sum(L(1:7,1));
Ltr_ss=sum(L(8:9,1));
MTTRtr_n=sum(L(1:7,1).*MTTR(1:7,1))/sum(L(1:7,1));% For traction network
MTTRtr_ss=sum(L(8:9,1).*MTTR(8:9,1))/sum(L(8:9,1));% for traction substation
end
end
disp('AALRT TPSS Subsystems Reliability Parameters ')
VarNames2={'MTTR','MTBF','Unavailability'};
fprintf(1, '%s\t%s\t%s\t%s\t\n', VarNames2{:})
fprintf(1, '\n')
Lsub=[Ltr_n;Ltr_ss;L(10:11)];
MTTRsub=[MTTRtr_n;MTTRtr_ss;MTTR(10:11)];
MTBFsub=1./Lsub;
Usub=Lsub.*MTTRsub;%Unavailability
M=[MTTRsub, MTBFsub,Usub];
fprintf(1, '\n')
disp(M)
end
end
```

### Result

```
AALRT TPSS Subsystems Reliability Parameters
MTTR    MTBF    Unavailability
      1.0e+04 *
216.4607  0.3177  0.0681
  3.8650  1.3678  0.0003
19.3571  0.9752  0.0020
  7.7864  0.1055  0.0074
```

### 3. Matlab Code for AALRT TPSS Overall Reliability Parameter Calculation

```
clear all;
clc
N = [84;20;1; 15; 9; 10; 6; 3; 7; 20; 4]; %Number of failed equipment
F= [186; 25; 1; 15; 9; 10; 6; 3; 7; 56; 103]; %Number of failures in 27,360hrs.
D= [1671.3; 27.05; 3.4; 26.27; 13.57; 5.5; 8.2; 3.34; 4.39; 54.2; 200.5];
% Total downtimes of TPSS components in 27,360hrs.
```

## RELIABILITY ANALYSIS OF AALRT TRACTION POWER SUPPLY SYSTEM

---

T = 27360; % Total operation time (h) for more than three years

Tup = T - D; % Total operating hours

[r1,c1] = size(F);

[r2,c2] = size(D);

if c1 ~ c2

input('Matrices cannot be divided!');

else if c1 == c2

for i = 1:c1;

for j = 1:c2;

% AALRT TPSS Components reliability parameter calculation

K1 = Tup.\*N;

L = (F./(K1)); % Failure rate

MTBF = K1./F; % Mean time between failure

K2 = D.\*N;

MTTR = K2./F; % Mean time to repair

% AALRT TPSS Subsystems reliability parameters

Ltr\_n = sum(L(1:7,1));

Ltr\_ss = sum(L(8:9,1));

MTTRtr\_n = sum(L(1:7,1).\*MTTR(1:7,1))/sum(L(1:7,1));

MTTRtr\_ss = sum(L(8:9,1).\*MTTR(8:9,1))/sum(L(8:9,1));

end

end

Lsub = [Ltr\_n; Ltr\_ss; L(10:11)];

MTTRsub = [MTTRtr\_n; MTTRtr\_ss; MTTR(10:11)];

MTBFsub = 1./Lsub;

disp('AALRT TPSS Calculated Reliability Parameters')

VarNames3 = {' ', 'MTTR', 'Repair rate', 'MTBF', 'Unavailability'};

fprintf(1, '%s\t%s\t%s\t%s\t%s\t\n', VarNames3{:})

fprintf(1, '\n')

Ls = sum(Lsub);

MTTRs = sum((Lsub.\*MTTRsub))/sum(Lsub);

Rr = 1/MTTRs;

MTBFs = 1/Ls;

## RELIABILITY ANALYSIS OF AALRT TRACTION POWER SUPPLY SYSTEM

---

Us= Ls\*MTTRs; %Unavailability

Reliability\_Indices = [MTTRs, Rr, MTBFs, Us];

disp(Reliability\_Indices)

end

end

### Result

```
AALRT TPSS Calculated Reliability Parameters
  MTR      Repair rate MTBF      Unavailability
  54.0710   0.0185  695.1643   0.0778
```