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Title

Design of DC Tramway Traction Power Network in Hebron

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الإهداء

إلى من جرع الكأس فارغاً لي إلى إلى من جرع الكأس فارغاً ليسقيني قطرة حب
إلى من كلّت أنامله ليقدم لنا لحظة سعادة
إلى من حصد الأشواك عن دربي ليمهد لي طريق العلم
إلى من ارضعتني الحب والحنان
إلى رمز الحب وبلسم الشفاء ....(والدتي الحبيبة)

إلى من أزال اشواك الحياة ومهد طريقنا للنجاح وزينه بالورود العطرة .... (ابي الغالي)

إلى القلوب الطاهرة الرقيقة والنفوس البريئة إلى رياحين حياتي

إلى من يحملون في عيونهم ذكريات طفولتي وشبابي .... إخوتي وأخواتي
الى من سرنا سويا و نحن نشق الطريق معا نحو النجاح والإبداع .... زملائي وزميلاتي

إلى من ضحوا بحريتهم من اجل حرية غيرهم .... الاسرى والمعتقلين

الى من هم أكرم منا مكانة .... شهداء فلسطين

إلى هذا الصرح العلمي الفتي والجبار .... جامعة بوليتكنك فلسطين
إلى من احتضنتني كل هذا الكم من السنين .... فلسطين الحبيبة

Abstract

Urban traction systems such as subways and trams transport millions of people every day. Hebron city suffers from the traffic issues, in order to solve the problem, a tramway network will be established in Ein Sara with 3.2 Km track covered with 7 passenger station spaced each 550 m. A brief introduction about electrical railway has been introduced and railway dynamics have been illustrated. DC traction substation was rated and located and the required equipment were selected. A proper earthing system for DC system and equipment was illustrated and current return circuit was designed. Over-head contact lines system and suspension system were designed. A protection scheme for DC traction system was designed. Also the system was simulated to study the system performance.

الملخص

تقوم أنظمة الجر الحضرية مثل مترو الأنفاق والترام بنقل ملايين الأشخاص يوميًا. تشهد مدينة الخليل مشكلة الأزمة المرورية، ولحل هذه المشكلة، تم تصميم شبكة ترام في مدينة الخليل في شارع عين ساره لتغطية مسار طوله ٣٫٢ كيلو متر مع وجود ٧ محطات للمسافرين موزعة عبر المسار كل ٥٥٠ متر. مقدمة مختصرة عن القطارات الكهربائية تم عرضها و الديناميكا لقطارات السكك الجديدة تم توضيحها. تم تحديد موقع و سعة محطة التيار الثابت للقطارات و تم اختيار المعدات اللازمة لها. تم أيضاً تقديم نظام تأريض مناسب للشبكة و معدات التيار الثابت المستخدمة في المحطة الكهربائية، بالإضافة إلى تصميم دائرة رجوع التيار. و أيضا تم تصميم خطوط نقل الكهرباء إلى القطارات و تم تثبيت الأسلاك بالشكل المناسب. تم تصميم نظام حماية مناسب للشبكة والنظام و تمت محاكاة النظام لدراسة أدائه.

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Chapter 1

Introduction

Railway transport is one of the most important transport systems, also known as train transport. It transfers passengers and goods on wheeled vehicles running on rails over long, as well as, short distances. It becomes one of the most dependable modes of transport in terms of safety, since it's better organized than any other medium of transport, and it's the least affected by usual weather turbulence like rain or fog, compared to other transportation systems, Through centuries these vehicles were dragged and moved by several means and different power sources. Through the time and due to the advance of science, railway vehicles were powered by different sources, like steam, diesel and electricity. Nowadays, almost all metropolitan areas are equipped with subway systems or trams, Subway systems are commonly referred to as mass rapid transit systems, whereas trams are usually called light transit systems.. They have been implemented to solve two problems : the congestion due to cars and the pollution, also due to cars. Urban rail systems usually offer a very good capacity, compared to other modes, and very good performances.

Up to now, electricity has always been the main type of energy for urban rail systems because it is the only energy which has all the qualities required to operate such systems. Indeed the pollution is very limited in the area where the energy is consumed. Vibrations and noise due to electric motors transforming electricity into mechanical energy are also limited. In case of underground systems, electricity is a good solution because the primary energy does not need to be carried by the train, thus avoiding serious safety issues that would be raised with diesel trains. Electric motors are also a lot more energy efficient and less noisy than diesel motors. Without electricity urban rail systems would be unable to offer such a high level of service, in terms of capacity, performance, availability and quality. This shows that electricity is a major component of every urban rail system.[1]

1.1 Electrical Railway

Electrical railway system is a system which supplies electrical energy to railway locomotives without the need of on-board prime mover or fuel source. The first electric train that transports passengers was presented by Werner von Siemens at Berlin in 1879, it was powered by (150 V DC) supplied through a third insulated rail between the tracks. A contact roller was used to collect the electricity. Electric traction has many advantages, the main advantage is the higher power-to-weight ratio than the other type of traction like diesel or steam that generate power on board, also, it provides faster acceleration and higher tractive effort on steep gradients. Besides, electric trains are more environmentally friendly, they emit between 20% - 30% less carbon monoxide than their diesel counterparts, it also has disadvantages, the main one is the capital cost of the electrification equipment, especially on long distance lines that don't get many users.

1.1.1 Electrical Railway Classification

Electrification systems are classified by three main parameters:

1. Voltage
2. Current
   - Direct current (DC)
   - Alternating current (AC)
3. Contact System
   - third rail
   - overhead contact line

Providing electric power to a railway train is done through the contact system, Transferring energy to electrical traction vehicles may be performed with a few different techniques. The oldest and most commonly method is to use overhead catenary made of copper as phase conductor and the track as return conductor. This method is used in both tram and train electrification all over the world. The advantage is that the voltage is high up in the air, and the track voltage level is low enough to be considered safe. This way, it is safe for pedestrians and cars to cross a tramway track without the risk of electrocution.

Electrical traction vehicles uses a sliding device that collects electric current from overhead lines called Panatograph, as shown in Figure 1.1.

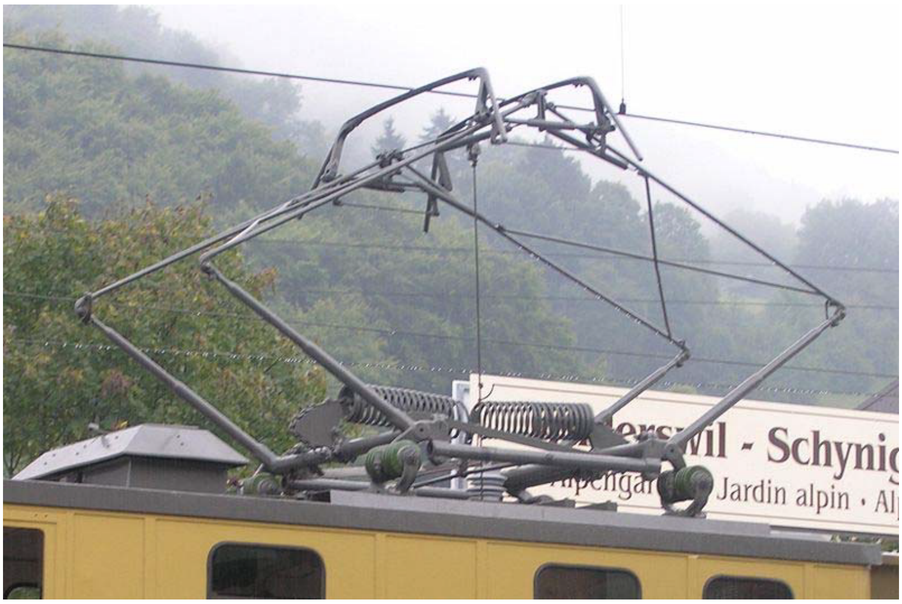

Figure 1.1: Panatograph[2]

To know the difference between the various types of electrical energy supplied for the electric locomotives, it's by determining the type of the current, AC or DC. Figure 1.2 shows how electrification systems are contributed over Europe. Six of the most commonly used voltages have been selected for European and international standardization.[2]

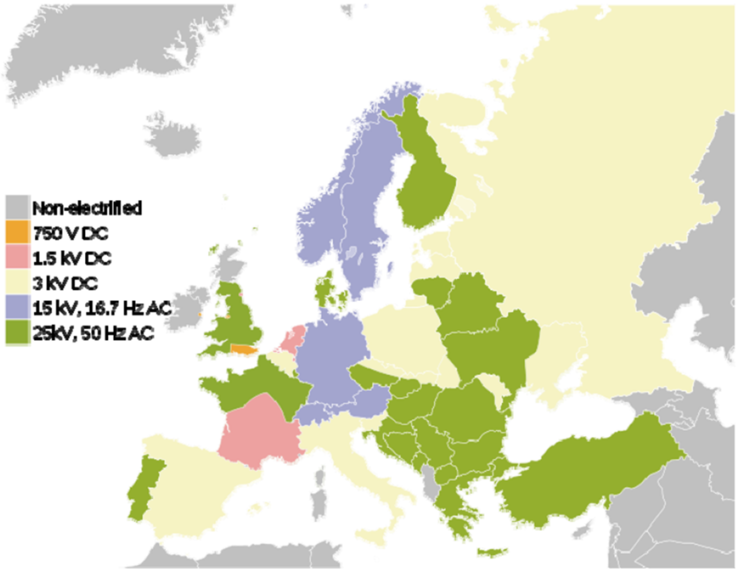

Figure 1.2: Railway Electrification systems in Europe[2]

– DC 750-1500V : Tramways and underground railway Suburban

- DC 3kV : Long distance networks
- AC 15kV 16.7 Hz (50/3=16.7 Hz) : Long distance networks
- AC 25kV 50/60Hz : High-speed or heavy-duty new lines

The permissible range of voltages allowed for the standardized voltages is as stated in standards BS EN 50163 and IEC 60850

Table 1.1: European voltage systems of electric railways according to EN 50163[1]

Type of power supply	U_n	U_{min2}	U_{min1}	U_{max1}	U_{max2}	U_{max3}
DC 600 V	600		400	720	770	1015
DC 750 V	750		500	900	950	1269
DC 1.5 KV	1500		1000	1800	1950	2538
DC 3.0 KV	300		2000	3600	3900	5075
AC 15KV 16.7Hz	1500	11000	12000	17250	18000	24311
AC 25KV 50Hz	25000	17500	19000	27500	29000	38746

U_n nominal voltage
U_{min2} lowest permanent voltage
U_{min1} lowest non-permanent voltage, maximum duration 10 min
U_{max1} highest permanent voltage
U_{max2} highest non-permanent voltage, maximum duration 5 min
U_{max3} low-term overvoltage with a duration more than 20 ms

1.1.2 DC Electrical Railway

Direct current is used for electric rail transport. On a global scale, over half of all electric traction systems use DC. In mass transit systems, maximum nominal voltages of up to 1500 V are used because of the potential danger by higher voltages. The most common DC voltages are 600 V and 750 V for trams and metros and 1,500 V. During the mid-20th century, rotary converters or mercury arc rectifiers were used to convert utility (mains) AC power to the required DC voltage at feeder stations. Today, this is usually done by semiconductor rectifiers after stepping down the voltage from the utility supply. In DC systems only one conductor or rail is required to supply power to locomotive while track rails are used as return conductors in majority of cases. In the past DC motors were used in such system, but nowadays with the advent of 3 phase drives, the DC voltage is inverted to 380 V AC, which supplies 3-phase induction motors by varying the frequency. Other converters on the tram converts the catenary voltage to 24 V DC and 380/220 V AC, 50 Hz, to supply the rest of the electrical equipment. The driver of the tram controls the speed with a joystick which gives a reference speed to the inverter controlling the motors. The motor controller then varies the frequency of the AC voltage feeding the motors and the tram is increasing or decreasing the speed. The basic principle of supplying the catenary with DC voltage is shown in Figure 1.3[3].

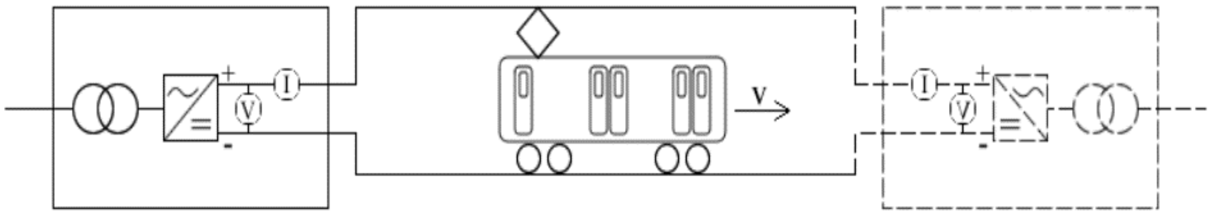

Figure 1.3: The power is transferred to the catenary from one or two rectifying stations.[3]

There are many advantages with 3-phase induction motors compared to DC motors. They generally need less maintenance, they are more robust, they are relatively cheap, they have higher efficiency and they are produced in large scales. The difficulty with induction motors is that they need to be supplied with AC voltage in order to control them. Since the catenary contains DC voltage, it needs to be inverted by power electronics, something that is much easier to come by today compared to a few decades ago.

1.2 Project Aim and Objectives

Aim: It's desired to establish a tramway network in Hebron to reduce the traffic and help the city to gain such a good looking. Suggestions has been made to establish this network in Ein-Sara street, for a 3.2 km long track for a start, in the future the track will be expanded. the track will contain two trams operating at the same time. Figure 1.4 shows the track length and elevations extracted from google maps.

Objectives : The objectives of this project are to

- Design a traction power substation that rectifies the AC voltage to a 750 V DC nominal voltage to be delivered to the trams.

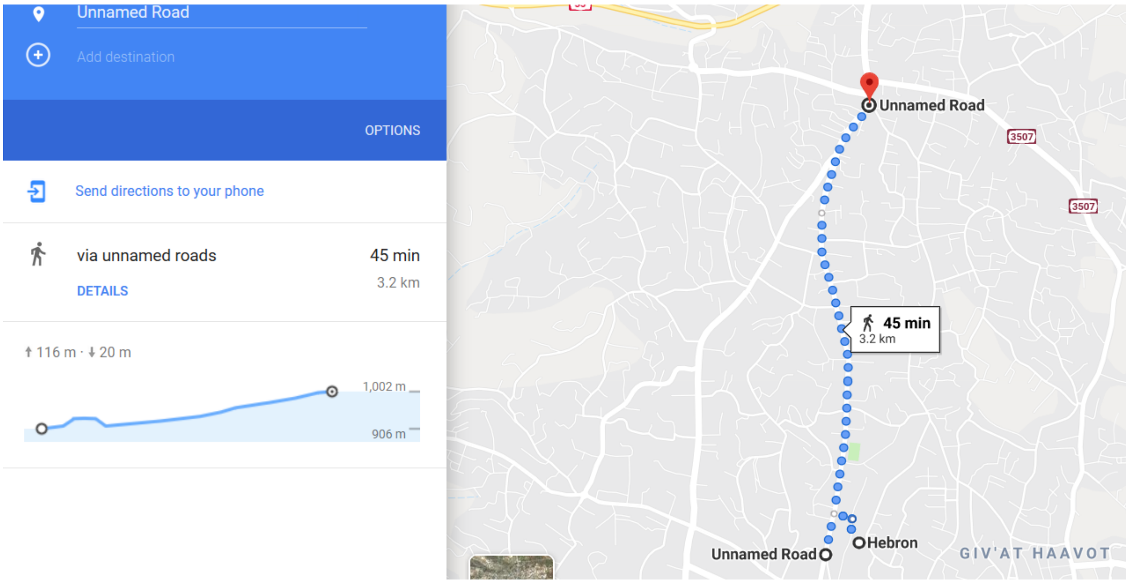

Figure 1.4: Ein-Sara street

- Design the proper current return circuit that ensures the safety in operation and the best return current path.
- Establish a proper DC equipment and system earthing to protect the devices and personnel from any fault condition in the substation.
- Design of the overhead contact line and suspension system in order to achieve the best current-collection possible.
- Provide a protection scheme against direct and indirect contact to guarantee the safety of humans and equipment operation.
- Simulate the system in etap or matlab software to see the performance of the system.

DC traction system block-diagram

A block diagram for the system proposed is illustrated in figure 1.5.

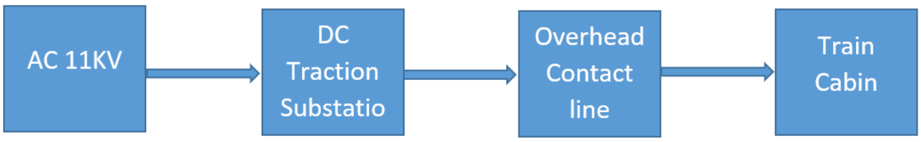

Figure 1.5: DC traction system block-diagram

1.3 Railway dynamics and Tram selection

In this section, the dynamics of the electrical railway will be illustrated to know the forces acting on a running vehicle and what power does it consume, the equations used to calculate the motion of the train are introduced and to see if the trams suits the proposed track.

1.3.1 Tram selection

Trams were selected with 200 kW nominal power from Durmaray company in turkey, called "Silkwarm Tram". Figure 1.6 shows the tram, table 1.1 shows it technical specifications.

Table 1.2: Technical specifications of "silkworm tram"[4]

Main faetures	%100 Low floor, Bidirectional tram, 750V DC
Vehicle Length	29 m
Vehicle Width	2.450 mm
Vehicle Heigth	3.500 mm
Seats	50
Standing Passenger Capacity(8 People/m^2)	224
Total Passenger Capacity	274
Maximum Speed	70 km/h
Minimum Turning Radius	18 m
Vehicle Weigth	38.5 t
Maximum acceleration	1.3 m/s^2
Maximum deceleration	2.8 m/s^2

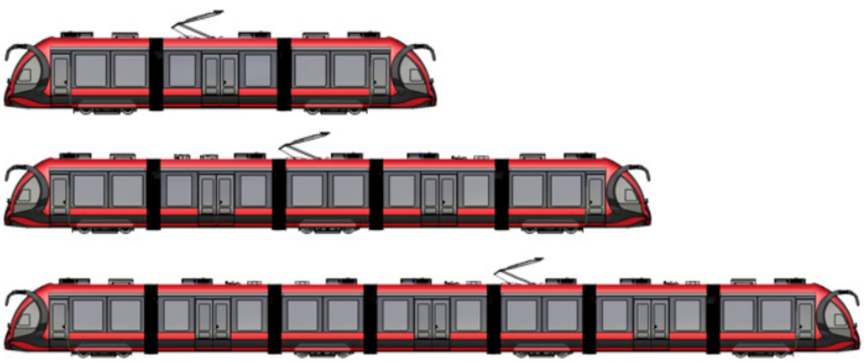

Figure 1.6: Silkworm Tram from Durmaray Company[4]

1.3.2 Railway dynamics

For a moving vehicle to increase its speed, it can be described in many different ways, the simplest and most common way is to describe the motion using Newton's second law.

$$\sum F = ma \tag{1.1}$$

To analyze this motion a free body diagram should be illustrated, Figure 1.7 show the forces acting on the tram, these forces are the tractive effort produced from the motors and the resistive forces opposing the tram motion. The reason of using tractive effort approach instead of instance power or torque is that it is easy to compare it with the resistive forces and get the net force acting on the tram. However, the tractive effort is limited by 3 things,

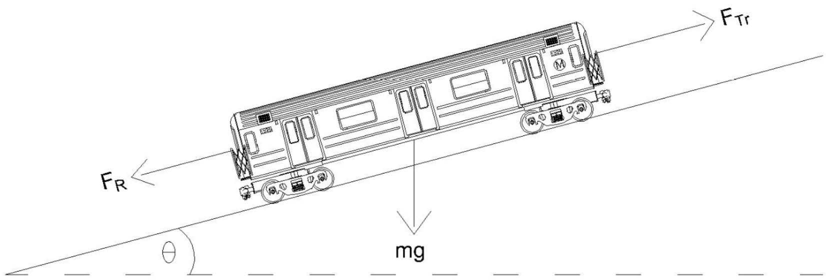

Figure 1.7: A free body diagram of the tram

first factor is the adhesion between the wheels and the track when the tram starts from standstill. To increase the adhesion when starting in a slope or when the track is slippery due to rain, trams have built in anti-spin control and automated sand spreaders in front of the traction wheels. Second factor is the inversely proportionality of the Tractive effort to the speed of the tram and can be calculated with the formula.[3]

$$F = \frac{P}{v} \tag{1.2}$$

where P is the output power of the motors and v is the speed of the tram. The last factor is the acceleration requested from the speed controller in the tram. Figure 1.7 shows example of tractive effort as a function of time during an acceleration from 0 to 60 km/h.

1.3.2.1 Resistive forces

The resistive forces encounter the motion of the tram can be divided into

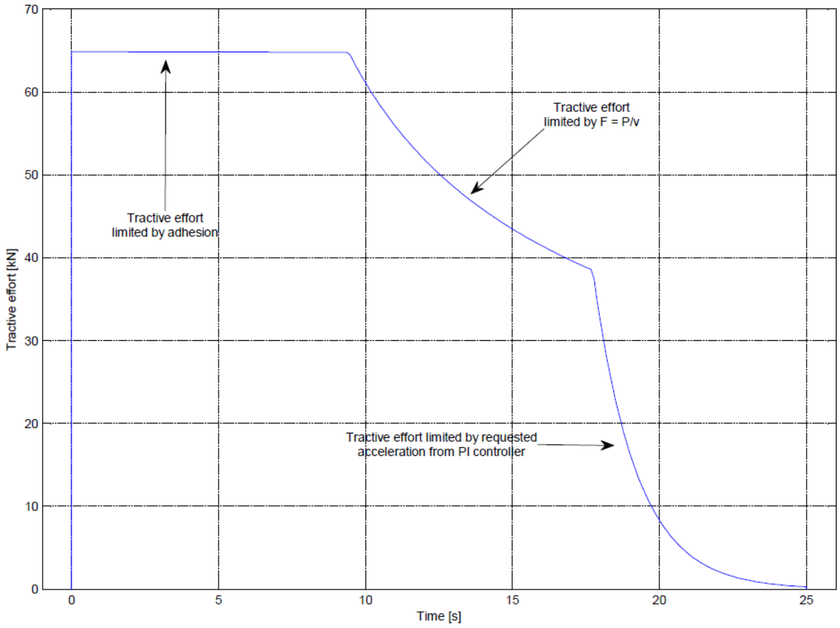

Figure 1.8: Example of tractive effort as a function of time during an acceleration[3]

- starting resistance.
- rolling resistance.
- grade resistance

The starting resistance is where the locomotive must have enough tractive effort to overcome the starting resistance in order to move the train. However it's not a big deal due to the high power-to-weight ratio of the trams. For the grade resistance, it's the gravitational (gradient) force and it depends on the weight of the tram and the inclination of the track.

$$F_{grad} = mgsin(\theta) \tag{1.3}$$

The rolling resistance is important in the total resistive effort as it increases rapidly with the speed of the tram. It includes the journal and bearing resistances (wheel axle), flange resistance (wheels) and the air drag resistance. In 1926, the American W.J. David presented a formula to calculate the total rolling resistance in his paper The "Tractive Resistance of Electric Locomotives and Cars", however The American Railway Engineering (AREA) has altered David original formula so that it's valid for most kinds of trains.[3]

$$R_{total} = (0.6wn + 20n) + bwnV + KV^2 + 20wnG \quad [3] \tag{1.4}$$

where R_{total} is the total rolling resistance in pounds-force, w is weight per axle in tonnes, n is number of axles, b is the coefficient of moving friction, V is velocity in miles per hour, K is a lumped coefficient for aerodynamic resistance and G is the grade in percentage (positive for uphill slopes and negative for downhill slopes). These coefficient sometimes can't be founded easily, so Ansaldobreda company created their own their own version of the David formula to calculate the rolling resistances, it works well and has only a two per cent difference from the AREA formula. The formula is

$$R_{total} = Mg(0.1G + A + \frac{S^2}{B}) \quad [3] \tag{1.5}$$

where R_{total} is the total resistance in Newton, M is the mass in tonnes, G is the grade in percentage, A is a constant equal to 2.5, S is the vehicle speed in kilometer per hour and B is a constant equal to 850.

