



**Addis Ababa University**

**Addis Ababa Institute of Technology (AAiT)**

**School of Electrical and Computer Engineering**

**Customized Guideline for Designing Overhead Contact System for  
Ethiopian Railway: Case Study of Indode Station**

**A thesis submitted to the School of Graduate Studies of Addis Ababa University in partial  
fulfillment of the requirement for the Degree of Master of Science in Electrical and  
Computer Engineering (Railway)**

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**August, 2014**

**Addis Ababa University**  
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## Declaration

I declare that this thesis is composed by myself, that the work contained herein is my own except where explicitly stated otherwise in the text, and that this work has not been submitted for any other degree or professional qualification.

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# Abstract

This thesis presents Overhead Contact Line System design for Indode station. Overhead Contact System (OCS) is an essential interface between fixed installation and moving energy consumer for electric railway. Its design depends on mechanical, electrical and environmental loads. Therefore proper design and standard of overhead contact line system for a particular environment according to specific service requirement is necessary. In this work detailed technical design of overhead contact system for Indode station as reference to review other overhead contact line system design in Ethiopia Railway is done.

In this thesis first overhead contact system for electrified root is modeled based on bottom to top approach. Trolley and simple catenary of both semi and auto compensated Overhead Contact System is modeled. Traction impedance of overhead contact system especially double track of simple catenary equivalent impedance is determined. Then based on this model and meteorological data, maximum span length, critical span length, maximum sag height, and maximum anchoring length are derived and determined. From this determined parameter and site plan of Indode station, Overhead contact system plan is prepared according to planning rules and standard using Microsoft Visio. Finally main thesis work is summarized by preparing overhead contact system design manual for Ethiopia Railway.

**Keywords:** OCS, trolley and simple catenary OCS, maximum span length, critical span length, maximum anchoring length, maximum sag height, traction impedance, OCS plan, Microsoft Visio

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## List of abbreviations and symbols

OCS	Overhead Contact System
PC/PS	Point Center/Point Start
$E$	Conductors modulus of elasticity (Young's module)
$f$	Sag height of OCS
$F'_w$	Force of wind (wind load) per unit length
$g$	Conductor weight per unit length
$I$	Current
$l$	Span length
$L$	Conductor length
$q_i$	Resultant force per unit length of conductor weight and wind load
$R'$	Resistance per unit length( $\Omega/km$ )
$S_{\min}$ , $S_{\max}$ and $S_{\text{wind}}$	Extreme weather state at minimum temperature, maximum temperature and maximum wind speed
$t$	Temperature
$T, H$	Tensile force and its horizontal component
$V$	Voltage
$v_{\text{ref}}$	Maximum reference wind speed at 10 meter
$v_z$	Maximum wind speed at height $z$ meter
$X$	Reactance
$Y_i$	Construction coefficient of catenary
$Z$	Impedence
$\alpha$	Coefficient of thermal expansion
$\sigma$	Stress
$\psi$	Flux linkage

# Chapter One

## 1. Introduction and Background

Overhead power supply was initially almost exclusively used on tramway-like railways, though it also appeared slowly on mainline systems. A third rail is a method of providing electric power to a railway train, through a continuous rigid conductor (conductor rail) placed alongside or between the rails of a railway track. In most cases, third rail systems supply direct current electricity. The trains have metal contact blocks called "shoes" which make contact with the conductor rail. The traction current is returned to the generating station through the running rails.

Third-rail systems are relatively cheap to install, compared to overhead wire contact systems, as no structures for carrying the overhead contact wires are required, and there is no need to reconstruct over bridges to provide clearances. There is much less visual intrusion on the environment. However as third rail systems present the hazard of electric shock and higher system voltages (above 1500V) are not considered safe. Very high currents are therefore used, resulting in considerable power loss in the system, and requiring relatively closely spaced feed points (sub-stations). The presence of an electrified rail also makes it extremely dangerous for a person to fall into the tracks. This, however, can be avoided using platform screen doors or the risk minimized by ensuring that the conductor rail is on the side of the track away from the platform. Furthermore, third rail systems must either be fully grade-separated, or, if they operate at-grade, they must implement some kind of mechanism to effectively stop pedestrians from walking onto the tracks at grade crossings [1].

OCS used to transmit electrical energy to trams, trolleybuses or trains at a distance from the energy supply point. Electric trains that collect their current from an overhead line system use a device such as a pantograph or current collector. The device presses against the underside of the lowest wire of an overhead line system, the contact wire. The current collectors are electrically conductive and allow current to flow through to the train or tram and back to the feeder station through the steel wheels on one or both running rails [1] [2].