1.3.2.2 Calculating the resistive forces acting on the silkworm tram

The following assumptions will be used to calculate the net resistive forces

- Vehicle effective weight with full load 240 passengers at 60kg/person is 52 ton.
- vehicle average speed is 30 km/h
- Track grade is 3% from figure 1.4

Grade resistance: After substitution in equation 1.3 $F_{grad} = 15.3$ kN
Rolling and starting resistance: After substitution in equation 1.5 $R_{total} = 2$ kN

1.3.2.3 Calculating the tractive force and Power needed from the tram

Under the acceleration mode the vehicle starts to raise it's speed from rest to maximum speed, in this mode the tractive force (F_{Tr}) need to accelerate the vehicle is

$$F_{Tr} = ma + F_R \tag{1.6}$$

where F_R is the total resistive forces opposing the vehicle motion, if the acceleration is set to 0.2 m/s the tram will reach 30 km/h speed in 40 seconds, and the tractive force needed is 27.5 kN, and for a 30 km/h speed, after substitution in equation 1.2 the power required from the vehicle is 228 kW, so in full load the tram can operate well and can delivers the required power since in nominal power in 200 kW it can reach up to 230 kW rated power.

Chapter 2

DC Traction Power Substation

The dc traction power shall be supplied to the overhead contact lines by traction power substation with a 750 volts nominal output. One of the main drawbacks when using DC traction systems is the fact that electrical energy is universally generated by supply authorities in the form of alternating current. All DC powered tramway networks need to convert the grid AC voltage to a lower DC voltage. The 11 KV AC incoming supplied from distribution network operator provide the feed for the DC traction power substation. The substation controls and rectifies the utility supplied ac power to the dc power required for operation of the vehicles.

2.1 Substation Location and Rating

Traction power substations should be located at or near trams stops, whenever possible. Locations should be optimized with respect to safety, efficiency, access, availability of land or existing structures, stray current control, and minimum life-cycle costs. Due to the high levels of current that are drawn in overhead contact lines, the system voltage can experience severe regulations. To overcome this, substations are spaced at regular intervals.

2.1.1 Substation Location

The substation may be located in underground vaults, as pre-fabricated units or within a building or custom enclosure. when siting a substation the availability of adequate electrical service must be found, either from 33 kV or 11 kV networks. substation shall be located as close as practicable to the wayside tracks but, where feasible, away from the public. The substation location is determined by the traction loads and the maximum permissible voltage drop in the conductor system, in 750 DC systems a voltage drop in the order of 15 to 30% has usually been allowed. To overcome the losses and voltage drop the substation will be located in the middle of the track.

2.1.2 System Loading

The system loading can be obtained from the kW ratings of the trams operating in the system and the corresponding power losses due to the resistances of outgoing and return conductors . This will enable the optimum number of rectifier substations to be selected and also the substation plant capacity. Each tram has a 200 kW nominal power.

2.1.3 Power Losses and Voltage Drop

The conductor losses depends on the current and the resistance of overhead contact lines and return rails.

$$P_{losses} = I^2 R, \quad V_{drop} = IR \tag{2.1}$$

where I is the current drawn from the tram and R is the total resistance of the conductor, since the resistance of the rails is low and using stray current collection system which will be illustrated in chapter 3; resistance of the rails will be neglected. the maximum losses and voltage drop will occur when the tram at the end of the track, where it's in half the track length away from the substation (1.6 km), the contact lines has a 0.148 mΩ/m per meter resistance, for (1.6 km), R is 0.236 Ω, the current drawn from each tram is expected to be 270 A, the maximum voltage drop is 64 V, the maximum power losses for each track is 17.2 kW, for double track 34.4 kW.

Substation Capacity

The capacity of the substation should cover the traction loads and the losses on the way.

$$S_{KVA} = K_{sf} \cdot (P_{trams} + Losses) \tag{2.2}$$

where K_{sf} is a safety factor, choosing 1.2 safety factor, the capacity of substation will be 522 kVA.

2.2 Substation Equipment

Substations shall consist of pre-fabricated units or equipment installed in previously constructed enclosures or rooms. Equipment shall include:

- AC Ring main unit
- Surge arresters
- Traction transformer
- Traction rectifier
- DC switch-gear

The substation components should be standardized in size and configuration wherever possible to minimize the inventory of parts, substation shall include the connections from the utility ac supply to the ac switch-gear through an underground cable system, metering equipment, ac switch-gear, ground and test device, transformer/rectifier units with primary and secondary connecting cabling and buses, dc switch-gear, positive and negative buses, connections to the dc distribution system; grounding system, protective relay system. The substations shall be designed to operate unattended, but should be equipped with local control switches for operation of all ac and dc switch-gear.

2.2.1 Transformer Rectifier Unit

In the past the main advantage of the DC supply system compared to the AC supply system is that a less complex traction control system is required, however with the advent of high power GTO (gate turn off thyristor), IGBT (insulated gate bipolar transistors) and the microprocessor, 3 phase drives are becoming more common on both AC and DC electrification systems. With the advent of 3 phase drives the DC voltage is not a design requirement for the traction engineer due to the ability of the traction input converter to set the DC link voltage to the inverter drive.[5]

2.2.2 Transformer and Rectifier Circuit Arrangement

The pulse characteristic of the supply system is primarily defined by the transformer winding and converter arrangement. A number of simple arrangements of the transformer windings

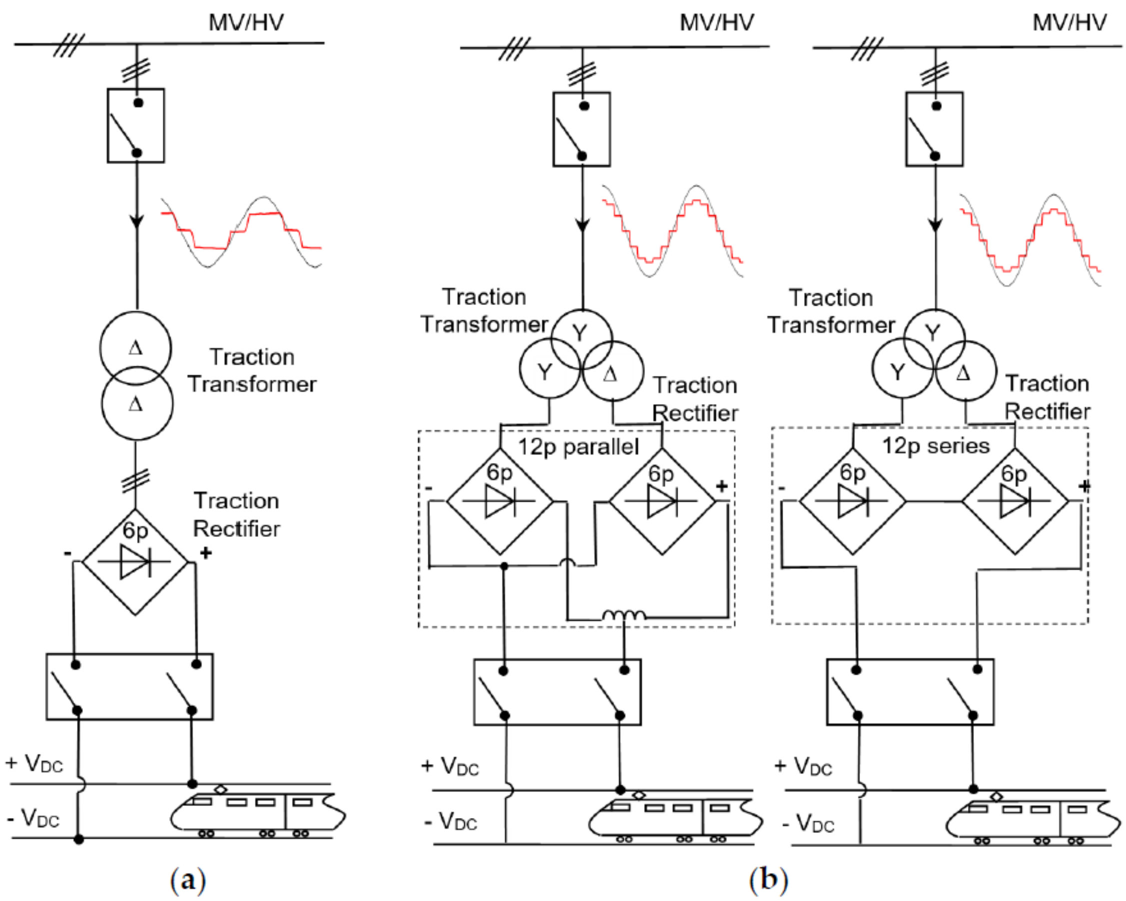

Figure 2.1: Simplified schemes of the usual DC-traction substations and specific waveforms of the supply phase current and voltage: (a) case of 6-pulse uncontrolled rectifier and (b) case of 12-pulse parallel and series uncontrolled[6]

may be chosen with a 3 phase AC supply system to provide 6, 12 and 24 pulse DC output voltage. Other ripple frequencies may be achieved using two converters and windings, which are phase displaced or wound in an alternative star/delta configuration. A 12 pulse rectifier therefore can be obtained by connecting two separately fed phase displaced, 6 pulse systems in series or parallel. The arrangement will provide the necessary 30° displacement of the supply to provide a twelve pulse ripple when the respective bridges are connected in series or parallel. Figure 2.1 illustrates the simplified structures of the common DC-traction substations based on six-pulse and twelve-pulse parallel/series uncontrolled rectifiers and the

associated waveforms of the phase voltages and currents. The arrangement of the windings during the design and construction of the transformer determine the short circuit reactance and the operating load loss due to winding resistance. These design parameters are responsible for dominating the DC short circuit fault current level, the operating DC voltage regulation level, transformer efficiency, transformer and converter power factor and the level of harmonics produced in the supply side.[5][6]

2.2.3 The selected transformer and rectifier circuit arrangement

12 pulse parallel uncontrolled rectification circuit will be used, using three winding transformer and 2 pair of 6 pulse diode rectifier to provide 12 pulse rectification as shown in figure 2.2 and 2.3

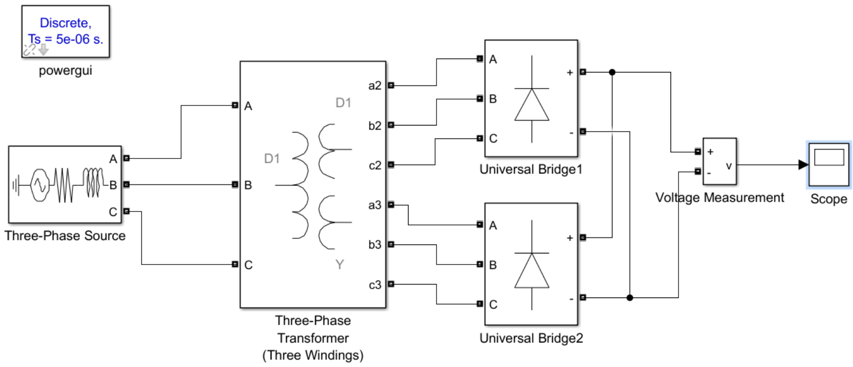

Figure 2.2: three winding transformer and 2 pair of 6 pulse diode rectifier

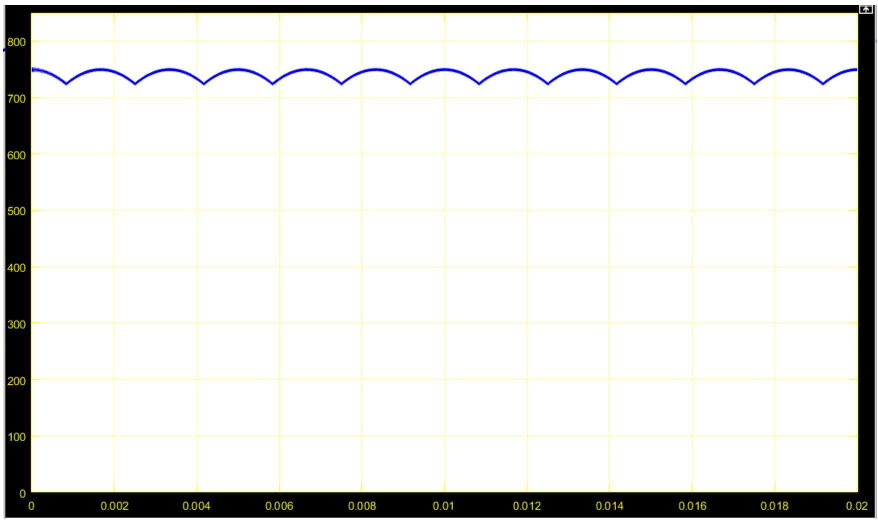

Figure 2.3: Output voltage from 12 pulse rectifier

2.2.4 Substation equipment selection

2.2.4.1 Traction transformer

Traction transformer is special purpose transformer for traction services and it should be indoor type with kVA rating suitable for the specified rectifier. It has three-winding (one primary winding(Δ), two secondary windings(Δ&Y)), and with 11/0.53 kV ratio for both secondaries with 600 kVA rating.

2.2.4.2 AC Ring main unit

Ring Main Unit (RMU) is a compact, sealed for life metal-enclosed switchgear widely used in Urban Power Distribution Network. A Ring Main Unit includes a combination of one or more Load Break Switch (LBS) cum Earth Switch as incomer and outgoing feeder and Vacuum Circuit Breaker with associated Disconnector and Earth Switch for load feeders.

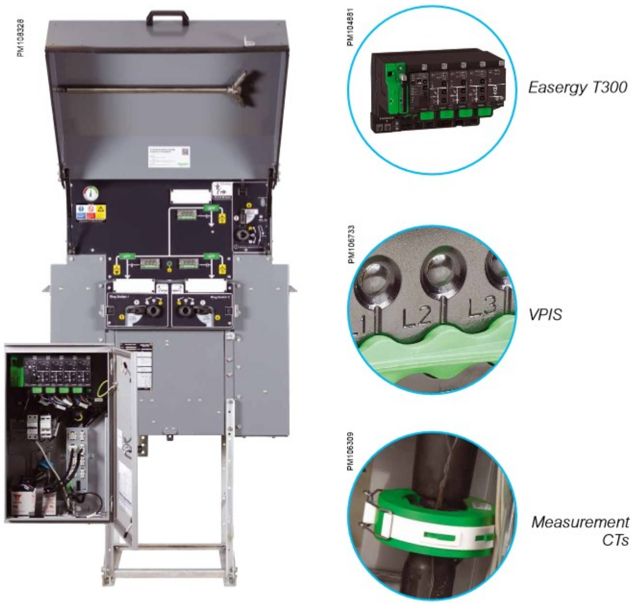

Figure 2.4: Schneider Ringmaster SE6-S2/21

Depending on the requirement, RMU is available in different voltage ratings and are suitable for both indoor and outdoor installation. All the switching devices and the busbars are enclosed in a sealed for life SS enclosure filled with SF6 to make the design compact while ensuring a high level of safety and reliability and also a maintenance-free system. Some of the key features of the RMU includes SF6 gas insulation, compact and modular construction, integral protection system, fully extendable options, and low maintenance.

The selected ring is **Schneider Ringmaster SE6-S2/21**, it's shown Figure 2.4, its specifications are shown in Figure 2.5 & 2.6.

Ringmaster SE6-S2/21	
Rated Voltage	3.3 - 13.8 kV
Service Voltage	13.8 kV
System Frequency	50/60 Hz
Lightning Impulse withstand Voltage Phase to phase, phase to earth Across the isolating distance	 75 - 95 kV 110 - 145 kV
Power Frequency withstand voltage	38 rms - 1 mn
Rated Normal Current Switch Isolator Circuit Breaker Busbars	 630 A 200-630 A 630 A
Rated Short time current withstand (3 sec)	16 - 21 kA
Rated Short circuit making capacity of line switches and earthing switches	40 - 52.5 kA peak at Rated Voltage
Number of operations at rated short circuit current on line switches, earthing switches and CB	5 closing operations
Rated load interrupting current Line switch	 630 A rms
Rated cable charging interrupting current Line switch	 33 A
Rated magnetising interrupting current Line switch	 10 A
Number of mechanical operations Earthing switches and Ring switches Circuit breaker	 5000 O/C 2000 O/C
Number of electrical operations at full loop current	100 O/C
Number of operations at rated short circuit current on circuit breaker	<10 breaking operations

Figure 2.5: Ringmaster SE6-S2/21 specification

Switch disconnector

Basic equipment
Indoor / Outdoor design, IP54, 12 kV, 21 kA 3s
One load break switches rated current 630 A with short bushing
630 A busbar
Internal arc class: IAC AF 12.5 kA/1s for indoor installation or IAC AF 21 kA 1s for outdoor installation (1)
Cable earth switch 21 kA 3s
Transformer earth switch 3.15 kA 3s
Independent manual operation mechanism
SF6 gas gauge
Mechanical ON/OFF indicator
Mechanical earth/main indicator
Switch auxiliary contacts 1NO 2NC
Integral ring switch cable test facility
Main cable box for cable bottom entry
Gland plate for 1 x 3C 300 mm²
Anti-reflex operating handle

Figure 2.6: Switch disconnector specification

2.2.4.3 Traction rectifier

The selected rectifier is **ABB Enviline WDR**(withdrawable diode rectifier). It's shown in Figure 2.7 and it's technical specifications in Figure 2.8.

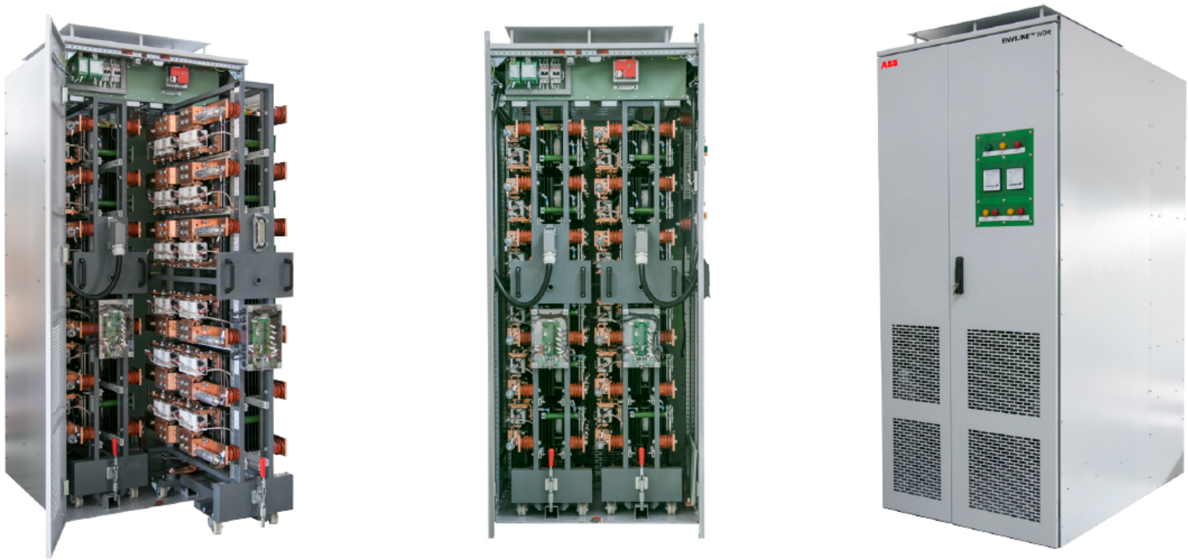

Figure 2.7: ABB Enviline WDR(withdrawable diode rectifier)

Technical data	**Enviline WDR 750**
Nominal TPS (Traction Power Supply)	600 / 750 V_{DC}
Converter power range	0.5 to 4 MW
Pulsation	6, 12, pseudo 24 pulses
Overload capability	Class VI / NEMA RI-9 Extra Heavy Duty Traction (others on request)
Operating voltage range	500 to 1000 V_{DC}
Efficiency	Typically > 99.5 %
Cooling	Air natural
Cabinet Dimensions (WxHxD)	
Version 18	0.8 x 2.2 x 1.4 m
Version 24	1.0 x 2.2 x 1.4 m
Storage temperature	-20° to 60°C
Operating temperature	0° to 40°C (-20° to 50°C optionally)
Maximum temperature (with derating)	50° C
Elevation	1000 m (higher with derating)
Enclosure	IP21, IP31
Remote access	IEC61850 / MODBUS TCP/IP
EMC	EN 50121-5
Redundancy	Optional
Standards	EN 50328 / IEC 60146 / IEEE 1653.2 / ANSI C34.2

Figure 2.8: Technical specification

Rectifiers shall be natural, convection-cooled rectifier, with 12-pulse rectification (6-Phase input). Each rectifier shall be a complete self-contained unit, including bus, connections and hardware from the rectifier transformer output flange to the flange for connection of the bus to the dc switch gear. Each rectifier shall be a complete, operative assembly, consisting of silicon diodes. The rectifier shall comply with and be tested to IEEE 1653.

2.2.4.4 DC switch-gear

Switch-gear is composed of electrical disconnect switches, fuses or circuit breakers used to control, protect and isolate electrical equipment. Switchgear is used both to de-energize equipment to allow work to be done and to clear faults downstream.

Figure 2.9: ABB Enviline™ DCGear DC Switchgear

The positive dc output of the rectifier shall be distributed via a dc switch-gear lineup. The dc switch-gear assembly shall be in the form of a lineup of dead-front, metal-enclosed, freestanding enclosures suitable for indoor service. Use the switch-gear to serve as the control and protective equipment for the distribution of dc power to the streetcar vehicles. Include in the switch-gear assembly draw out, single pole, dc circuit breakers, dc positive buses and bus connections, positive feeder cable terminal connectors, indicating lights, terminal blocks,

Specifications

Feeder panel 750V

Technical data	Enviline DCGear 750V
Normal voltage	750VDC
Highest permanent voltage	900VDC
Rated insulation voltage	1200V OV3
Power frequency withstand voltage	3,6kV
50Hz, 1min	
Rated service current	up to 6 kA
Main busbar current	up to 9 kA
Rated short time withstand current	up to 125kA
Protection degree	IP21/31
Internal fault resistance	50kA 150ms
Dimensions in mm (WxDxH)	600 x 1500 x 2300
Ambient temperature range	-5–40° C
Standards	EN50123-6, IEC61992-6

Figure 2.10: ABB DC switch-gear for 750 V specifications

protective and auxiliary relays, control circuitry, wiring, and other devices necessary to make a complete and operable assembly.

The selected DC switch-gear is **ABB Enviline™** specially designed for traction heavy duty services according to EN 50123-6 as shown in Figure 2.9. Its specification is shown in Figure 2.10.

Chapter 3

Earthing and Current Return Circuit

3.1 Introduction

The traction current which, in conjunction with the voltage applied to the collectors, supplies power to the railway traction vehicle through the contact line. This current must have a return path. As the current path can be considered to constitute a closed loop, the total return current must be equal to the current flowing through the contact line.

As mentioned previously the running rails serve as conductors for the return current. This arrangement mainly focuses on economic considerations, since it does not require the installation of an additional return conductor. The track is laid on the ground and is extremely long in relation to its width. This, coupled with the fact that the resistance between the rails and earth is finite and the rails have a longitudinal resistance, causes a portion of the return current to flow to earth and back to the substation via earth. Near the substation, this current flow back into the running rails and into the substation earthing system. The sum total of the currents flowing through the rails, earth and any metal objects running parallel to the track in the railway track area, such as cable sheaths and pipelines, is equal to the current flowing to the train.[1]

Up to several thousand Amperes may flow in the running rails and cause accessible voltage at the running rails and conductive parts of the vehicles during normal operation. This voltage can be dangerous potentially and can be bridged by passengers and staff. In DC railway systems, the coupling between the rails and earth is found to be completely galvanic in nature, also the current flowing through earth can lead to dangerous DC stray current corrosion, so this portion of the return current must be minimized.[1]

3.2 DC Stray Current

Low resistance between the traction return rails and the ground allows a significant part of the return current to leak into the ground. This is normally referred to as leakage current or stray current. The amount of leaking current depends on the conductance of the return tracks compared to the soil and on the quality of the insulation between the tracks and soil. The stray currents represent serious problems for any electrified rail transit system.

The corrosion problem has been a major concern to the railway and other parties involved since the early days of DC railways. The stray currents create or accelerate the electrolytic corrosion of metallic structures located in the proximity of the transit system as shown in Figure 3.1. This causes metal pipes, cables and earthing grids laid in the ground near the tracks have a much shorter life which is high importance in regard to safety and economy. Hence, great efforts and research have been carried out to control stray current in DC electrified rail transit system. Stray current control is essential in these railway transit systems where the rail insulation is not of sufficient quality to prevent severe corrosion to the rails and third-party infrastructure. The design objective to limit the intensity of the current which leaks to ground is based on the requirement to force the return current flow back to the traction power substation through its intended return path, good control of stray current is also of direct benefit to the operational and safety aspects of the DC electrified railway systems; it could reduce the rail touch voltage.[7]

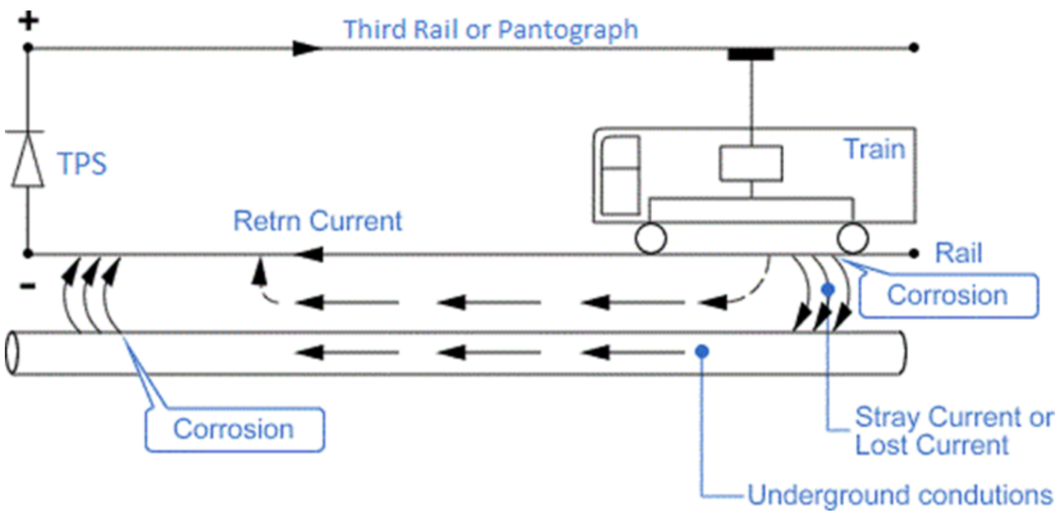

Figure 3.1: Electric interference generated by a dc railway on a metallic structure.[8]

3.2.1 Rail Longitudinal Electrical Resistance

The longitudinal rail resistance is dependent on the type of rail material, the cross-sectional area of the rail, the length of the rail between adjacent substations and the type of construction methods used. This is to ensure low resistance joints between rails of the same track and rails of adjacent bonds. When the return current (negative return) is flowing through the running rails back to the subsystem it encounters resistance from the rail steel and this resistance causes the voltage to drop. In order to keep this voltage drop within the desired limits and ultimately as low as possible, it is sometimes required to increase the conductance of the negative return path

Ultimately, the rail to structure earth (or mesh) potential is dependent on the current flowing in the running rails and the longitudinal resistance of the running rails, which create a voltage drop. This voltage drop is the driving potential that forces the return current to leak from the running rails to the railway structure. Thus, by providing a low resistance return path and a highly insulated support system, the return current will be encouraged to follow the designed path to earth and not seek alternative routes.[7]

3.2.2 Stray Current Modeling

A simplified single traction substation (TSS) and single-train model is shown in Figure 3.2, where I_T is the train current, I_R is the running rail current, R_R is the running rail resistance, R_s is the earth resistance at the TSS, and R_T is the earth resistance as seen at the train.

The touch voltage and stray current of the model are:

$$V_{Touch} = I_R R_R \tag{3.1}$$

$$I_s = \frac{I_T R_R}{R_R + R_T + R_S} \tag{3.2}$$

The problem of reducing the touch voltage and stray current in DC railways is multi-objective and conflicting. The maximum value of stray current leaving the tramway network, and finding its way into the ground, is a function of two parameters. One is the voltage of the rails above true earth, and the other is the resistance of the insulation between the rails and the surrounding road structure or ballast.[9]

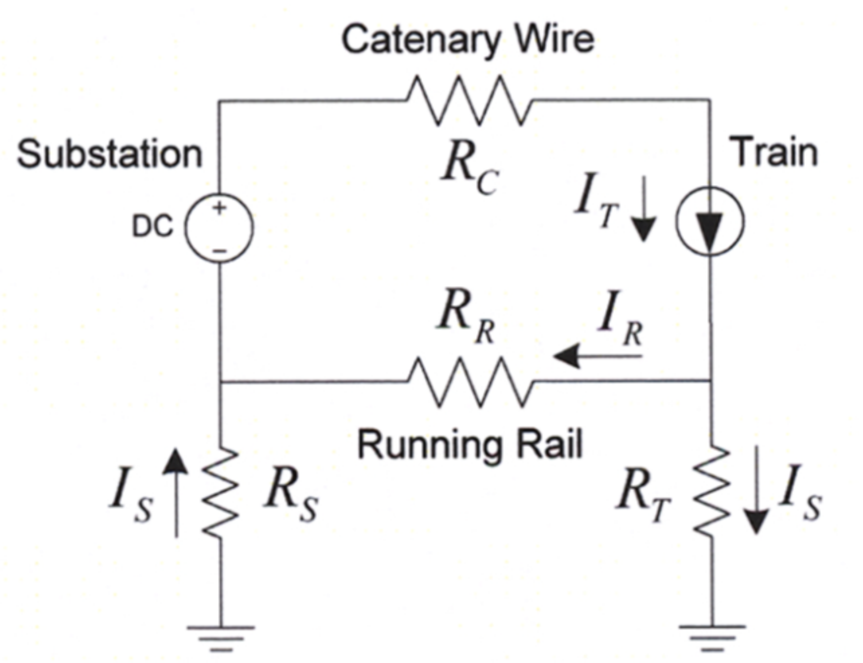

Figure 3.2: A simple case study of stray current and touch voltage modeling[9]

3.2.3 Protective Measures Against Stray Current Corrosion

The objective of protective provisions against the effects of stray currents is to avoid the danger of corrosion on third-party and railway-owned installations. A low longitudinal voltage drop in the return circuit and good insulation of the running rails against earth are the most significant factors in limiting stray currents. Since the longitudinal voltage drop depends upon the distance between the substations and the resistance of the return circuit, stray current protection also influences the required number of substations and, as consequence project costs.[1]

In EN 50122-2 shows that experience proves that there is no damage in the tracks over a period of 25 years, if the average stray current per unit length does not exceed the following value: I_{max} = 2,5 mA/m, this value is the average stray current per length of a single track line. For double track system this value will be multiplied by two.

Stray Current Control

stray current leakage can cause corrosion damage to both the rails and any other surrounding metallic elements. Therefore, there is a stray current control requirement to minimize the impact of the stray current on the rail system, supporting infrastructure, and third-party infrastructure. Therefore, it is good practice to limit the level of stray currents at the source through specific stray current control methods, rather than to mitigate the effects on the transit and other underground structures.[7]

Reduction of the source of stray current is the best strategy for electrical corrosion protection. To reduce the source of leakage current in electrified railway systems. It can be done by

- Reducing the resistance of the running rail
- Increasing the insulating resistance of the rail and the earth
- Raising the voltage level of a substation
- Shortening a distance between substations,
- Adopting the fourth rail as the traction current return conductor

These solutions can be done, but they would cost much also they are not easy to execute and install, their is a better solution though which cost less and Serves well for stray current protection, the solution is called stray current collection system.

3.2.4 Stray Current Collection System

A stray current collection system can be constructed under the rails in order to capture the stray current and avoid damage to the segments. Such collection systems usually take the form of reinforcement in the concrete track bed of a traction system. This reinforcement is bonded along its length to provide a continuous and relatively low resistance path. The stray current leaking from the running rails is intended to flow into this collection system and be captured upon it, as opposed to flowing through the tunnel construction or other local conductors such as utility pipes/cables. For this strategy to succeed, the mat must offer a significantly lower resistance path than segment reinforcement in a tunnel, buried services, and the surrounding soil itself. In a floating system, the stray current collection system will not be bonded to the running rails.[7]

The stray current design philosophy is based on the requirement to minimize the initial generation of stray current, control the flow of the leakage current and ensure adequate electrical separation between the stray collection system and railway and external structures. This is achieved through the following design activities

- Minimizing the potential for stray current through an effective Traction Power Substation (TPS) design and rail return current circuit;

- Minimizing the leakage of current through the provision of high insulation between rail and the structure

- Controlling the distribution of stray current by the construction and maintenance of stray current collection systems, to provide an efficient low resistance preferential path for current collection and return;

- Maintaining either electrical separation between the collection system and other conductive parts of the structure (tunnels and Cut and Cover) or the total inclusion of all potential paths to earth within the system; and

- Minimizing the longitudinal electrical conductivity of supporting structures.

3.2.4.1 Rail to Structure Earth (Mesh) Resistance

The rail to structure earth (or stray current mesh) resistance is dependent on the trackwork design and construction, environmental conditions and the level of maintenance. As a consequence, this parameter may vary at the same location over time and most likely be different at other locations. In theory, increasing rail to structure earth resistance to a large value should reduce stray current leakage correspondingly. Therefore, rail to structure earth resistance is one of the most important and effective aspects of stray current control. The main principle is to arrest stray current at its source, the running rails. As a result, the higher the insulation of the running rails the better the stray current mitigation. In EN 50122-2, a value of 10 Ωkm is specified as adequate, however for modern track systems this value is considered low and in reality most modern track systems individual components will deliver an insulation in excess of 60 Ωkm under dry conditions.[7]

3.2.4.2 Rail Longitudinal Electrical Resistance

The longitudinal rail resistance is dependent on the type of rail material, the cross sectional area of the rail, the length of the rail between adjacent substations and the type of construction methods used. This is to ensure low resistance joints between rails of the same track and rails of adjacent bonds. When the return current (negative return) is flowing through the running rails back to the subsystem it encounters resistance from the rail steel and this resistance causes the voltage to drop. In order to keep this voltage drop within the desired limits and ultimately as low as possible, it is sometimes required to increase the conductance of the negative return path.[7]

An example of stray current collection system is shown in Fig 3.3 and 3.4 The reinforced concrete mat placed underneath the rails is used for both structural support and as a conductive path for a stray current. Connected to this mat is an insulated cable, generally copper, that increases the overall conductivity of the stray current collection circuit relative to the alternative stray current paths in the soil and other buried objects. Stray current control mats have generally been constructed in 100-m sections with the starts/ends of each section being electrically connected to each other and to the stray current collector cable producing a continuous stray current path. If a designer considered that stray current was likely to be a problem in a specific region of the transit system, local stray current collection systems could be used but careful attention would have to be given to the design of the terminations of the system in which severe corrosion could occur.[10]

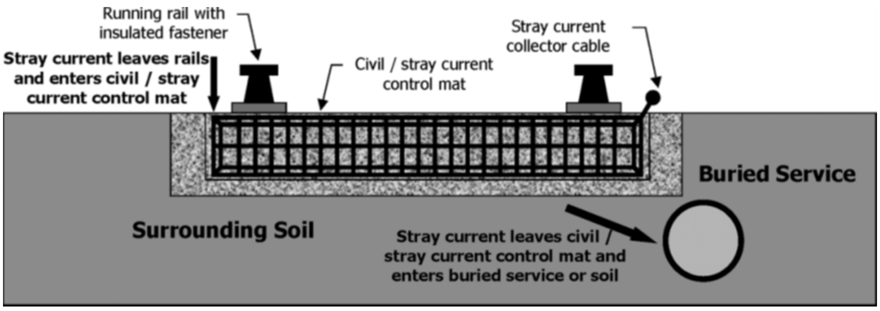

Figure 3.3: Path of stray current leaving the running rails.[10]

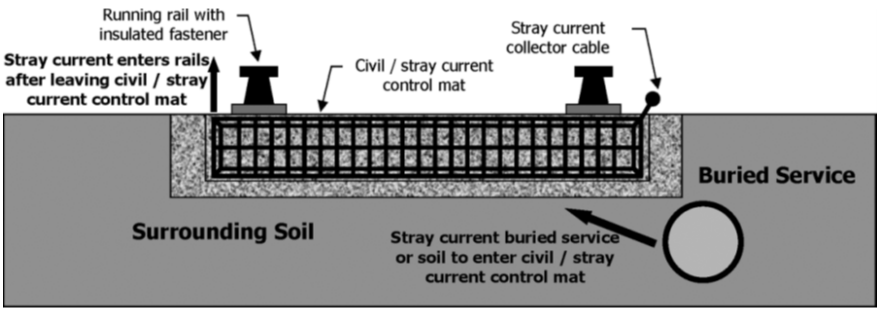

Figure 3.4: Path of stray current leaving the running rails.[10]

Stray Current Collection Cable

The stray current collector cable, is provided along the length of the viaducts which is laid on cable trays installed inside the deck. The reinforcement within each precast segment is electrically bonded to each segment and finally the stray current collector cable.It's connected directly to the stray current control mat at 100-m intervals, at which point the stray current control mat is also sectioned (as in practice for ease of construction). As with the dimensions of all conductors in the model, the size of the stray current collector cable can be altered to assess the impact it has on the system performance.

3.2.5 Rail Traction System Modeling

A generic model for a dc electrified railway is shown in Fig 3.5 In order to model with a sufficient accuracy the return current and the stray current in the stray current collection mat, a transmission line of the type of the distributed two-layer ladder circuit model use is adopted. In Fig, it is represented a section of length L of the traction line between two TPSs, where the vehicle (considered as a lumped load) occupies the position x variable between 0 and L and pulls the current I, sourced as currents I1 and I2 from the two TPSs Where

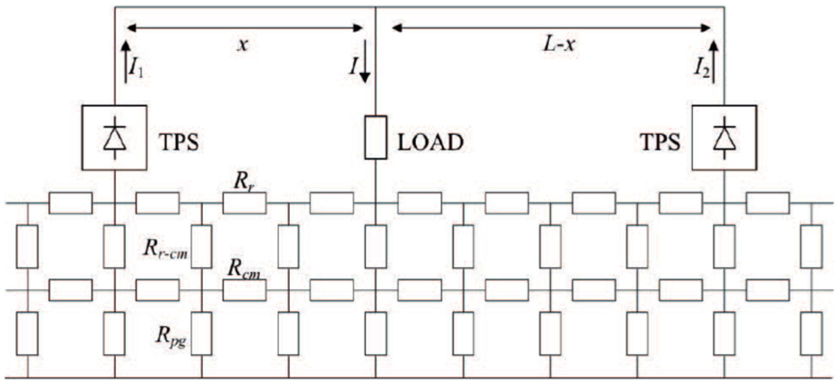

Figure 3.5: Rail Traction System Modeling[7]

R_r is the running rail longitudinal resistance, R_{r-cm} is the resistance of the rail to the stray current collection mat, R_{cm} is the longitudinal stray current collector mat resistance, and R_{pg} is the insulation resistance of the piers with respect to ground, including the longitudinal resistance of the pier itself.[7]

3.3 Grounding System of Traction Power Substation

Safety provisions and protective measures against stray currents significantly determine the design of the traction return circuit and the earthing installations of DC supplied railways. Based on what we encountered in the previous section, stray current problem deals with grounding system configurations, planning and implementation, with strict separation between the return circuit and structure earth, complying with the stipulations of Railway

Standards EN 50122-1 and EN 50122-2, these standards deal with electrical safety, earthing and the return circuit, also the protective measures against electrical shock, it doesn't give the priority to provisions against stray current corrosion.[1]

Present practice when designing the dc traction power system is to keep rated voltage in the range of 600–1500-V dc with 750- V dc the normal choice of many projects. The dc switchgear consists of single-polarity (positive) dc circuit breakers of either the high-speed or the semihigh-speed type to supply dc power to the train propulsion system via overhead catenary or third rail system. The negative-polarity bus box is physically kept separated from the dc switchgear. Fig 3.6 represents various components of the dc electrification system including the vehicle. It should be noted that the vehicle touch potential is practically the same as the rail-to-ground potential, especially if there is no other provision for grounding the vehicle.[11]

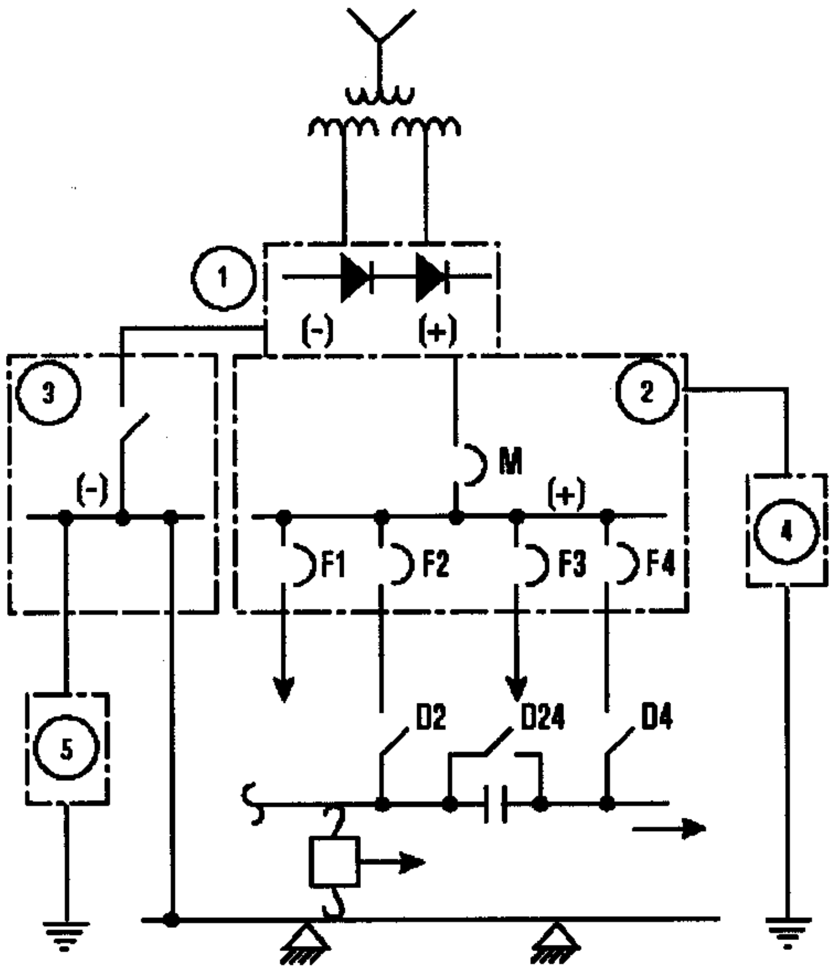

Figure 3.6: DC electrification one-line diagram. 1: Rectifier unit; 2: dc switchgear; 3: negative bus box; 4: equipment grounding protection; 5: system grounding protection.[11]

To properly address the subject of grounding, there should be a clear understanding of the differences between "equipment" grounding and "system" grounding. Equipment grounding refers to grounding of the enclosures of the rectifier unit and dc switchgear. System grounding refers to grounding of the current-carrying conductor of the dc negative system. This negative system is the negative of the rectifier unit at each traction power substation and the track running rails carrying negative return current[11]. The system could be

- Underground
- Impedance grounding
- Effectively grounded that apply to ac power systems

Under normal system operation, there is no direct intentional electrical connection between the dc negative and the ground. However, this ungrounded system establishes reference to ground through leakage resistance of the running rails. This leakage resistance depends upon the track insulation material and is generally on the order of 200Ω /1000 ft/rail under normal dry weather condition sand age of the tracks due to accumulation of metallic dust, this value considered when the system doesn't have stray current collection system.[11]

3.3.1 Equipment Grounding

Grounding of dc equipment enclosures in dc traction power substations include many features not found in ac power distribution systems. The practices and methods vary throughout the industry. DC equipment in traction power substations, which commonly consists of the rectifier enclosure, dc bus enclosures, and dc switch-gear, can be solidly grounded, high-resistance grounded, or low-resistance grounded. Each method will be described.

Design of the dc equipment enclosure grounding shall assure maximum safety of personnel and equipment under fault conditions. According to the IEEE recommended practice of grounding of DC structures and enclosures, the danger to personnel results from high dc short-circuit currents due to associated fire, molten metal, and brilliant flash rather than electric shock risk due to dc voltage present at the equipment enclosure under fault conditions. At that time, grounding of one polarity of the dc system was standard practice for the railway and mining industries. As a result of these experiences, the development of high-resistance equipment grounding protective relay schemes became the norm of the transit industry in USA[11].

It has been recognized by the transit industry that dc equipment enclosure rectifiers and metal-enclosed dc switchgear should be grounded by using an appropriate protective relay scheme for safety of personnel and equipment. This protection relay scheme, which employs either high-resistance or low-resistance equipment grounding methods, has been a subject of many debates and discussions among equipment suppliers, design engineers, and transit authority representatives. Each transit property employs one or the other grounding method depending upon their own understanding of the safety and design issues, so to make the right choice of grounding method, it must ensure the balance between safety of personnel and stray current level[11]. There are three methods for equipment grounding, solidly grounded, high-resistance grounded, or low-resistance grounded.

3.3.1.1 Solid Grounding

Solidly grounded dc enclosures are connected to earth ground through the bonding of neighboring equipment, building structure, and grounded electrodes with no intentional impedances installed between the enclosure and ground. The operation of solidly grounded equipment relies on the presence of very low-impedance connections between equipment enclosures and ground in order to minimize voltage potentials during normal operation and during fault conditions[12].

Due to the low operating voltage and correspondingly high operating current, particular attention must be paid to providing an adequate earthing system and bonding conductor size. Insufficiently sized conductors may simply fuse (open circuit) and allow the affected equipment enclosure to elevate to the system voltage. An earthing system that exhibits excessive resistance may raise an entire building to the system voltage. If the fault is remote from the supply, as is often the case in transit systems, conductor resistance may limit currents below feeder breaker trip settings and the fault may continue indefinitely.[12]

An enclosure fault to railway negative may go almost totally unnoticed. Over time, the fault may cause earthing electrodes to be rendered ineffective by stray current corrosion. A negative fault may also cause enough current to flow to ground such that equipment bonds melt unnoticed and inadvertently isolate the equipment from safety grounds[12].

It is generally not recommended to solidly ground positive polarity dc equipment enclosures due to the high-energy nature of dc faults and the fact that some ground faults can be low in magnitude and not detectable by overcurrent protective devices.

3.3.1.2 High Resistance Grounding Method

High-resistance grounding is performed by isolating dc equipment enclosures from ground through the use of insulation and connecting the equipment chassis to ground through a high-resistance protective relay device as shown in Fig 3.7.[12]

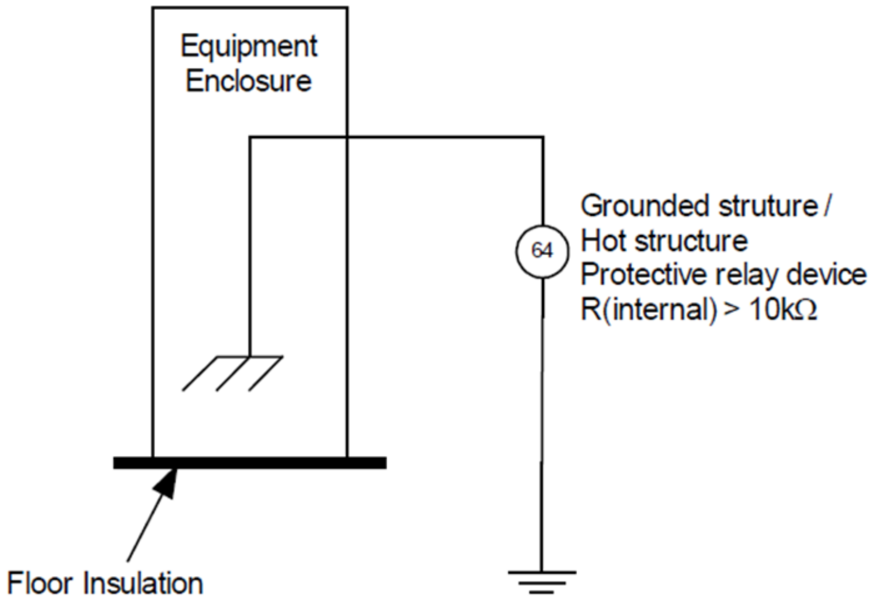

Figure 3.7: High-resistance grounding schematic[12]

Protective relays function by applying a small dc voltage on the structure at all times and continuously monitoring the voltage on the enclosure. In the event that the measured voltage rises above its high-voltage trigger during a hot structure fault or diminishes below the low-voltage trigger during a grounded structure fault, the 64 device initiates output signals in accordance with protective schemes implemented for the device.[12]

Since fault currents in high-resistance grounded enclosures are limited to below 1 A or less during a positive-to-enclosure fault, there is little to no damage to wiring, components, or equipment. Repairs can be made at very little cost, and equipment can be quickly restored to service once the fault condition has been removed. However, the potentially high voltages necessitated the development of methods to protect personnel by designing equipment that could tolerate being energized to full system voltage during an enclosure fault. These methods also included the development of relay schemes that could detect an energized structure as well as unintentionally grounded structures in the event of a fault.[12]

Protection practices for high-resistance grounding depend primarily on the operating procedures of a transit agency. Some agencies may decide to only monitor hot or grounded structure faults and trigger an alarm. Others may decide to trip traction power ac and dc breakers upon a hot structure fault event. Regardless of the protection scheme, the protective device should feature outputs that indicate when a hot or grounded structure fault occurs. These outputs should then be used to employ the preferred protection scheme of the agency. The recommended protection scheme for high-resistance grounding is to trip the ac breaker feeding the rectifier transformer, dc cathode breaker, and dc feeder breakers upon a hot structure fault. For grounded structure faults, an alarm should be triggered to a local alarm panel at minimum.[12]

3.3.1.3 Low Resistance Grounding Method

Low-resistance grounding is performed by bonding enclosures through a bidirectional diode current sensing device with a ground protective relay monitoring the fault status of the enclosure. In addition, dc equipment enclosures are isolated from ground to reduce the chance of inadvertent bridging of the ground detection circuit, as shown in Fig 3.8.

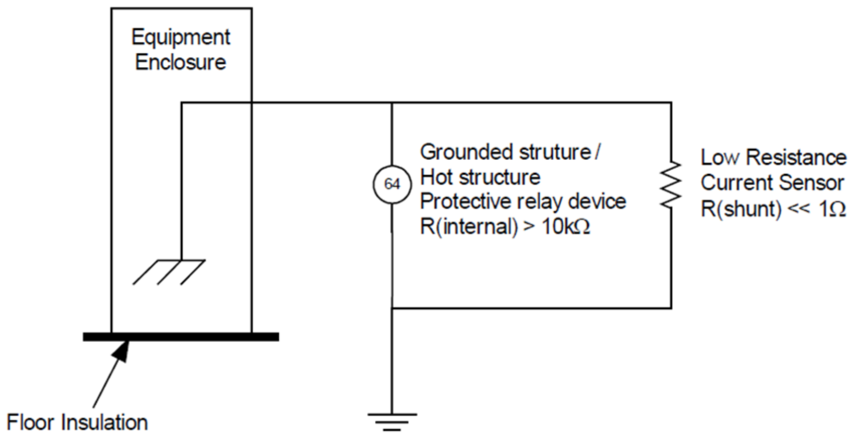

Figure 3.8: Low-resistance grounding schematic[12]

Fault detection in a low-resistance grounding scheme is similar to high-resistance grounding in that a small voltage is maintained on the structure at all times and continuously monitored by the protective relay. But unlike the high resistance scheme, the voltage from a hot structure fault only elevates to the voltage drop across the current sensing device, and the voltage potential on the structure is typically less than five volts to ground. In the event that the measured voltage rises above its voltage trigger during a hot structure fault or diminishes below the low-voltage trigger during a grounded structure fault, the 64 device initiates alarms and sends trip signals to circuit breakers in accordance with the protective scheme implemented for the device.[12]

Low-resistance grounding has the benefit of limiting voltage potential on equipment enclosures for personnel, but the high-fault currents that result can cause damage to equipment, including steel panels, structural members, and copper bars. Ground conductors should be sized to sustain the maximum dc fault for 0.25 s while maintaining a continuous ground path to allow for protective devices to clear the fault.[12]

The recommended protection scheme for high-resistance grounding can also be applied for low-resistance ground protective relays.

3.3.2 DC Power System Grounding

Design of the dc power system grounding needs to compromise two contradictory requirements, minimum dc stray current and maximum personnel and equipment safety. To achieve this objective, system grounding should be designed to satisfy the following basic requirements:

Under Normal System Operation

The grounding system should minimize dc stray current. This can be achieved by keeping the system un-grounded, i.e., floating. No intentional connection is made between system negative and ground.[11]

Under abnormal system operation

With unsafe rail-to-ground potential, the system should be grounded by shorting the negative polarity to ground to suppress the unsafe voltage. The method of shorting the rail or the substation negative bus box to ground shall be achieved automatically through protection relays and shorting devices in the shortest possible time. Upon clearing this abnormal situation, the system will automatically return to the original stage of an un-grounded power system[11]. Various methods employed to achieve the system grounding schemes and their limitations are discussed.

3.3.2.1 Solidly Grounded System

The negative of each substation is grounded to the local ground grid without any intentional impedance in the grounding circuit as shown in Fig 3.9.

It should be recognized that the running rails' negative return circuit effectively becomes in parallel with the ground and, thus, a considerable part of the negative return current

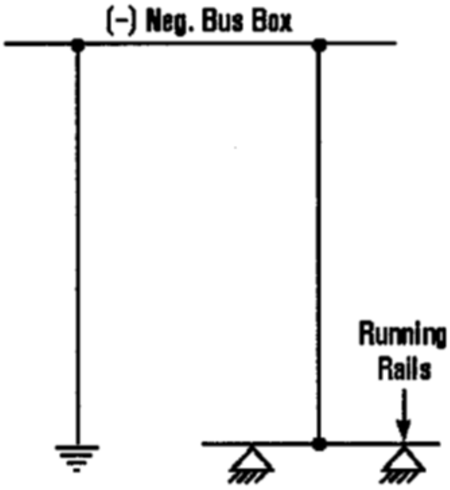

Figure 3.9: Solidly Grounded System[11]

may seek the path of ground, increasing the threat of corrosion to underground utilities in vicinity of the tracks. Drainage bonds between underground utilities near the traction power substation and electrical bonding of underground utilities in the vicinity of the tracks is mandatory to mitigate the corrosion effect of dc currents. This method may exist only in older transit systems. The modern systems do not employ such a grounding system.[11]

3.3.2.2 Diode Grounded System

Paralleled array of diodes with a shorting dc contactor and protection relays are employed at each traction power substation as shown in Fig 3.10. Upon detecting a set voltage level, relay

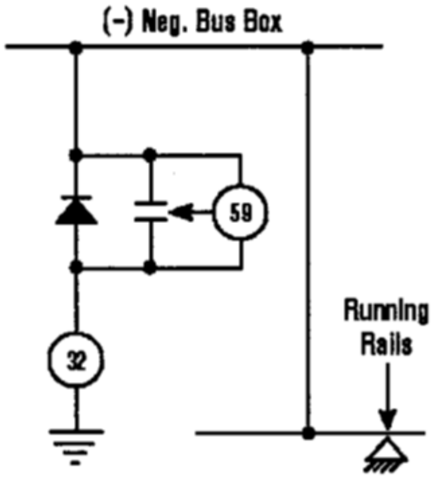

Figure 3.10: Diode-grounded system[11]

device 59 energizes a dc contactor to automatically ground the negative system. Directional overcurrent relay device 32 opens the shorting contactor for low-level "forward" currents and trips the traction power system if high-level ground-fault current continues to flow. It should be noted that, under normal system operation, for small magnitudes of voltage difference between rail and ground, the diodes are always conductive, thus setting a stage for relatively higher stray currents.[11]

3.3.2.3 Automatic Grounding Switch

Shorting switch device 57, over-voltage relay device 59, and over-current relay device 50 are employed at each traction power substation as shown in Fig 3.11. Upon detecting a set voltage level, device 59 activates and closes the shorting switch to automatically ground the negative system. Upon sensing short-circuit current, device 50 activates to deenergize the traction power substation. In addition, device 50 provides local indication and remote alarm to manually reset the shorting switch. It should be mentioned that a shorting switch is a mechanical device and takes definite time to activate; dangerous voltage could occur during this time.[11]

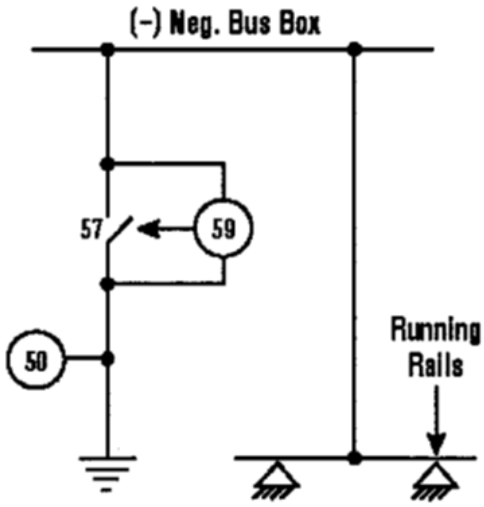

Figure 3.11: Automatic Grounding Switch[11]

3.3.2.4 Ungrounded (Floating) System

The system is kept ungrounded under normal and abnormal conditions as shown in Fig 3.12. This system provides the least stray current; however, it may prove to be dangerous to the general public and maintenance persons as the vehicle or running rails may be at an elevated

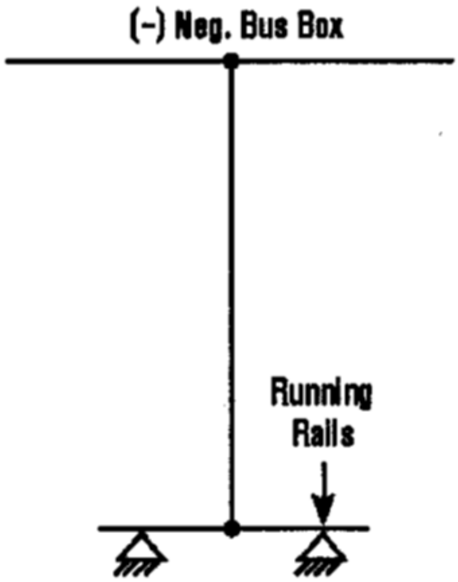

Figure 3.12: Ungrounded (Floating) System[11].

dc voltage with respect to ground, especially during positive-to-ground fault. This method is not used in present transit systems for safety reasons, especially under abnormal fault conditions.[11]

3.3.2.5 Thyristor Grounding Method

The various protective relay devices of the Thyristor grounding scheme are shown in Fig 3.13 Over-voltage relay device 59 continuously checks the negative-to-ground voltage. When this voltage exceeds a preset value, the relay triggers the Thyristor gate [gate-turn-off Thyristor (GTO)] by auxiliary relay device 59X to ground the negative system. This limits the potentially dangerous rail-to-ground voltage by allowing current to return to the source. The contacts of instantaneous current relay device 50 energize time delay auxiliary relays 50X1 and 50X2. After a short delay upon sensing decrease in the current, device 50X1 provides an alarm as well as provides gate-turn-off signal to the Thyristor to resume its normal position of an ungrounded system. However, if the current continues to flow in case of positive-to-ground fault, then after a preset time delay device 50X2 will trip all dc feeder breakers. The setting of relay device 59 may be set on the order of 60 V, which is considered safe touch potential. This will allow the system to operate ungrounded for normal conditions until ground-to-negative rail potential rises to the set limit of 60 V under abnormal positive feeder-to-ground fault condition.[11]

It should be mentioned that a bidirectional GTO unit may be required, depending upon the

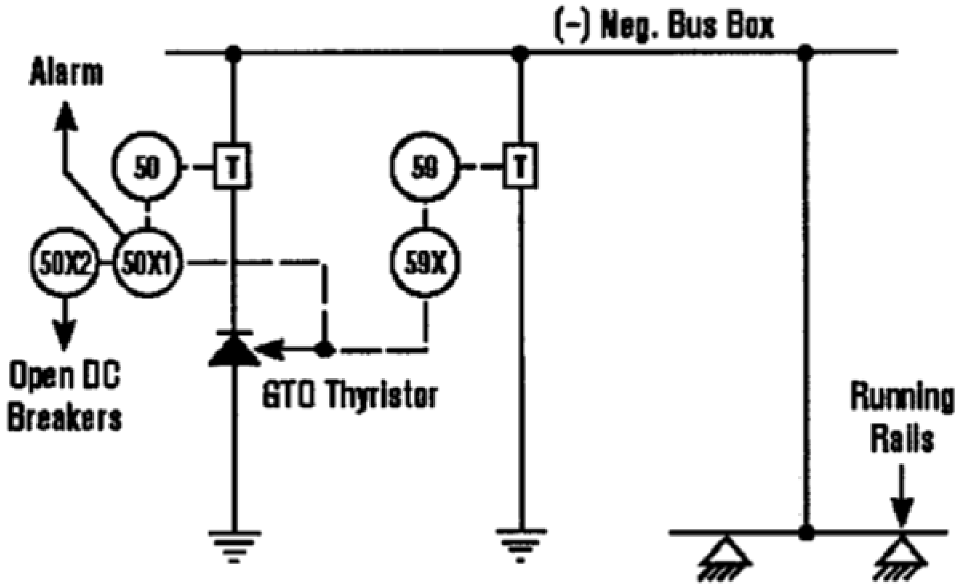

Figure 3.13: Thyristor Grounding Method[11]

system configuration and excessive train starting currents resulting in dangerous rail voltage rise above ground. Such a design if implemented should have GTO activation counters, and a voltage and current monitoring device scheme to optimize the settings of device 59 to assure maximum safety and minimum stray current injection.[11]

The advantage of the bidirectional thyristor scheme over the grounding diode scheme is that the thyristor unit will ground the system only when the set dangerous voltage occurs due to either train bunching load currents or due to positive-to-ground faults that develop. Under normal system operation below the set negative- to-ground over-voltage, the system is kept ungrounded and, thus, stray leakage current is minimum.[11]

Comparison Between System Grounding Methods

The relative magnitude of the stray current and the vehicle touch potential for various system grounding configurations is shown in Table 3.1. Both the stray current and the human safety seem to be balanced by the Thyristor grounding method as compared to other system grounding methods. The protective relays shown in Fig 3.13 provide complete tripping and isolation of the traction power system in case of heavy short-circuit current due to positive-to-ground fault, and automatically return to normal configuration once the fault is cleared. Reverse GTO may be used at the stations to suppress dangerous vehicle touch potential; however, it may unnecessarily increase stray current magnitude[11]

Table 3.1: System grounding versus touch potential and stray current[11]

System Grounding Method	Rail to Ground Potential	Stray Current Level
Solidly Grounded	Low	High
Diode Grounded	Moderate/Low	Moderate/High
Thyristor Grounded	Moderate/High	Moderate/Low
Ungrounded System	High	Low

Making Decisions

After presenting various methods of equipment enclosure grounding and system grounding, in the end we want to keep the balance between stray current level and safety of personnel and equipments, so this project will adopt high resistant grounding for the equipment grounding and thyristor grounding method for the system grounding.

3.3.3 Floor and Wall Insulation Practices

Facilities utilizing either high- or low-resistance grounding methods should employ insulated floors under and surrounding dc equipment. As shown in Figure 3.14, floors and walls are

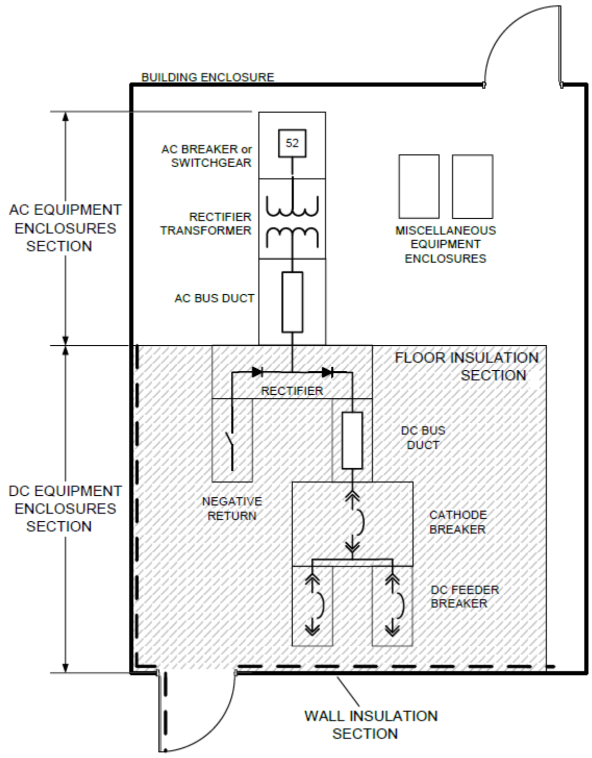

Figure 3.14: Typical dc traction power distribution facility[12]

insulated for the purpose of isolating ungrounded (low or high resistance grounded) equipment within the proximity of the equipment from ground. In masonry and prefabricated type substations, epoxy is commonly used for insulating material, although fiberglass laminates and rubber mats have also been used.

The dielectric properties of floor insulation material should be capable of withstanding the voltage limits, the recommended test voltage for insulation used in 750 Vdc systems is 2500 Vdc and should be applied between the equipment and ground for 1 min. Ground detection protective relay devices must be disconnected from ground prior to commencing the test. The test is successful if there is no breakdown in the insulation and the leakage current does not exceed 50 μA. The Ground detection relaying devices/systems should be re-connected and tested after dielectric tests of flooring are completed. As for installation, insulation should extend horizontally at a minimum 1.83 m (6 ft) beyond insulated enclosures and with a height of 2.44 m (8 ft) to minimize potential personnel contact with grounded enclosures.

Dielectric tests of floors and walls should be conducted before and after installation of dc equipment on insulated floors. The test area can be reduced to the exposed floor around the equipment for tests conducted after equipment is installed. Insulated floors in prefabricated distribution facilities should be retested in the field after delivery to verify the integrity of the insulation.[12]

Chapter 4

Overhead Contact Lines and Supports Design

Contact lines are a system of electrical conductors used in conjunction with a sliding current collector to supply electrical energy to vehicles. Overhead contact lines are contact-lines located above or at the side of the top line of the vehicle gauge for supplying vehicles with electrical energy through roof-mounted current collector devices(pantographs).

For safety reasons, only overhead contact lines are permitted for operation at voltages up to AC 1000 V and DC 1500 V. For high running speeds, above 100 km/h especially, energy transmission becomes an increasingly challenging task. Because of this, overhead contact lines have undergone continuous development through a wide variety of designs, beginning with simple trolley-type overhead lines for tramways in 1881 up to the present-day high-speed overhead contact lines. The decisive factors in this development process were the requirements of the type of traffic to be served, the means available to the different railway authorities and the experience and abilities of the companies involved.[1]

The overhead line systems which evolved can be classified according to either their applications or to essential structural design characteristics such as the voltage, the use and arrangement of specific components, the method of tensile forces compensation and the type of the suspension.

Overhead contact line systems include, foundations, supporting and any other components which serve to hold structure and support, align and insulate the contact wire and conductors. The design of the overhead contact line in a railway system should be done in order to achieve the best current-collection possible. The goodness of this current collection depends on the particular characteristics of the infrastructure, such as the gauge, the tolerances, etc.

and also on the speed of the vehicles and their geometry. There are other factors to be considered, such as safety requirements and structural isolation distances, as a result, the design of the catenary is a complex process, where all the electrical, geometrical and mechanical characteristics should be taken into account. Design of the catenary should determine the type of supports that should be used and their position and the suspension method used.[1]

4.1 Overhead Contact Line Equipment

4.1.1 Contact Wire

The main purpose of the contact wires is to act as a contact slide ensuring uninterrupted transmission of electrical energy to the collectors on a vehicle's pantograph. There are different contact wire types and cross sections to suit the different fields of application. The preferred cross section for overhead contact wires is circular. The contact wire cross-sectional area selected depends mainly on the current required, the voltage stability and the tensile forces to be applied, for tramway applications the best selection is the Contact wires which have grooves on either side of the top section to enable them to be clamped by clips, it called grooved contact wires.

Grooved Contact Wires

These wires are made of hard-drawn electrolytic copper and copper alloys, thanks to their high conductivity, tensile strength and hardness as well as their ability to withstand temperature changes and corrosion, hard-drawn electrolytic copper and copper alloys have become the established global conductor wire material. Upon exposure to air, copper forms a hard but conductive oxide layer which does not prevent the current from flowing. This is the reason why copper, as opposed to aluminum, which forms an oxide layer of poor conductivity, is suitable as a material for sliding contacts. All attempts to use aluminum as contact wire material have failed.[1]

The grooved contact wires shall conform to the requirements of EN 50149 standard. This European Standard specifies the characteristics of copper and copper alloy wires of cross sections of 80 mm^2, 100 mm^2, 107 mm^2, 120 mm^2 and 150 mm^2 for use on overhead contact lines. The cross-section area, dimensions of such wires made of only electrolytic copper according to EN 50149 are shown in Fig 4.1 and table 4.1.

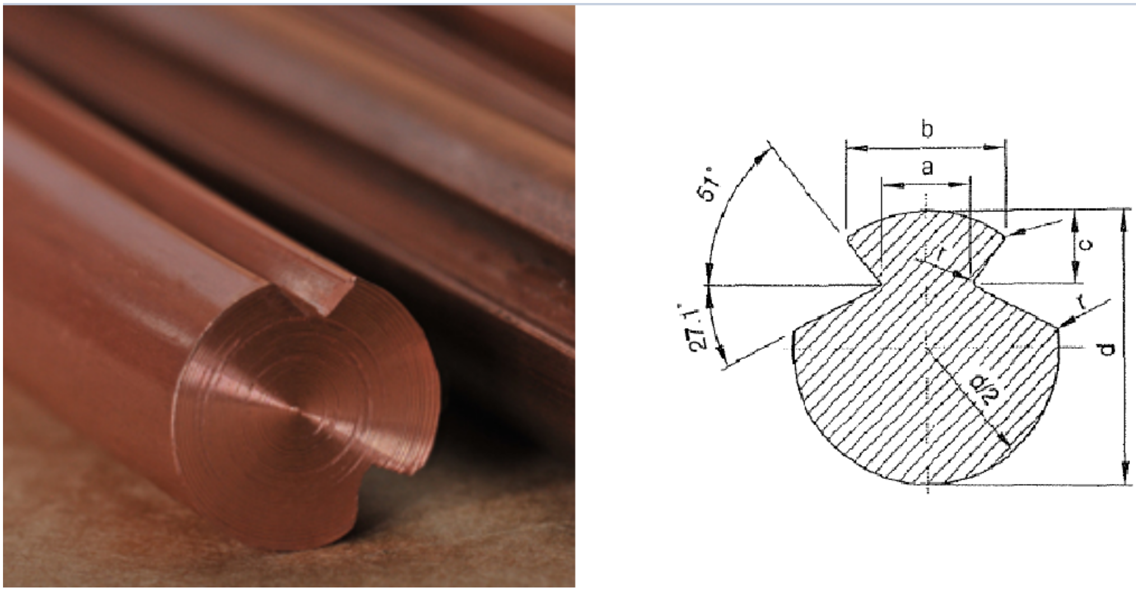

Figure 4.1: Grooved contact wire cross-section.[1]

Table 4.1: Geometrical data of grooved contact wires.

Designation according to EN 50149	Nominal cross-sectional area mm^2	Dimensions (as shown in Figure 4.1) mm				
		a	b	c	d	r
AC-80	80	5.6	8.0	3.8	10.6	0.4
AC-100	100	5.6	8.6	4.0	12.0	0.4
AC-107	107	5.6	8.6	4.0	12.3	0.4
AC-120	120	5.6	8.6	4.0	13.2	0.4
AC-150	150	5.6	8.6	4.0	14.8	0.4

4.1.2 Suspension System

There are many suspension ways to support and hold overhead line equipment, the most popular ways are

- Cantilevers suspension system
- Cross-span wire suspension system

for tramway applications the preferred way is to use cross-span wires and building fixings for suspension, in case where this way is impossible, specific poles or combined poles with street lighting or supporting cross-span wires and cantilever arms will be used. Figure 4.2

shows a suspension system using cross-span wire. Figure 4.3 shows a suspension system using cantilevers

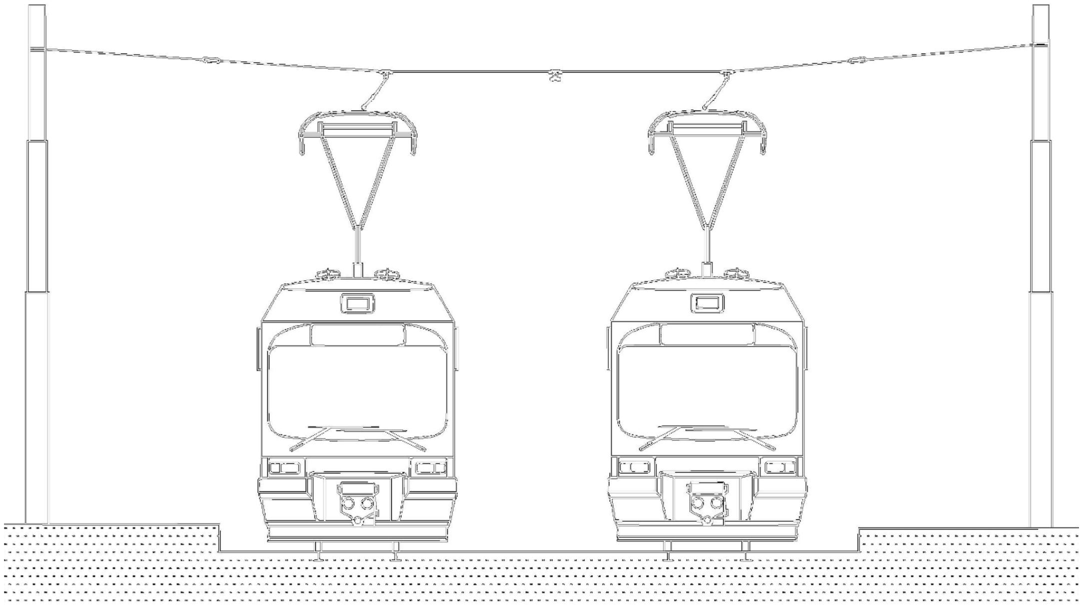

Figure 4.2: cross-span suspension with poles

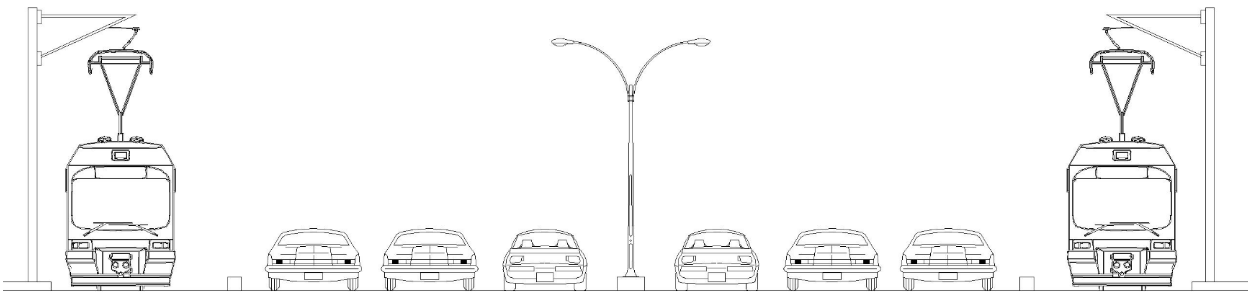

Figure 4.3: suspension system using cantilevers

4.1.3 Supports and Suspension System Components

Supports are the components carrying and aligning the conductors and associated insulating elements of an overhead contact line installation, poles and cantilever generally used to support the overhead contact line equipment.

4.1.3.1 Poles

Poles may take a number of standard forms e.g. hollow circular, hollow circular and stepped, universal columns, hollow square (special fabrication). Circular options are generally preferred and allow easier attachment of equipment at different angles. The height of poles is dependent on the location and there is a preference to adopt a limited number of standard lengths and diameters of pole, EN 50119 is the standard that deal with the fixed installations and electric traction overhead contact lines. Poles may be placed centrally between tracks or to the side of a single track or of double track.

4.1.3.2 Cantilevers

Cantilevers are attached to poles used to hold, support and suspend the contact wire with single point suspension, the contact wire is fixed only by a contact wire clip directly mounted on a cantilever support. Cantilever support and it's components are shown in Fig 4.4.

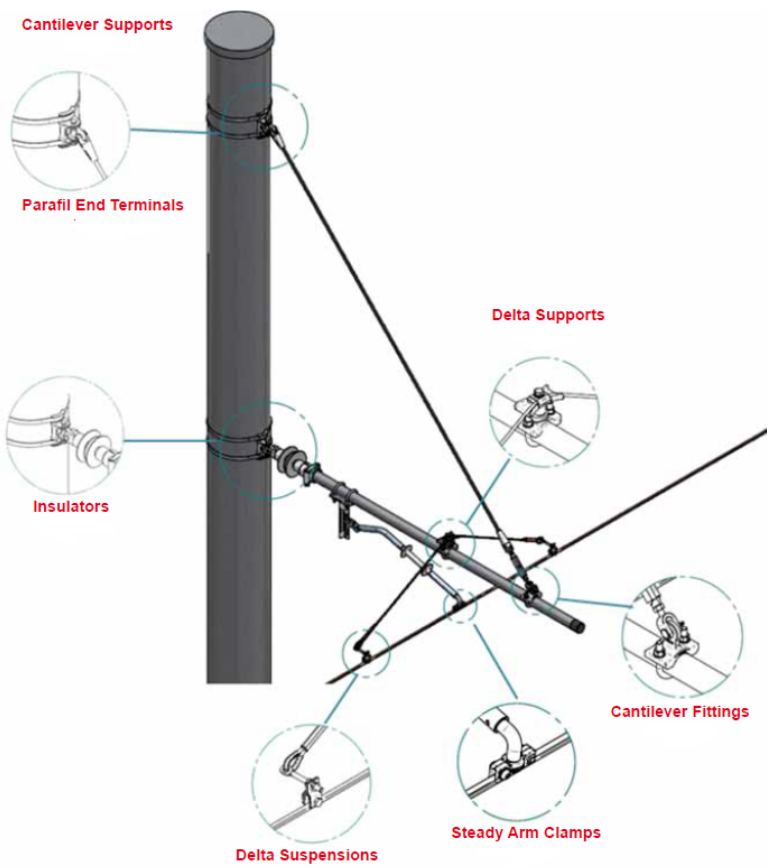

Figure 4.4: Cantilever support and suspension

Cantilever arm: They are made of Galvanized steel and come with four types, short,

medium, long and overlap.
Steady arms: There are two types, plain and insulated, when a plain arm is used, insulation is obtained through a parafil sling connecting the arm to the cantilever or span wire.
Delta suspension: They are used for variable tension areas where radial loads are small.
Fitting and clamps: Corrosion preventative material such as aluminum bronze, galvanized steel and stainless steel with bi-metallic connections where required. Insulators: They are used as secondary insulation, between the cantilever arm and pole for cantilever supports.

4.1.3.3 Foundations

Reinforced concrete is the typical foundation construction According to EN 50119, foundations of supports have to be capable of transferring the structural loads resulting from the actions on the support into the subsoil.

4.2 System Design Parameters and Considerations

The design procedure shall determine the type of supports should be used and their position and suspension system according to environmental requirements and parameters extracted from previously issued documentation, applicable standards and usual design considerations. So in this section the main electrical, mechanical and geometrical design parameters will be provided, and it'll be used as the basis of the overhead contact line design.

4.2.1 System parameters and considerations

4.2.1.1 Contact wire specifications and considerations

Contact Wire: Trolley Cu grooved contact wire, with cross-sectional area 120 mm^2, tensile strength 330 N/mm^2, 0,01777 Ω·mm^2/m specific resistivity at °20 C and 1,068 kg/m of mass per unit length
Contact Wire Gradient: The Variation in contact wire height for speeds up to 50 Km/hr shall not exceed 25% extracted from EN 50119
Contact Wire Height: According to EN 50119 standard the minimum and maximum height for grooved contact wire is 5.2m and 6.3m respectively, the nominal height will be determined according to the minimum working height of the pantograph

4.2.1.2 Poles

Stepped circular hollow section. Steel tube galvanized inside and out. Combined street lighting with cross-spans.

4.2.1.3 Maximum longitudinal span length

Longitudinal span length, or span is the term used to designate the distance, in running track direction, between two successive supports. The track is almost direct and has curves with minimum radius of 500 m, so the maximum span will be 25m according to pre-calculated value for tracks with curved radius of 500 m or above.[1]

The number of poles distributed along the track will be **258** poles. Part of the track is shown in figure 4.5 with the poles in yellow circuit are placed on the track.

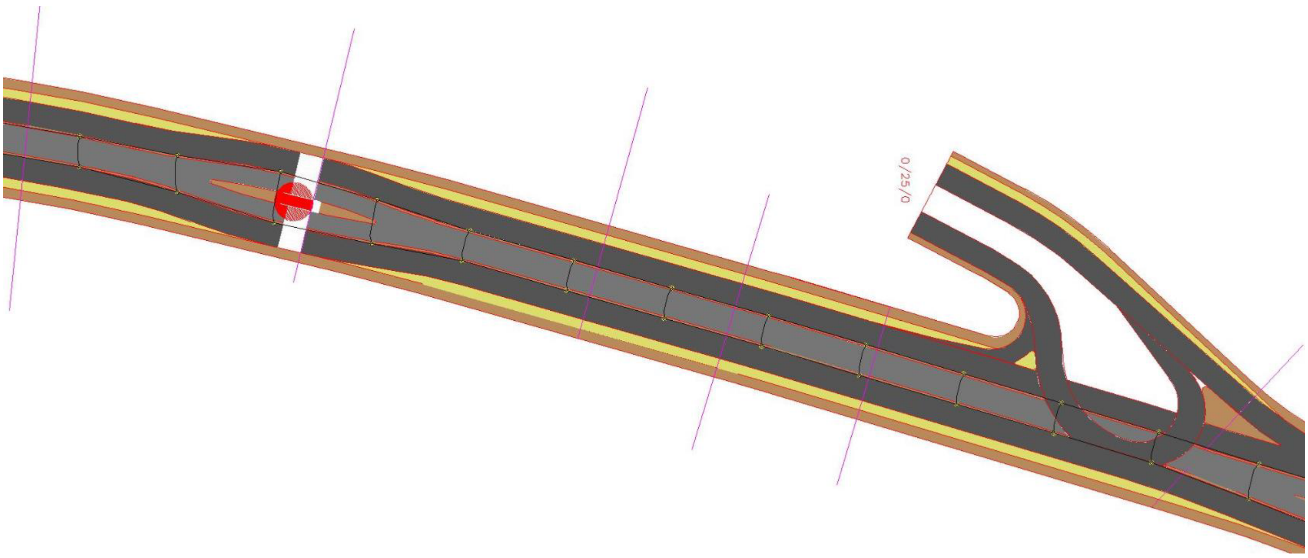

Figure 4.5: Part of the electrical map

4.2.1.4 Environmental requirements

Contact line systems have to be designed to function in a defined range of ambient temperature, in Palestine from -°7 to °40 C. Lateral deflections of the contact lines are caused by wind loading, which in turn could lead to the pantograph de-wiring under extreme conditions. For this reason, contact lines have to be designed for particular wind velocities, under which operation remains possible. Contact line installation may be loaded additionally by icing. These ice loads have to be taken into account in the design. The outdoor environmental considerations in Hebron are defined in table 4.2. These data were taken from previous statistics in hebron city.

Table 4.2: Environmental considerations in Hebron

Maximum design wind speed	10 m/s
Maximum gust speed	25 m/s
Minimum design temperature	-7 °C
Maximum design temperature	40 °C
Maximum ice loading radial thickness	12 mm
Average solar radiation	650 W/m^2

4.2.1.5 Tensile Force Acting on Contact Wire

The tensile force acting on and within conductors and wires of overhead contact lines are determined by structural design principles. The basis of all calculations is the permissible stress of the respective materials which is used to determine the maximum permissible tensile force. From the maximum permissible tensile stress σ_{per} and cross-sectional area A of the respective wire the maximum permissible tensile force is calculated using the equation.

$$F_{per} = \sigma_{per} A \tag{4.1}$$

EN 50119 states that the maximum permissible tensile stress under operating conditions should be calculated as follows

$$\sigma_{per} = \sigma_{min} \cdot 0,65 \cdot k_{tcmp} \cdot k_{wear} \cdot k_{1oad} \cdot k_{eff} \cdot k_{c1amp} \cdot k_{joint} \tag{4.2}$$

where the abbreviations in equation in equation 1.2

- σ_{min} is the minimum tensile strength
- k_{tcmp} factor which gives the relation between the maximum operating temperature and permissible tensile stress.
- k_{wear} factor which expresses the permitted maximum wear.
- k_{1oad} factor which expresses the effect of wind and ice loads
- k_{eff} factor used to describe the characteristics of the tensioning equipment, in normal designs, k_{eff} can be assumed to be 0,95

- k_{c1amp} factor used to describe the characteristics of the tensioning clamps; if the force that can be transmitted by the clamps is greater than 95 % of the nominal tensile force on the contact wire, this factor can be assumed to be 1,0
- k_{joint} factor which describes the reduction of the tensile strength due to welded, brazed or soldered joints, this is normally 0,95. If no such joints are used, a value of 1,0 is assigned to k_{joint} in the equation.

The operating tensile stress may not exceed 65% of the nominal tensile strength of the contact wire. For k_{tcmp} the maximum operating temperature according to EN 50119 for Cu contact wire is 80 °C and k_{tcmp} for this operating temperature can be obtained from the tables in EN 50119 and it equals 0.9. k_{1oad} also can be determined from the tables in EN 50119, for grooved contact wire with fixed tensioning the k_{1oad} for wind and ice loads is 0.7

For AC 120 mm^2 the σ_{min} is 330 N/mm^2, if k_{c1amp} is 1,0 and there will be no joints k_{joint} is 1,0 and for k_{wear} 80% and for k_{eff} 0.95, after substitution in equation 1.2, σ_{per}=158 N/mm^2, for 120 mm^2 the maximum permissible tensile force F_{per} = 18.9 kN

4.2.2 Contact Line Loading Assumption

Contact lines are subject to different loadings. Dead loads from conductors act permanently can be determined accurately from technical data and dimensions. The conductor tensile forces also act, contact lines are exposed to the weather and occasionally experience heavy additional loadings from wind action on conductors and structural components as well as from ice accretion on conductors. These loadings can be determined by statistically evaluating records of long-term weather observations.

4.2.2.1 Permanent Load on Conductors

The dead loads of conductors act vertically and the loads resulting from conductor tensile forces act horizontally in case of level attachment points. Dead loads are independent of the conductor temperature and result from the dimensions of the installation. During the life cycle of an installation they vary only because of the contact wire wear. The conductor tensile forces are more or less constant in the case of automatically tensioned contact wire. In the case of fixed terminated wires and conductors, they depend on the conductor temperature, which varies as a function of the ambient temperature, current loading and ice loads, if any, structural design must consider the maximum tensile forces generated.

Dead loads: The dead load on overhead contact lines results from the self or dead weight of wires, this is described as a whole by the 'mass per unit length' m' calculated relative to the mean support spacing. Expressed in general terms, the force due to gravity acting on a conductor's dead mass, in relation to its length, is termed load per unit length, G', from the expression

$$G' = m'g[1] \tag{4.3}$$

where g is the gravitational acceleration, for the contact wire, m'=1,068 kg/m, so, the load per unit length of the contact wire is G'= 10.47 N/m, for a 25 m span length the self-weight of the contact wire is G= 262 N

Radial forces: A radial forces occur in contact wires because of the change of direction of the overhead line at supports. Its value should remain within a specified range. On bends and curves, the horizontal components of forces acting on the conductors of overhead contact line installations are clue to the pulling of the line along the curve, so the maximum horizontal component occurs when track is curved. The curve pull-off force, which is often also termed the radial load, is the sum of the horizontal components of the conductor tensile force in the two adjacent spans, and, in the case of uniform spans the horizontal component of the tensile force can be calculated using the following equation[1]

$$F_H = Hl/R[1] \tag{4.4}$$

where

– H is the tensile force acting on the contact line

– l is the span length in m

— R is the curve radius in m

let the tensile force be 12 kN to suspend the wire along the track, in the track proposed in chapter 1 the maximum curve radius is 700 m, and for a span length of 25 m, the maximum horizontal force is

$$F_H = 428 \text{ N}$$

4.2.2.2 Variable Loads on Conductors

Wind loads: The wind load on the individual elements of overhead contact line installations depend on the wind velocity, the shape of the area exposed to the wind and the wind direction. The wind load per unit length on contact wires of a diameter d is expressed by the equation:

$$F_w^{'} = (1/2).\gamma.v_w^2.c_w.d[1] \tag{4.5}$$

where

- γ is the the drnsity of air at 20 °C = 1,25 kg/m^3
- v_w is is the gust speed in m/s
- c_w is The aerodynamic coefficient of resistance or drag factor, depends on the shape and surface characteristics of the body exposed to the wind, for AC 120 mm^2= 1.2 [1]
- d is the diameter of the wire in m

For 25 m/s gust speed and and wire diameter 0.0132 m $F_w^{'}$=6.2 N/m
For 25 m span length F_w=155 N

Ice load: the weights acting due to ice, hoarfrost or snow are all collectively termed ice loads, calculation values for ice deposits on suspended conductors have been derived and used from standards pertaining to overhead power lines. If the characteristics of ice loads are not known from local observations, then the values given in transmission line standards e.g. EN 50341-1 are used. for overhead wires and conductors, an ice load per unit length

$$G_{ice}^{'} = 5 + 0.1d[1] \tag{4.6}$$

where d is diameter of the wire in mm, for AC 120 mm^2 the diameter is 13.2 mm, $G_{ice}^{'} = 6.3$ N/m, for 25 m span length G_{ice}= 157 N

4.3 System design calculations

4.3.1 Grooved contact line capacity

In order to choose a conductor to carry the current to the load, it must handle the current drawn and the short circuit current in case of faults

4.3.1.1 Current-carrying capacity of overhead contact lines

The current-carrying capacity of a conductor in the steady state can be determined from equation 4.6

$$I = \sqrt{(dp_{out1} + dp_{out2} - dp_{in})/R_{20}[1 + \alpha_R(T - 20^{\circ})]}[1] \tag{4.7}$$

where

- dp_{out1} is the energy loss due convection in W/m
- dp_{out2} is the energy loss due radiation in W/m
- dp_{in} is the energy absorbed by solar radiation in W/m

$$dp_{out1} = \pi \cdot \lambda \cdot Nu(T - T_{air})[1] \tag{4.8}$$

where

- λ is the thermal conductivity of air, 0,0285 W/K·m
- Nu is the NuBelt number
- T is the Cu conductor temperature in operation condition, 80 C°

$$Nu = 0,65R_e^{0.2} + 0.23R_e^{0.61}[1] \tag{4.9}$$

where R_e is Reynolds Number

$$R_e = vl_w/\nu[1] \tag{4.10}$$

where

- v is 1 m/s velocity of air surrounding the conductor
- l_w is the flow contact length of the conductor, for cu AC 120 l_w is 0.0227
- ν is the kinetic viscosity of air, 0,202·10^{-4} N·s/m^2

after substitution in equation 4.10 and 4.9, Nu=19.3, substitution in equation 4.8,

$$dp_{out1}\text{=69.2 W/m}$$

The energy loss due radiation is

$$dp_{out2} = s \cdot \varepsilon \cdot d \cdot \pi(T^4 - T_{air}^4)[1] \tag{4.11}$$

where

- s is the Stefan-Boltzmann constant, 5,67·10-8 W.m^{-2}·K^{-4}
- λ is the emission coefficient, for Cu λ is 0.75 [1]
- d is the diameter of the conductor
- T is in Kelvin

after substitution in equation 4.11,

$$dp_{out2} = 11.5 \text{ W/m}$$

the energy absorbed by solar radiation is

$$dp_{in} = d \cdot \varepsilon \cdot p_{so}^{''} \tag{4.12}$$

where

- ε is the solar absorption coefficient, for Cu ε is 0.75
- $p_{so}^{''}$ is the solar radiation intensity, in Hebron $p_{so}^{''}$ is 650 W/m^2

after substitution in equation 4.12,

$$dp_{in} = 6.4$$

From EN 50149, the contact wire AC 120 has 0.148 mΩ/m and the coefficient of temperature is 3.8·10^{-3} K^{-1}, after substitution in equation 4.7,

$$\text{I=639.3 A}$$

4.3.1.2 Grooved contact line short circuit capacity

The short-Circuit current-carrying capacity is important for the thermal design considerations of overhead contact line installations, it can be obtained sing the following equation

$$I_{sc} = \sqrt{\frac{c \cdot \gamma \cdot A^2}{\rho_{20} \cdot \alpha_R \cdot t_k} \cdot ln \frac{1 + \alpha_R \cdot (T_{klim} - 20°C)}{1 + \alpha_R \cdot (T_a - 20°C)}} \tag{4.13}$$

where

- c is the specific heat, from EN 60865-1 c for cu=390 J/kg·K

– γ is the specific mass of Cu, from EN 60865-1, γ=8900 kg/m^3

– ρ_{20} is the specific resistivity of the wire at 20 °C, from EN 50149 ρ_{20}=1.7777·10^{-8} Ω.m

– α_R is the thermal coefficient of resistance, α_R=3.9.10^{-3} C^{-1}

– t_k is the duration of short circuit current, from EN 50119, t_k=1 s

– T_{klim} is the permissible maximum temperature of the Cu wire in case of a short-circuit, from EN 50119, T_{klim}=170 °C

– T_a is the initial temperature of the Cu wire when the short circuit occurs, from EN 50119, T_a=80 °C

after the substitution in equation 4.13, I_{sc}=13.48 kA

4.3.2 Cross Span Arrangement of a Trolley Contact Line

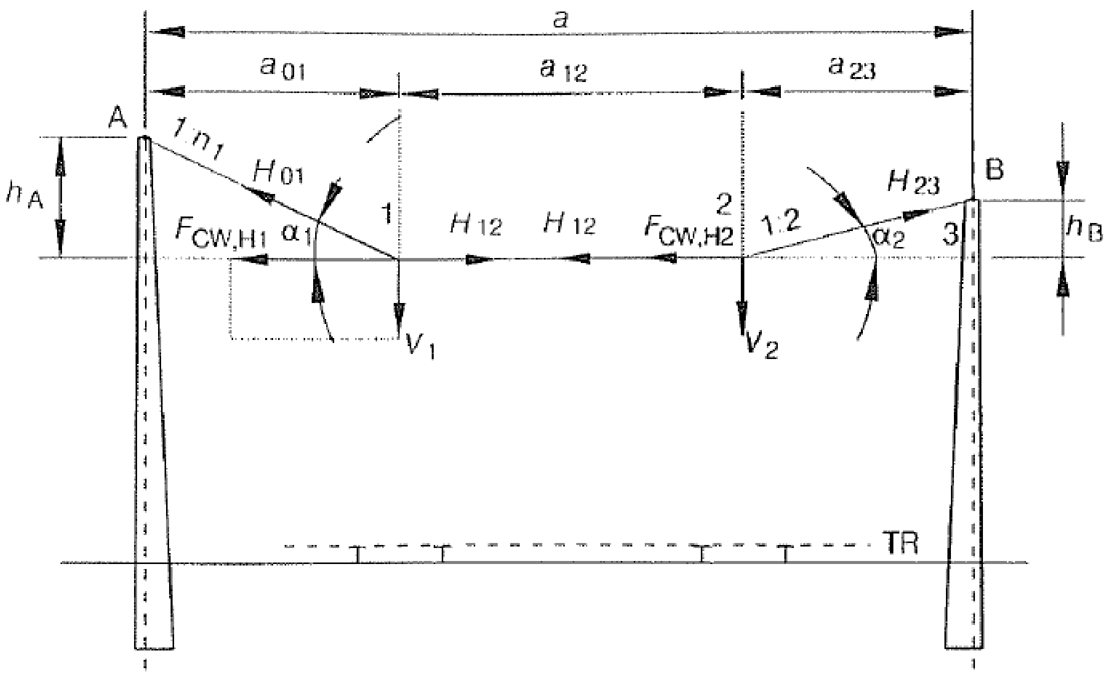

Figure 4.6: Cross Span Arrangement of a Trolley Contact Line[1]

When the loads acting on wires are known, the geometry calculation is easy. A cross-span for a double-track line is shown in Figure 4.6. The loads V_1 and V_2 follow from the contact wires, as well as the radial forces $F_{CW,H1}$ and $F_{CW,H2}$. Since the radial forces act in the direction of pole A, the wire 0-1 is designed to carry the load V_1. The gradient of the wire can be chosen between 1:10 and 1:15. The following applies to the tensile force of the wire$_{01}$:

$$H_{01} = V_1/sin\alpha_1 \sim V_1/tan\alpha_1 = V_1 \cdot a_{01}/h_A \tag{4.14}$$

The transverse wire in between the supports carries the load

$$H_{12} = F_{CW,H1} + H_{01} \cdot cos\alpha_1 \approx F_{CW,H1} + V_1 \cdot a_{01}/h_A \tag{4.15}$$

The tensioed wire supporting support 2 must carry the resultant force from H_{12}, $F_{CW,H2}$ and V_2 and since the gradient of the tensile wires is low only, it applies

$$H_{23} \sim H_{12} + F_{CW,H2} = F_{CW,H1} + F_{CW,H2} + V_1 \cdot a_{01}/h_A \tag{4.16}$$

The gradient of the tensioned wire$_{23}$ follows from

$$tan\alpha_2 = V_2/(F_{CW,H1} + F_{CW,H2} + V_1 \cdot a_{01}/h_A) \tag{4.17}$$

From the distance a_{23} to the pole the difference between the height of support 2 and the attachment at the pole follows

$$h_B = a_{23} \cdot tan\alpha_2 \tag{4.18}$$

The poles have to be rated for the forces H_{01} and H_{23} respectively, which act at a height corresponding to the sum of contact wire height, the design height of the supports and the values h_A and h_B.

$$V_1 = V_2 = (Gice + G)/2 \tag{4.19}$$

$$F_{CW,H1} = F_{CW,H2} = F_H + F_w \tag{4.20}$$

substitution in equation 4.19 and 4.20 gives:

$$V_1 = V_2 = 209.5 \text{ N}$$
$$F_{CW,H1} = F_{CW,H2} = 583 \text{ N}$$

the width of the trams track is 7 m and each tram is 2.5 m wide, so a_{12} should be 4 m, a_{01} and a_{23} will be 1.5 m. If the gradient of wire is 1:12

$$h_A = h_B = 0.125 \text{ m}$$

substitution in the equations 4.14-4.16,

$$H_{01}\text{=2514 N}$$
$$H_{12}\text{=3097 N}$$
$$H_{23}\text{=3680 N}$$

Chapter 5

Protection of DC traction system

The difficulty of protection of DC urban tram systems is due to the problem of distinguishing a fault current from the currents related to the normal operation, mainly because of the following factors[12]:

- Fault currents can be small, due to high impedance ground faults.
- In urban tram systems, the network is meshed, more than one tram can be running at the same time, resulting in higher currents in normal operation.
- Modern trams are driven by asynchronous motors, fed by the DC over-head contact lines through IGBT DC/AC converters; these trams have completely different absorbed current profiles during acceleration and much higher peak values.

In general the protection in electrical systems can be divided into:

Protection against direct contact: Which means protection against electrical shock which can be caused by touching electrical devices and equipment in which electrical current can flow in normal operation condition.
Protection against indirect contact: Which means protection against electrical shock which can be caused by touching of due to electrical fault electrified parts like metal cases.

5.1 Protection against indirect contact

Provisions for protection against indirect contact shall be provided for exposed conductive parts and for components of contact line systems. In traction systems connection to the return circuit is the preferred method to achieve electrical safety. In overhead contact line systems one of the following protective provisions shall be utilized for protection against indirect contact:

- Protection against electrical shock.
- Protection against direct lightning strike.

5.1.1 Protection of DC traction system against electrical shock

Different types of faults can happen on the DC urban rail traction systems, Figure 5.1 shows these faults.

1. Ground fault in the substation
2. Short circuit in the substation
3. Fault to a pole (to ground) along the line
4. Short circuit along the line
5. Ground fault along the line

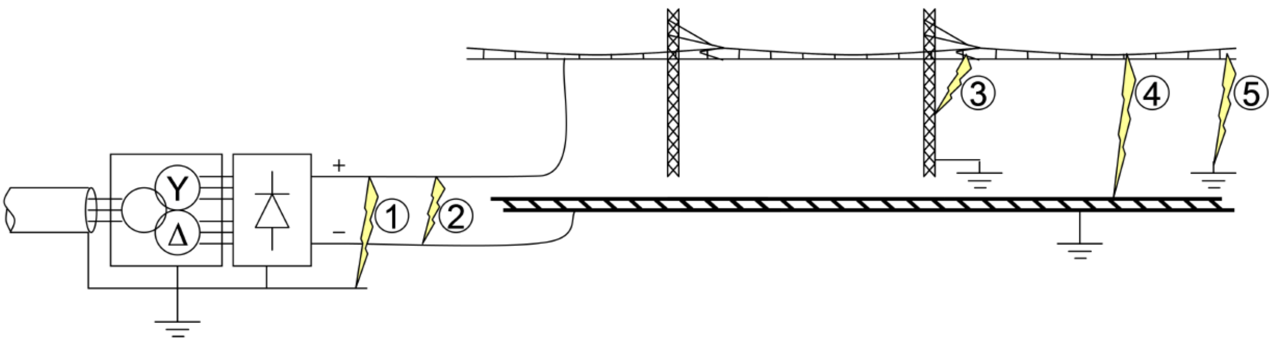

Figure 5.1: Possible faults on DC traction systems.[13]

When a short circuit happens in the substation(fault type 2), the fault current magnitude will be high enough to make the extra rapid circuit breaker trip as shown in Figure 5.2. The maximum short circuit current occurs in the substation, it's expected to be 11 kA using matlab simulink software to simulate the dc short circuit. The ABB DC switch gear placed

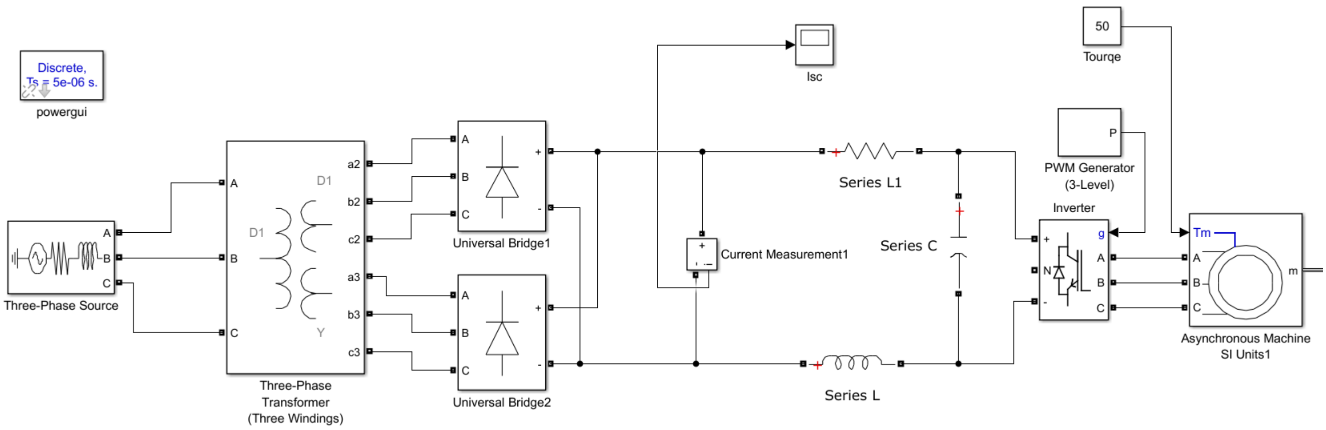

Figure 5.2: Matlab simulink simulation of DC short circuit

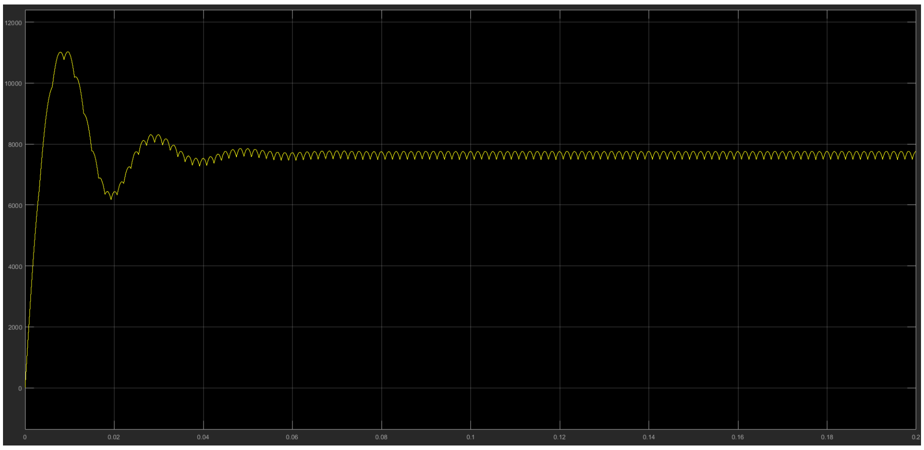

Figure 5.3: DC short circuit

in the substation described in chapter 2 can be programmed to handle this short circuit current.

But in case the short circuit happens outside the substation, for example on a vehicle, or in case a ground fault happens(fault type 3,4 & 5), the current would be limited by the circuit resistances, resulting in a current comparable with normal operation ones. In this case dangerous voltages can last for long periods without any maximum current protection intervention, these faults are arcing fault (positive to ground) and bolted short-circuit fault (positive to- negative). The arcing fault will generally involve high impedance at the fault location, whereas the bolted fault will have no intentional fault impedance at the fault location. Both types of fault currents will be controlled by the system grounding resistance parameters and/or rail-to-ground leakage resistance introduced in chapter 3.

The protective relays shown in Figure 3.13 provide complete tripping and isolation of the

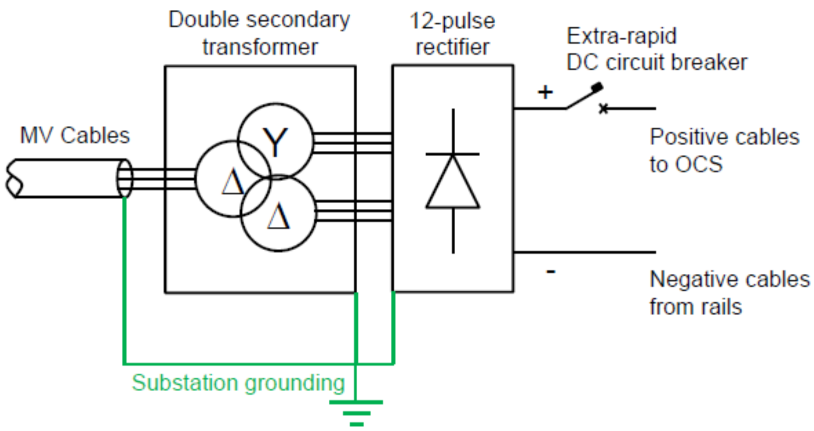

Figure 5.4: Power substation for DC traction with DC breaker.[13]

traction power system in case of heavy short-circuit current due to positive-to-ground fault, and automatically return to normal configuration once the fault is cleared. Reverse GTO may be used at the stations to suppress dangerous vehicle touch potential; however, it may unnecessarily increase stray current magnitude.

If positive touches ground away from the traction power substation, it will lead to a high-impedance fault with low current magnitude. However, the ground potential will be elevated with respect to the rail with the possibility of activating relay device 59 as shown in system grounding methods. This, in turn, will trip the substation feeder breakers to clear the fault condition. Unless the negative is shorted to ground by an appropriate protection relay scheme, fault current is controlled by the rail-to-ground leakage resistance and the fault impedance.

5.1.2 The protection of DC traction system against direct lightning strike

In modern railway tracks, a system with a group connection to the rails is currently used in an open system. In this type of system, the metal structure of traction masts is not directly connected to the running rails. All masts are grounded and connected to interconnect (bonded) with the use of overhead group connection wire. The railway line is divided into isolated sections of the power supply with a length of 2.5 - 3.5 km. For protection against electric shock, the group connection wire of each section is indirectly connected to the rails at both ends by means of a low voltage limiter (LVD).[14]

From the point of view of lightning protection, in comparison to the old type of traction construction the main difference is an overhead group connection wire suspended over the catenary wire. The connection wire composes the highest part of traction construction and therefore is most of all subjected to direct lightning strikes. The wire is grounded through masts therefore, it may be assumed as a natural air-termination. In the case of double (or more) parallel track lines, group connection wires provide lightning protection zone LPZ 0B for trains, trackside equipment and power supply wires as well (Figure 5.5)[14]. Therefore,

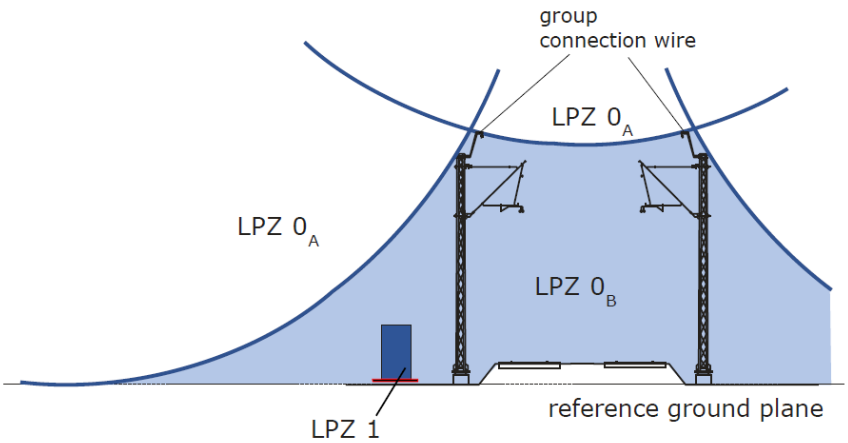

Figure 5.5: Lightning protection zones in the case of traction system with group open connection to the rail

the modern construction of traction system provide protection against direct lightning strike by itself. However, due to possible very high potential at connection wire and metal masts during lightning current flow, there is a risk of breakdown of insulation between the masts and construction suspending power supply wires. To ensure proper coordination of the insulation, additional protective measures are necessary.[14]

5.1.2.1 Surge Protection of DC Railway System

The overhead traction supply system is exposed to direct lightning just like a typical overhead power line. The use of the group connection wire as a natural lightning air-termination wire protecting against the spreading of this current in traction systems radically improves safety. However, it should be remembered that lightning strikes forming surge waves in the extended conductors of the traction network, in addition to damage to the power or control circuits, may damage the basic insulation of traction network which provide basic protection against electric shock resulting in damage to the insulators separating live parts from the traction support structure. Therefore, surge arresters are required to coordinate the insulation.[14]

Surge protection for DC systems is more complicated than for AC systems. Especially in the case of high-voltage systems, where the main problem is related to following currents. For this reason, the use of spark gap arresters, such as horn spark gaps, requires the use of high-speed circuit breakers or special construction of arresters to provide extinguishing of the following current. Such problem does not concern varistor type arresters. However, there are serious doubts regarding to the uncritical use of only the varistor arresters to protect the overhead contact line due to their low resistance to the effects of partial lightning currents.[14]

5.1.2.2 Spark gap horn

A traction protection system against lightning surges is not effective for modern train control systems. The current extensive systems based today on sensitive electronic devices are also loaded with over voltages in the traction system. Of course, the horn spark gap provides protection for the basic insulation, however, due to the very high spark over voltage, they are unable to protect the trackside equipment. In addition, its electrical parameters are very unstable and strongly depend on weather conditions (air pressure, humidity, ambient temperature) On the other hand, the spark gap has two significant advantages: firstly, it has

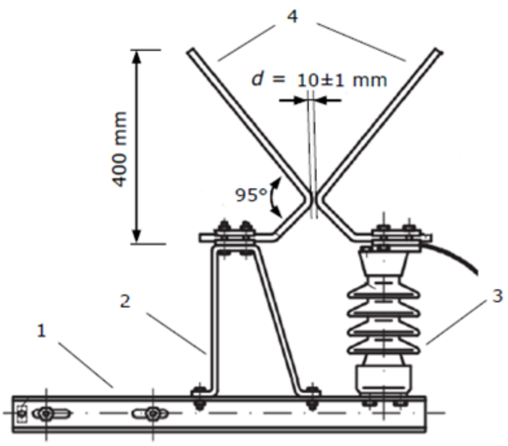

Figure 5.6: The construction of a horn spark gap 1) mounting metal base; 2) electrode support; 3) isolator; 4) electrodes[14]

a simple design, which ensures a very low price and the easiness of detecting malfunctioning, and secondly: the horn sparks have very high resistance to lightning currents due to the lack of any parts that may be damaged.

5.1.2.3 Varistors

It is well known that, the current development of surge arresters for high voltage power supply systems is basically limited to metal-oxide varistors of (MOV). Especially in the case of DC systems varistors are most commonly used. The main advantage of varistors when using them for DC systems is lack of problems related with following currents. Varistors ensure stable operation of the power supply system during atmospheric discharges causing over voltages as well as disturbances occurring during switching operations. Furthermore, MOV arresters provide several times lower voltage protection levels than horn spark gaps. Due to the application of hermetic silicone enclosure (Fig) MOV provides stable parameters not dependent on weather conditions[14]. It should be remembered that there are serious

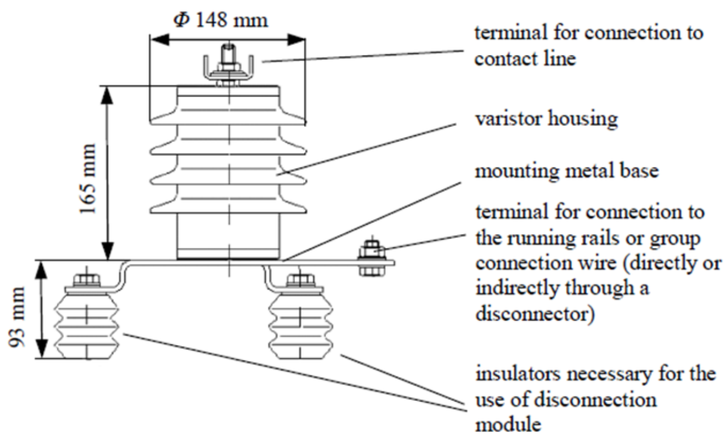

Figure 5.7: The typical construction of varistor used at DC railways[14]

doubts about the surge withstand of the varistors because, as is known, it is much smaller than in the case of spark gaps. MOV arresters are suitable for protection against short time surges such as 8/20 μs impulse. It is incomparably small in relation to the energy of a lightning strike, which corresponds to much longer 10/350 μs surge impulses, which can damage varistors as a result of their thermal overload. Another disadvantage of MOV is the characteristic leakage current, which is the cause of ageing process and gradual degradation of its parameters with time[14].

5.1.2.4 Distribution of a lightning current in a traction system

In the case of modern traction systems, surge current distribution is significantly more complicated. As described earlier, the lightning with highest probability hits a group connection wire which acts like horizontal air-termination conductor. The possible paths of lightning current in the group open connection system to rails are presented in Figure 5.8. The lightning current is conducted to the ground through paths of a lowest resistance. Because the bonding wire, which intercept the lightning strike, is directly grounded through each traction mast, the lightning surge current is distributed to the ground in significant part through traction construction. The current distribution between the masts depends on their individual earth resistance – each supporting construction has own grounding system. According to present regulations individual earth resistance of each mast should not be higher than 50 Ω. Part of lightning current may be conducted to a feeding wires through arresters, which are necessary for insulation coordination. Some of the surge may flow through low voltage limiting devices also, which connect bonding wire to rails[14].

In the case of group open connection system to rails, surge arresters are subjected only to partial lightning current. The main part of lightning discharge is conducted to the earth through grounded supporting construction. The basic function of surge arresters in this case is the insulation coordination and protection of insulators against damage. Therefore, varistor type arresters may be more suited to use in the group open connection traction power system than horn spark gaps. Despite the lower withstand, MOV's is sufficient in this

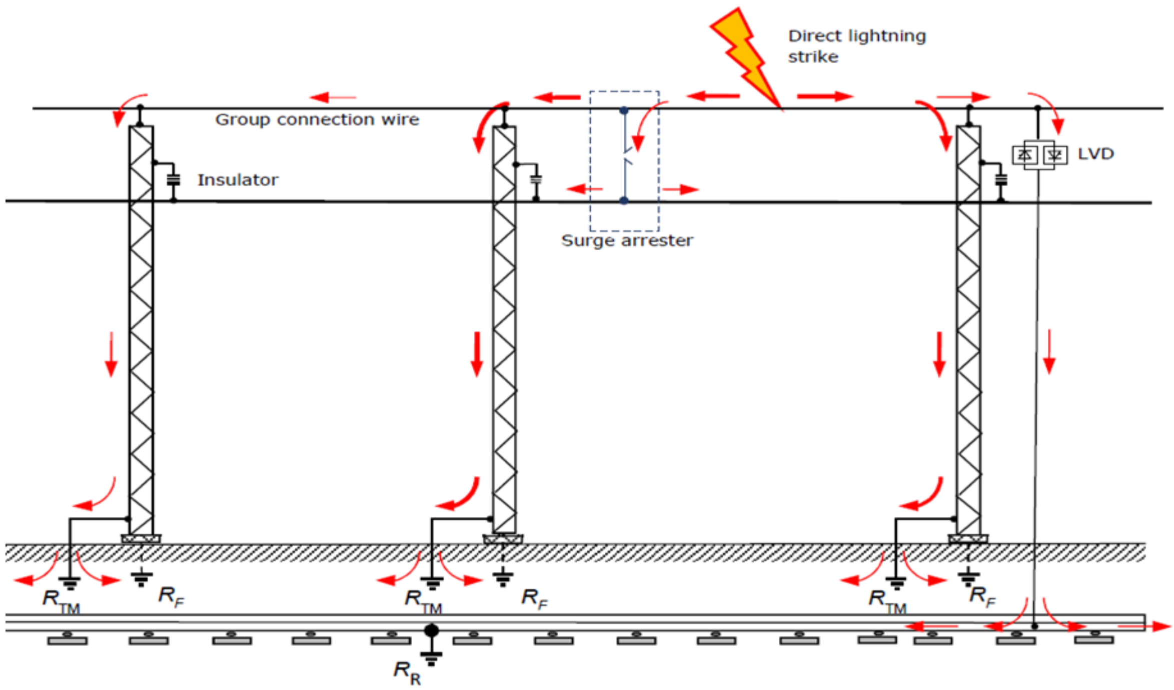

Figure 5.8: Lightning current distribution in the case of group open connection system to rails[14]

situation, and varistors can provide more stable operation of the power supply system.[14]

5.2 Protection against direct contact

In overhead contact line systems one of the following protective provisions shall be utilized for protection against direct contact:

- Protection by clearance.
- Protection by obstacles.

5.2.1 Protection by clearance

For standing surfaces accessible to persons, the clearance for touching in a straight line shown in Figure 5.9 shall be provided against direct contact with live parts of an overhead contact line system as well as live parts on the outside of a vehicle (e.g. current collectors, roof conductors, resistors). This does not apply to conductor rail systems near the running rails.

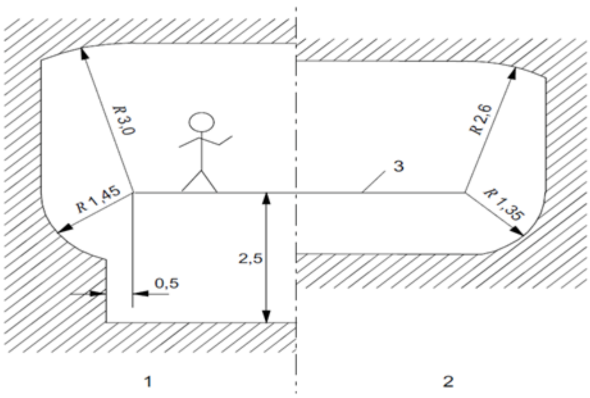

Figure 5.9: Minimum clearances to accessible live parts on the outside of vehicles as well as to live parts of overhead contact line systems from standing surfaces accessible to persons for low voltages ,where 1 public areas 2 restricted areas 3 standing surface.

5.2.1.1 Minimum height of overhead contact lines above roads

Where a road carrying normal vehicular traffic crosses or coincides with a railway, tramway or trolleybus electrified by means of an overhead contact line and no road traffic restrictions are specified, unless otherwise fixed by national regulation, a minimum vertical clearance as stated below shall be provided between the road surface and the lowest point of the overhead contact line and associated feeders. The minimum vertical clearance between the road surface and the overhead contact line according to EN 50119 shall be 5.2 m. If the required minimum clearance cannot be provided and unless otherwise specified by national regulation, the maximum height of road vehicles permitted to pass under the overhead contact line shall be limited so as to guarantee the following minimum vertical clearances between the highest point of road vehicle (load included) and the live parts:

1. 0.50 m, where only road traffic signs indicating the maximum permissible vehicle height are utilized.
2. 0.30 m, where additional fixed barriers (e.g. a rigid obstacle or a firmly fixed metallic wire made visible by means of a suspended warning sign) are erected on both sides of the crossing, physically limiting such vehicle height.

5.2.2 Protection by obstacles

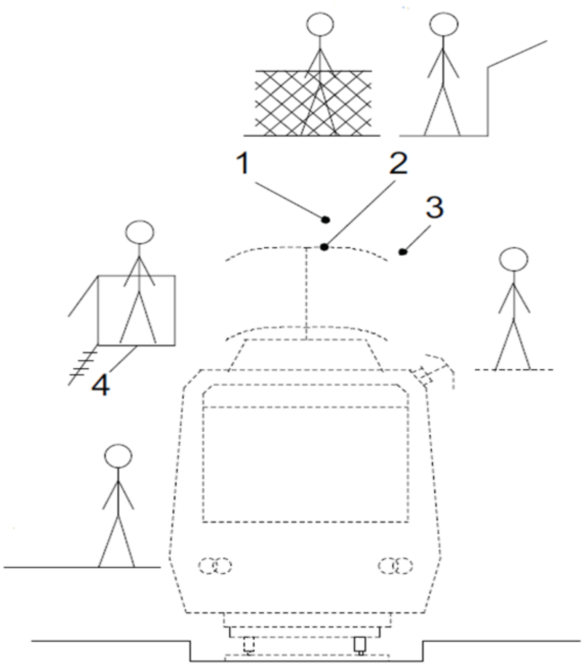

Figure 5.10: Standing surfaces for persons providing access to live parts on the outside of vehicles and to overhead contact line systems where 1.catanry wire 2.contact wire 3.feeder 4.working platform

If the clearances cannot be maintained, obstacles shall be provided as protection against direct contact with live parts. The design of obstacles is dependent on the location of the standing surfaces shown in figure relative to the live parts, on the nominal voltage, on the clearance between the obstacle and the live parts and on whether the standing surface is a restricted area or a public area. The dimensions of the obstacles shall be such that live parts cannot be touched in a straight line by persons on a standing surface. For low voltages the obstacles shall meet the requirements for protection degree IP2X according to EN 60529 with a minimum distance to live parts of 0.50 m or shall be of solid wall design.

Chapter 6

System modeling and simulation results

6.1 Vehicle kinematics

When a Vehicle travels from point A to point B as shown in figure 6.1, forces will be acting on the train that will affect its motion, in this case the train goes through four stages, accelerating mode, constant speed mode, coasting mode and braking mode as shown in figure 6.2. Under the acceleration mode the vehicle starts to raise it's speed from rest to

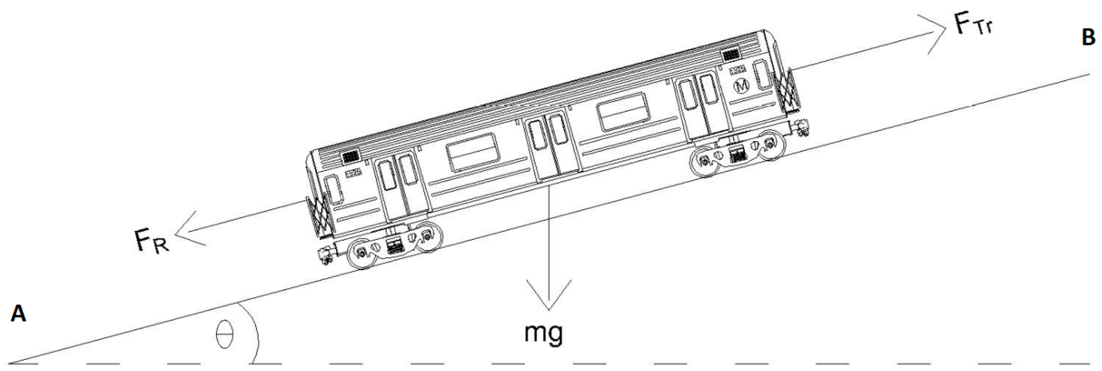

Figure 6.1: Forces affecting train motion

maximum speed, in this mode the tractive force (F_{Tr}) need to accelerate the vehicle is

$$F_{Tr} = ma + F_R \tag{6.1}$$

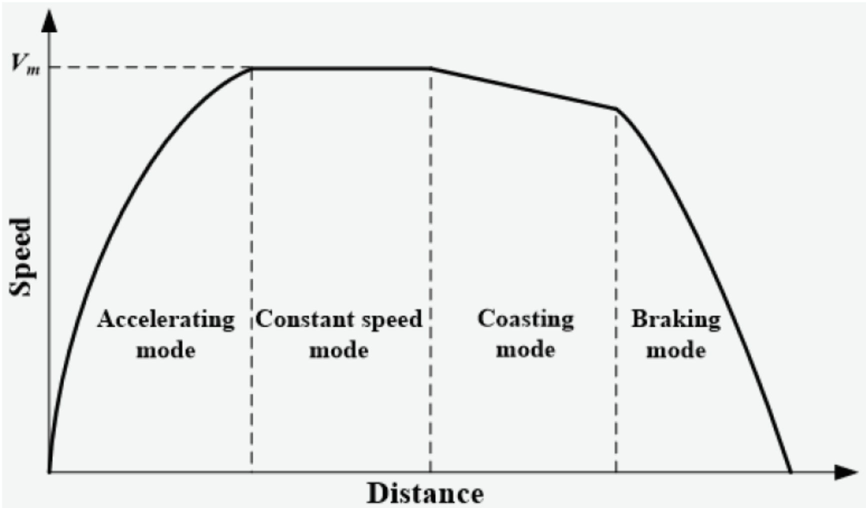

Figure 6.2: General vehicle speed profile[15]

where m is the effective mass of the vehicle, a the acceleration and F_R is the total resistive forrce opposing the motion. The tractive power drawn is to overcome the resistive force and accelerate the vehicle. Under constant speed mode the vehicle maintains it's speed reached in acceleration mode, so that the acceleration is zero, however the tractive force will be

$$F_{Tr} = F_R \tag{6.2}$$

The tractive power drawn is only to overcome the resistive force. Under coasting mode the vehicle draws no tractive power, it moves by its own momentum and it starts to decelerate due to the resistive forces opposing the motion. Finally in the braking mode the vehicle starts to stop after applying the brakes, in this mode the traction motors act like generators and the vehicle kinetic energy is converted into electrical energy.[15]

6.2 System modeling

In this section, analysis of the impact of vehicle dynamics parameters, DC/AC converter and motor efficiency on power during the tram speed profile has been conducted. A mathematical model for vehicle dynamics has been adopted from[16]. The main variables associated with the train motion are position, velocity and acceleration.

These variables, along with the forces affecting the motion of the train as shown in figure 6.1, are related through Newton's second law of motion, which can be used to describe the train's motion as in equation (6.1).

Presumably, the torque will be equally distributed among the trams, and considering the fact that each tram has four axles; the torque and speed for each axle can be calculated as in equation (6.3) and (6.4)[16]:

$$T_a = \frac{F_{Tr} r}{4n} \tag{6.3}$$

$$\omega_a = \frac{v}{r} \tag{6.4}$$

where r is the radius of the tram's wheel in (m), n is the number of the trams and v is the tram velocity in (m/s). In order to assure high torque at the wheels, a gearbox is utilized to increase the torque from the induction motor shaft. Therefore, to determine the torque and speed of induction motor shaft equation (6.5) and (6.6) can be used[2].

$$T_G = \frac{T_a}{\gamma_G} \pm \frac{B}{\gamma_G} \tag{6.5}$$

$$\omega_G = \omega_a \gamma_G \tag{6.6}$$

Where the sign in equation (6.5) depends on whether the train is in motoring or braking mode. Positive in motoring and negative in braking.

- T_G, ω_G is the torque and angular velocity upstream the gearbox, respectively.
- B is the vehicle losses.
- γ_G is the gearbox ratio.

The vehicle losses can be represented by the following equation

$$B = T_a(1 - \eta_G) \tag{6.7}$$

where η_G is the gearbox efficiency. Eventually the mechanical power can be represented as

$$P_m = T_G \omega_G \tag{6.8}$$

6.2.1 Trams simplified model

A DC traction system, powered by single DC substation, with a trams moving between two passenger stations as shown in figure 6.3 has been used to the study the system performance as it goes throw its speed profile shown in figure 6.4. The passenger stations will be spaced 550 m between each two. The trams will be modeled as AC controlled current source, dc

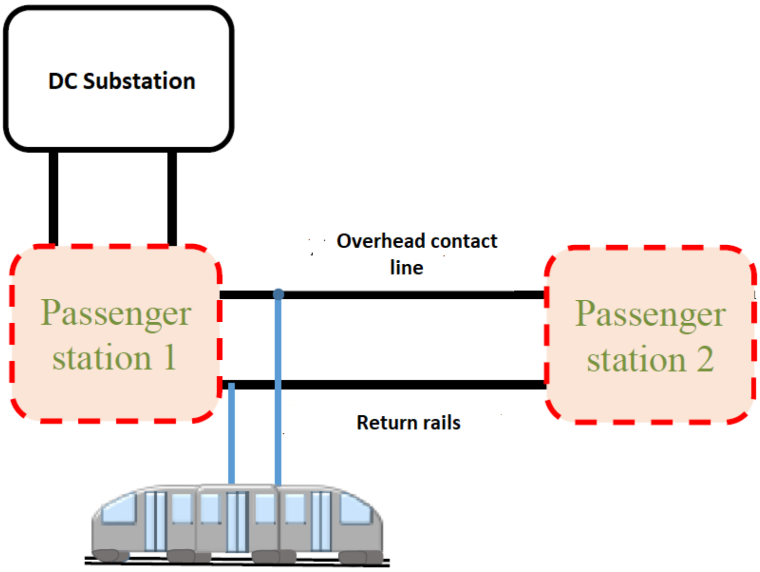

Figure 6.3: Tram moving between two substations[16]

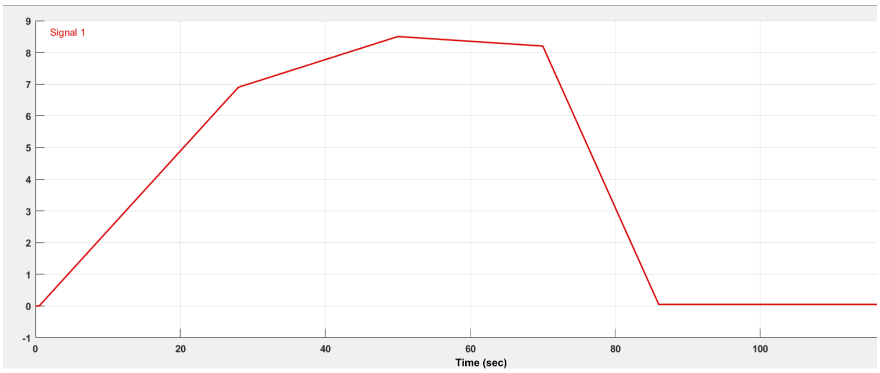

Figure 6.4: Tram speed profile m/s

filter and braking chopper as shown in figure 6.5. Here, the mechanical power required by one axle is multiplied by the number of axles and is then expressed in terms of a current reference, as follows[16].

$$I_T = 4n(\frac{P_m}{\eta_{inv}\eta_{motor}})\frac{1}{V_{DC}} \quad (6.9)$$

where,

- η_{inv}, η_{motor} is the inverter and motor efficiency, respectively.
- V_{DC} is is the measured value of the tram input voltage.

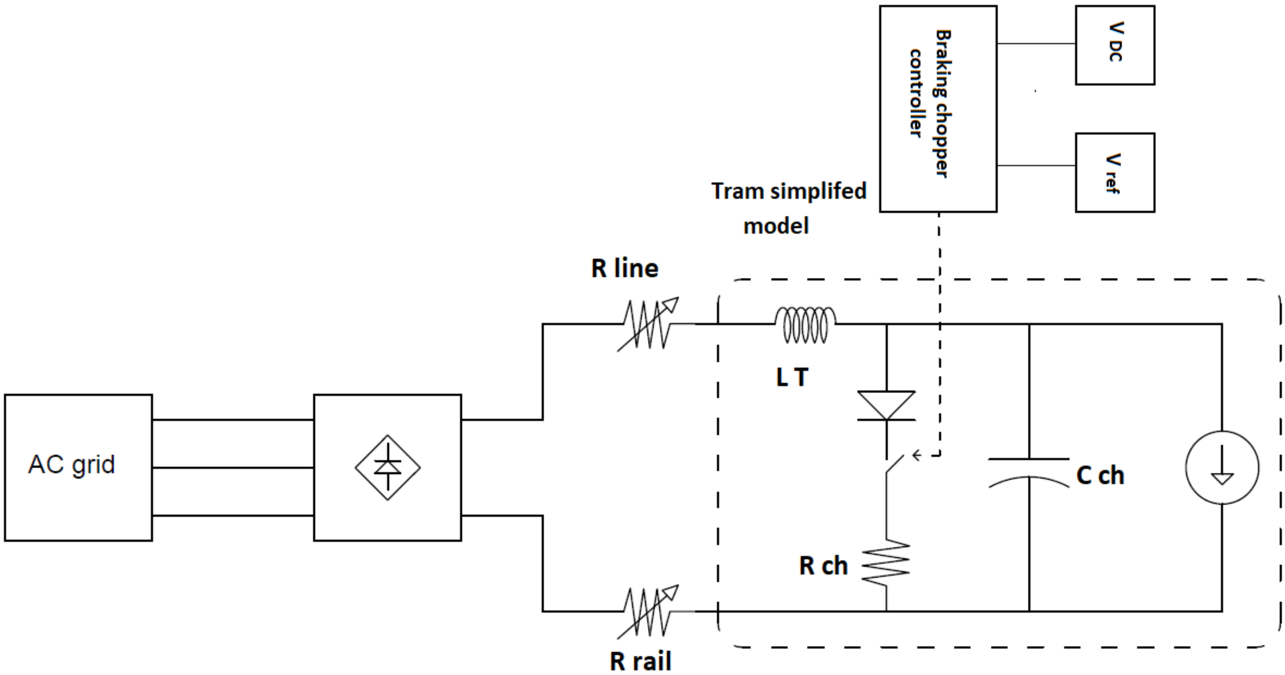

Figure 6.5: Tram simplified model

The chopper circuit, as shown in figure 6.5, has been modeled by employing a control system that activates a braking resistance based on a reference voltage V_{ref}. The chopper circuit is accompanied by a smoothing inductor L_T which filters out the high ripples in the current. The motion of the trams on the electrical rail has been designed by a pair of variable resistors as a function of the train position, one for the overhead contact line and the other for the running rail.

6.2.2 Matlab simulink DC traction system model

The system will be modeled using matlab simulink environment to simulate and see the system performance, the system model on simulink is shown in figure 6.6 The controlled current

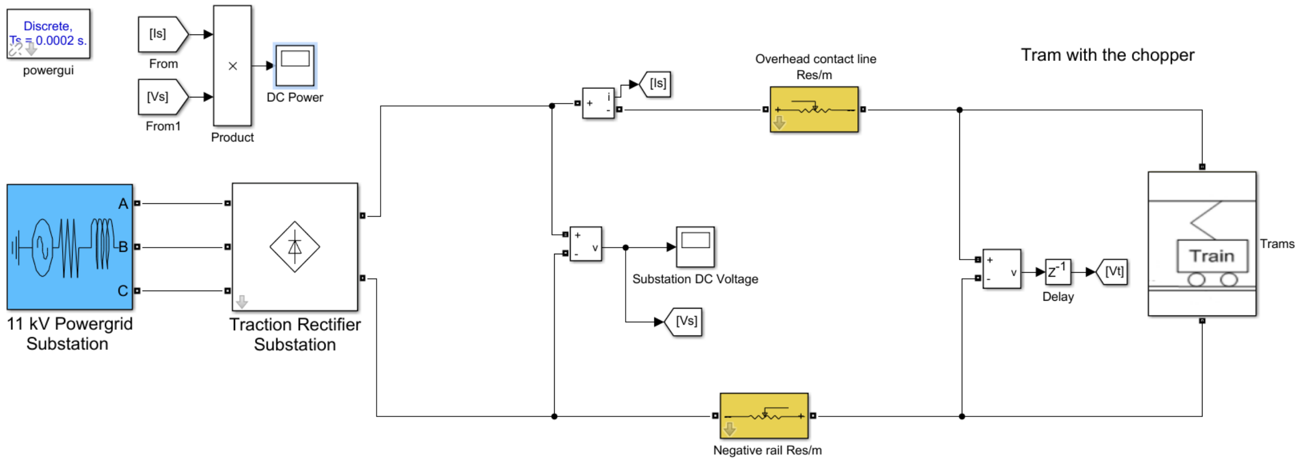

Figure 6.6: DC traction system model using matlab simulink

source representing the trams will be calculated using a mathematical model representing the equations (6.3 - 6.8) as shown in figure 6.6

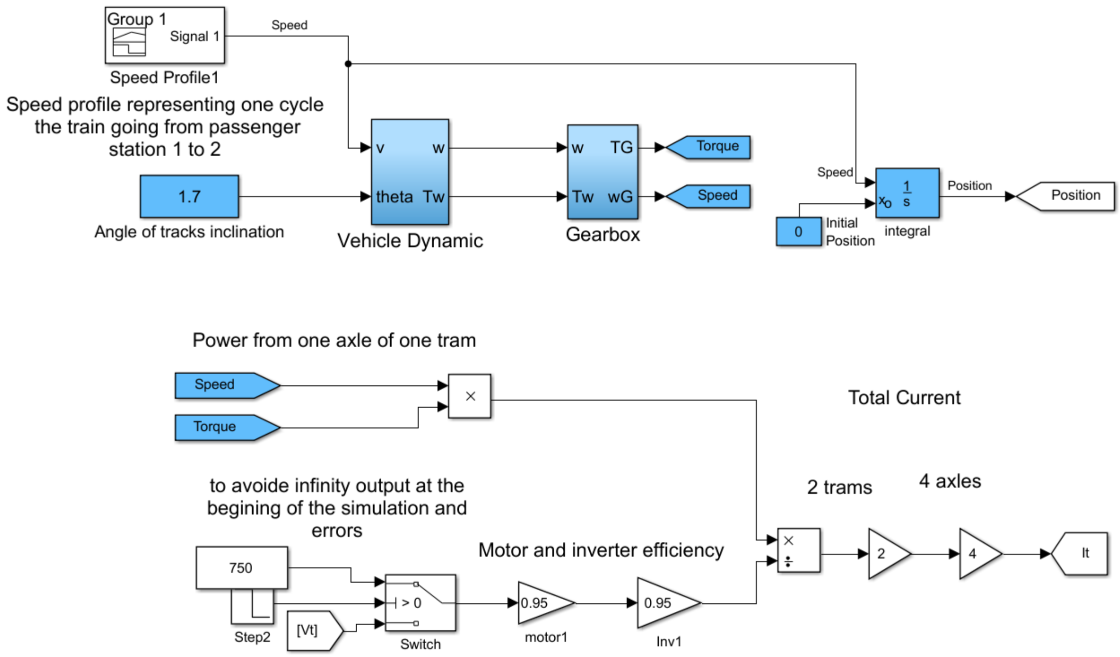

Figure 6.7: Mathematical model to calculate the trams current

The mechanical parameters used to describe the system motion and to calculate the trams current are shown in table 6.1, and the electrical circuit parameter are shown in table 6.2.

Table 6.1: Mechanical Parameters of the tram

Mechanical Parameter influencing tram motion and current	Value
M_{tram} @ 60 kg/p	52 ton
θ inclination angle	1.7°
g the gravity acceleration	9.81 m/s^2
F_{res} the resistive forces	2 kN
r wheel raduis	0.3 m
γ_G gearbox ratio	6
η_{motor}, η_g	95%, 96%
V_{max}	8.5 m/s, 31 km/hr
a_{max}, maximum acceleration	0.25 m/s^2
t_b braking time	70 s

Table 6.2: Electrical Circuit Parameter

Electrical Circuit Parameter	Value
Voltage level	11/0.53 kV
Nominal voltage	750 V
R_{pri}, L_{pri}	12.1Ω, 0.125 H
R_{sec}, L_{sec}	0.028Ω, 0.26 mH
η_{inv}	95%
R_{line}, R_{rail}	0.148 mΩ/m, 0.01 mΩ/m
η_{motor}, η_g	95%, 96%
v_{max}	8.5 m/s, 31 km/hr
L_T DC filter	100 μH
C_{ch}	7500 μF
V_{ref}, chopper shutdown voltage	900 V

6.3 Simulation results

The system will be be simulated for 100 seconds, which is the time needed for the trams to travel between two passengers substation. In this time a 550 m distance will be covered. Figure 6.8 shows the current drawn from the substation along with the trams motion, in the acceleration mode the current will continue to rise as the mechanical power rises and the maximum reached current is 700 A, and when it reaches the coasting mode the only mechanical power needed is to overcome the forces opposing the trams motion so the current drawn will be less. Finally in the braking mode the motors starts to act like generators, so the voltage at the substation terminals will arise as shown in figure 6.9 and the braking chopper will switch a braking resistance to dissipate the regenerative energy through it, in this mode the current drawn from the substation is zero.

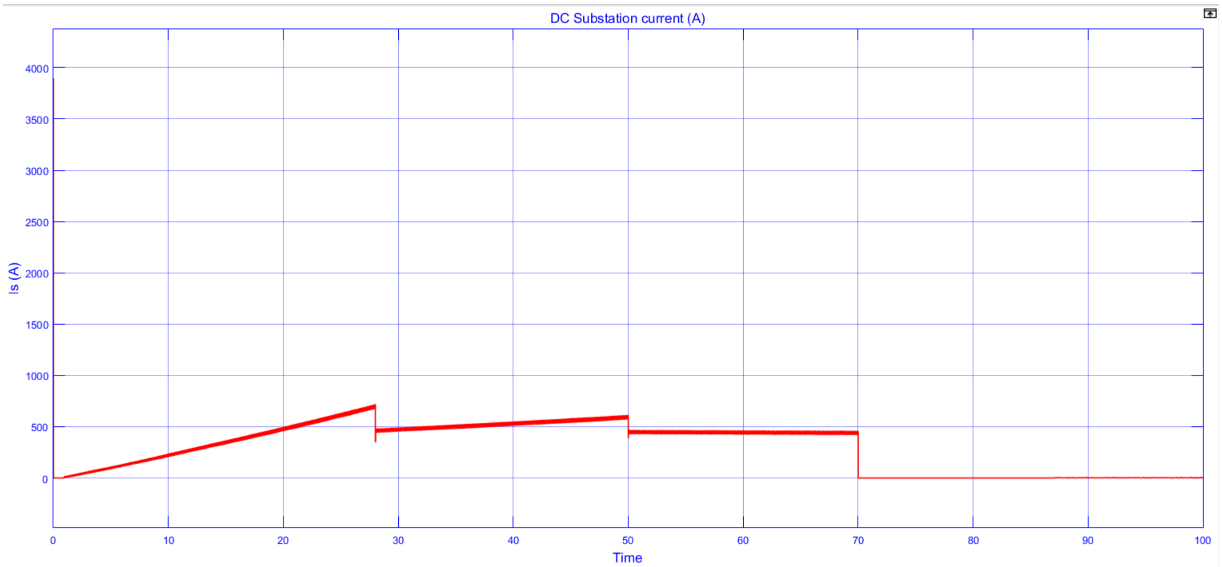

Figure 6.8: DC Substation current

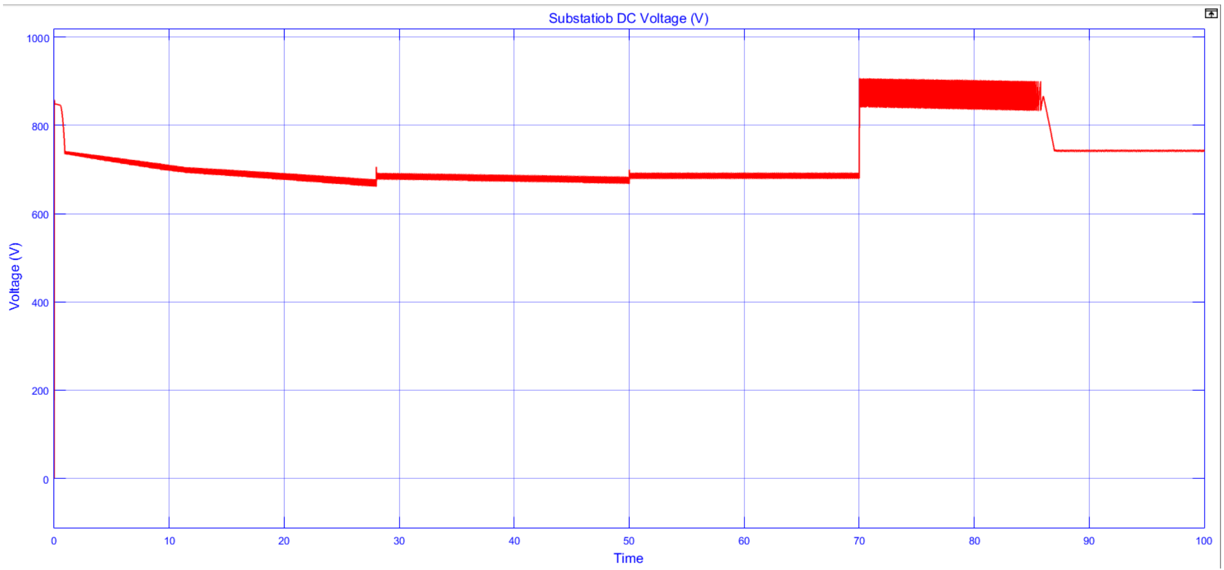

Figure 6.9: DC Substation voltage

The substation voltage will continue to drop due to the increase of the system rail and overhead line resistances and the current drawn from the trams. The minimum voltage reached is 620 V which is acceptable according to EN 50163. In the braking mode the voltage arise to 900 V which is acceptable according to EN 50163. After the trams perfectly stopped the voltage at the substation terminals will return to normal voltage 750 V. Figure

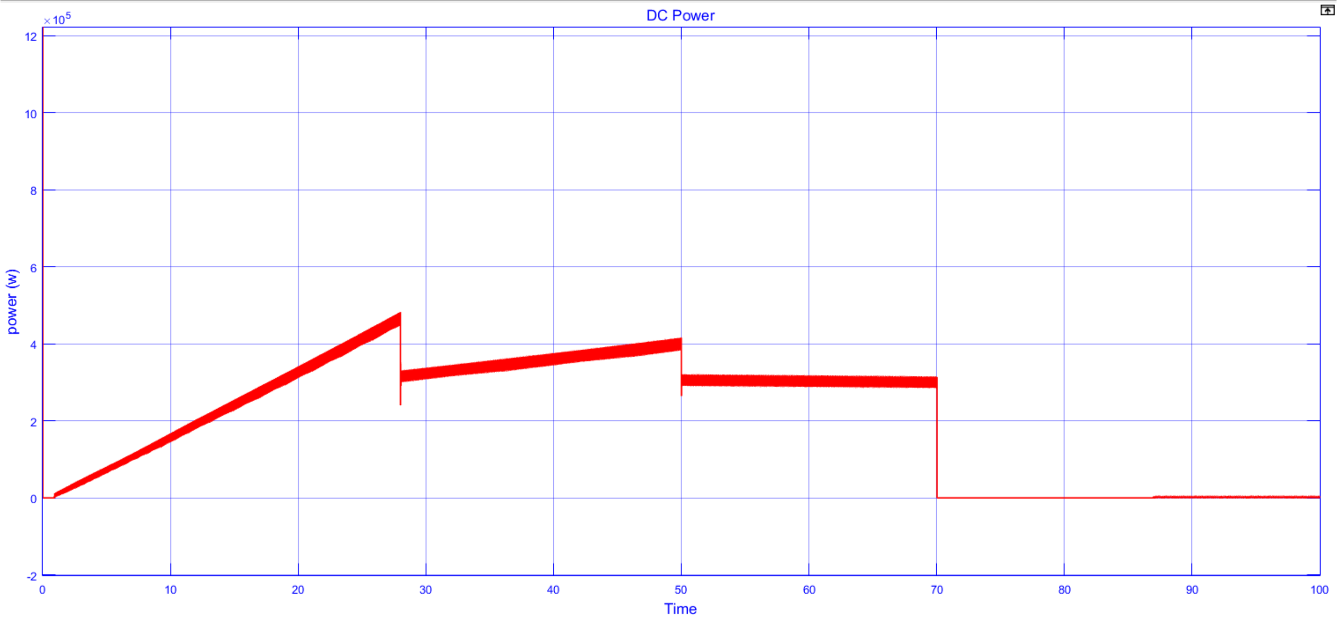

Figure 6.10: DC Power drawn from the substation

6.10 shows the DC power drawn from the substation, the maximum power drawn is when the trams are accelerating to reach 31 km/hr speed, in this mode the maximum power is 482 kW. In the coasting mode the power drawn will be less which is the power need to overcome the reistive forces opposing the trams motion, in this mode the maximum power drawn is 310 kW. Finally in the braking mode there will be no power drawn from the substation.

For the rail potential as shown in Figure 6.11, using the stray current system produces the rail potential, the voltage drop on the rails doesn't exceed 4 V and it's safe compared with the permissible touch voltage (60 V) in DC systems.

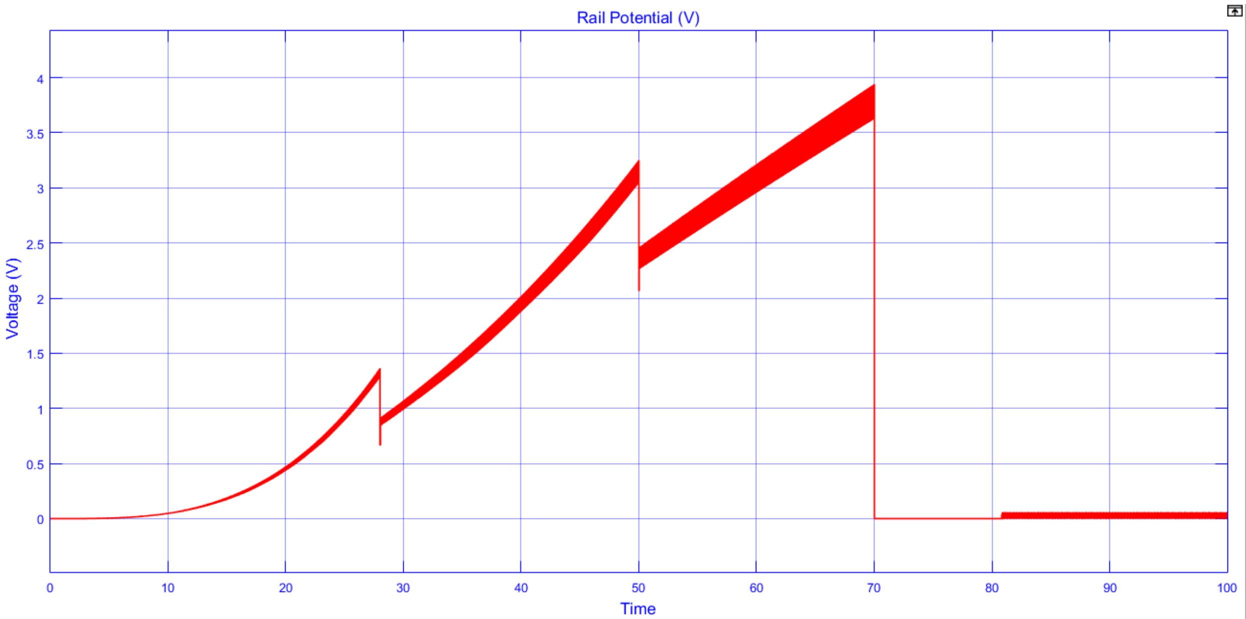

Figure 6.11: Rail Potential

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Appendix A

Standards used

Standard	**Year**	**Title**
EN 50163	2005	Railway applications - Supply voltages of traction systems.
EN 50122-1	2011	Railway applications - Fixed installations - Electrical safety, earthing and the return circuit - Part 1: Protective provisions against electric shock.
EN 50122-2	2011	Railway applications - Fixed installations - Electrical safety, earthing and the return circuit - Part 2: Provisions against the effects of stray currents caused by dc traction systems.
EN 50149	2009	Railway applications - Fixed installations - Electric traction - Copper and copper alloy grooved contact wires.
EN 50119	2009	Railway applications - Fixed installations - Electric traction overhead contact lines.
EN 50341-1	2007	Overhead electrical lines exceeding AC 1 kV - Part 1: General requirements - Common specifications.
EN 60865-1	2002	Short-circuit current – Calculation of effects - Part 1: Definitions and calculation methods.

Appendix B

Suspension equipment

B.1 Parafil Clamp & Ball-and-Socket Union Joint

These clamps are used to be mounted on parafil cables to hold and suspend the loads from contact wires, and the union joint is used to connect mechanically two parts lie parafil clamps and delta supports.

Parafil Clamp

No.	Parafil diameter (mm)	References
CPS-11	11	Oran Tramway
CPS-13	13	Oran Tramway

Ball-and-Socket Union Joint

This union joint is used to connect mechanically two parts lie parafil clamps and delta supports.

Material:
A2

No.	References
CL16	Oran Tramway

Figure B.1: Parafil Clamp & Ball-and-Socket Union Joint

B.2 Delta Suspensions

The delta suspensions are used to maintain the contact wire in tramways.

Material:
Parafil cable
Thimble in Cu
CW clamps in A2 or Cu

No.	Length (mm)	Parafil diameter (mm)	References
SD-1500	1500	7	Oran Tramway
SD-3000	3000	7	Oran Tramway
SD-1500P	1500	7	Oran Tramway
SD-3000P	3000	7	Oran Tramway

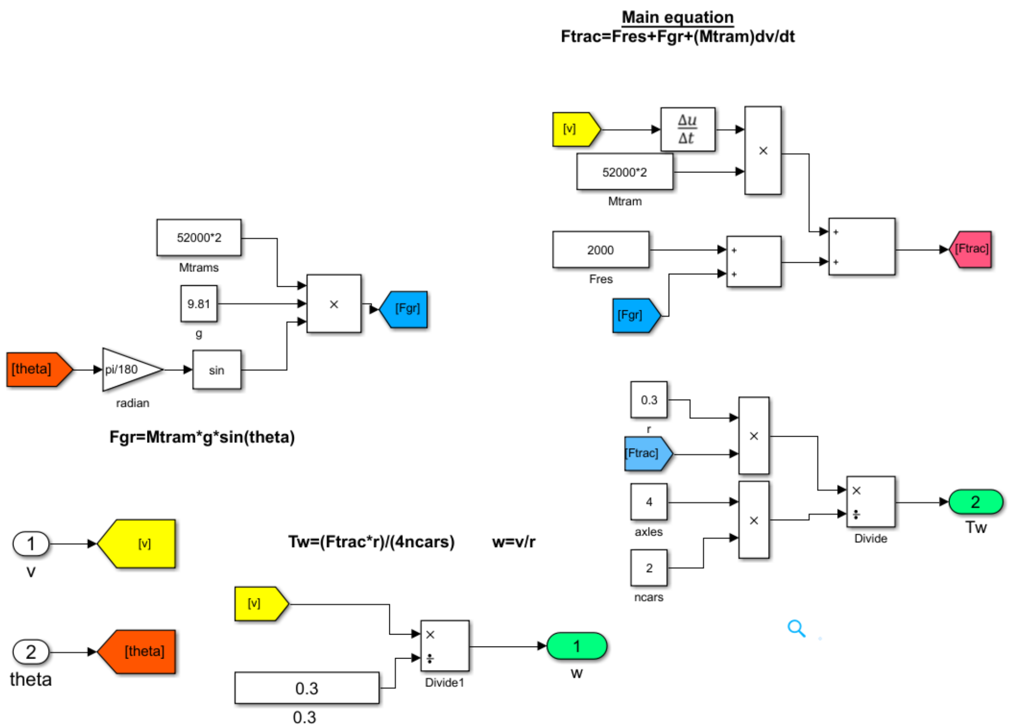
Please consult for other lengths / parafil diameters

Figure B.2: Delta Suspensions

Appendix C

Matlab Simulink model subsystems

C.1 Vehicle Dynamic



Ftrac is the tractive effort;

Fgr, the force due to the rails slope;

Fres is the total resistive forces

Mtram, the vehicle mass;

g, the gravity acceleration;

v, the imposed vehicle speed;

theta, the rails' slope;

Tw, torque at each axle

w is the speed at each axel

Figure C.1: Vehicle Dynamic

C.2 Gearbox

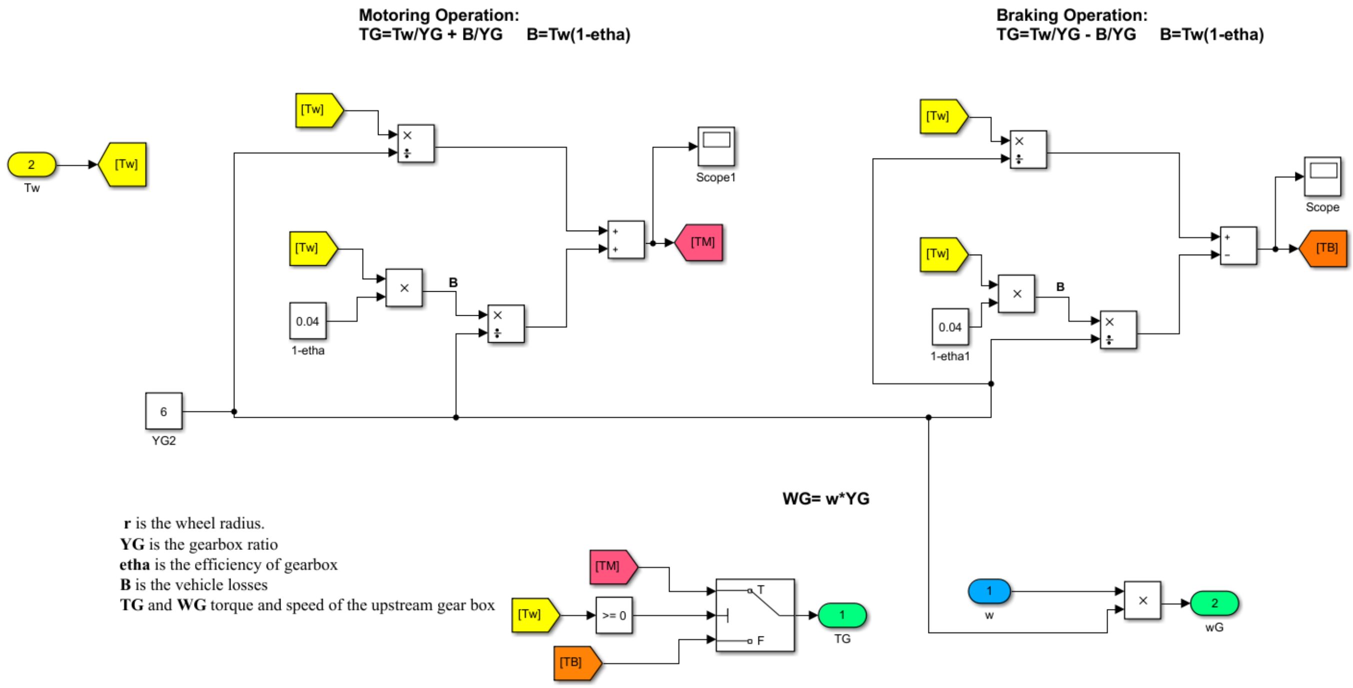


Figure C.2: Gearbox

C.3 Traction Rectifier Substation

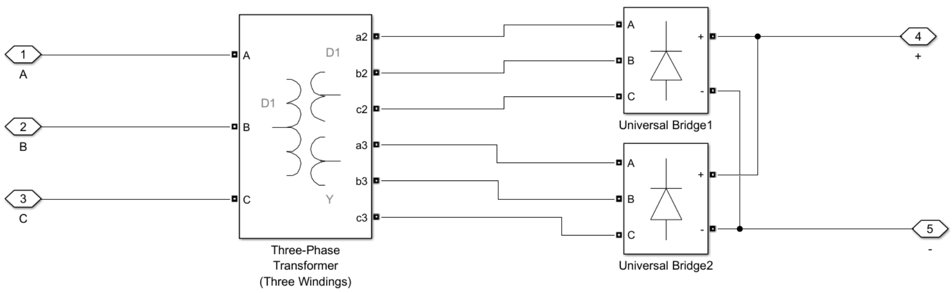


Figure C.3: Traction Rectifier Substation

C.4 Trams simplified model

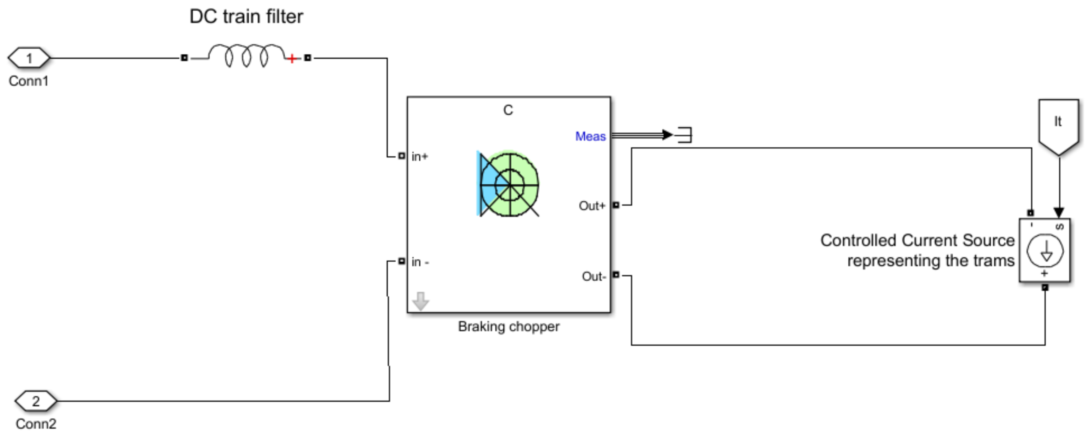


Figure C.4: Trams simplified model