The railway overhead wire system consists of a contact wire, a messenger wire, droppers, registration arms and brackets as seen in figure 1.1. The messenger wire carries the contact wire

via the droppers, and makes it possible to obtain the desired geometry, stiffness and elasticity. The brackets carry the messenger wire, and are fastened to the poles. The main function of the registration arms, which are fastened to the contact wire, is to obtain the right horizontal geometry of the contact wire. The contact wire is the conductive part which transfers the electricity to the train through the pantograph [3] [4].

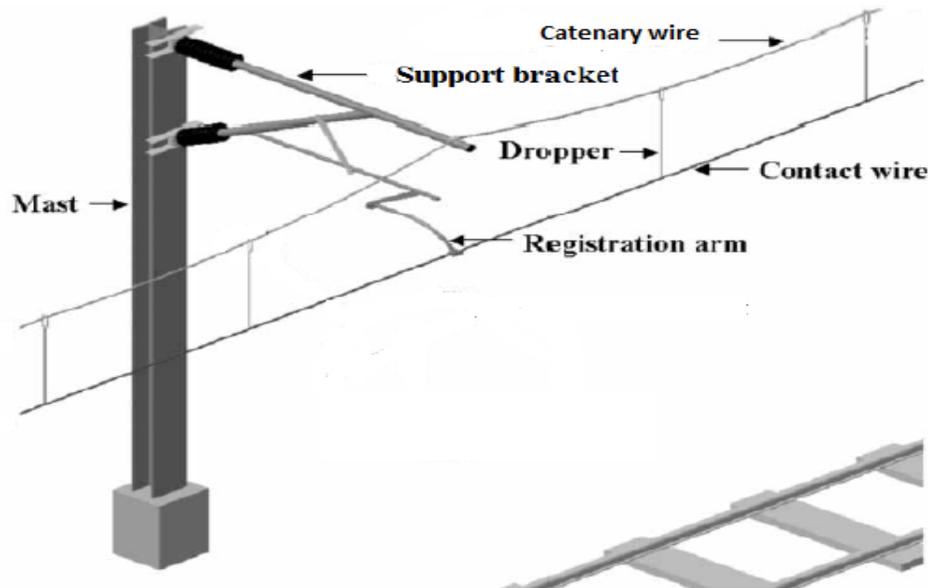


Figure 1.1 Overhead contact system components [3]

Today in Ethiopia, the implementation of modern electrified railways and light railway is the major breakthrough for the development of railway and related industries.

Implementing new electrification in Ethiopia by itself is an international technology transfer. However, complete new technology adaptation does not necessarily lead to more technological and economic development unless and otherwise that technology is tuned using the economical, geographical and environmental condition of Ethiopia. In addition, since the various projects are being in the stage of implementation by different developing partner countries, there are issues regarding to standards and system integrity due to unavailability of Ethiopian standard in the field of railway.

This generalization is also applicable to specific system in electrified railway. Hence, this thesis tries to investigate overhead contact system parameters for specific region and railway station in

Ethiopia, and tries to show the methodology to do so in the other regions and railway line in Ethiopia, so that the result could lead to the development of new OCS designing standard for Ethiopia Railway.

## **1.1 Motivation**

The first work that has been undertaken before the beginning of the thesis was problem and challenge identification around Ethiopia Railway Electrification. These are challenges in particular, under the scope of the current railway projects and in general related to the capacity for future project implementation strategy.

Generally there are four challenges that have been identified:

1. Electrified railway is new to Ethiopian and because of this the lack of knowledge pool and professional practitioner are one of the challenges in implementing the current electrified railway projects across Ethiopia.
2. Ethiopia do not have standards for railway electrification system, hence, in the current railway projects, contractors implement standards made for their countries in spite of the fact that, the standards may not comply with the environmental and geographical conditions of Ethiopia,
3. To have high quality and reliable railway electrification system on the current projects, there should be a clear, simplified and as universal as possible methodology to design, review designs, check quality and place requirements so that with the current minimum professionals, the huge railway electrification projects could be implemented with high quality and reliability.
4. Most design and manufacturing works are modulated work in which a subsystem of this system are designed and manufactured as a single unit to have universal functionalities. This creates a challenge specifically for countries like Ethiopia, since such design and manufacturing process are more abstractive and knowledge transfer to the acceptable level might not be achieved.

After identifying the above challenges; this thesis motivated to provide remedies for the challenges through thesis work titled as “Customized guideline for designing overhead contact system for Ethiopian Railway: Case study of Indode station”.

## **1.2 Problem Statement**

The requirements of the Overhead Contact System (now on OCS) need to consider that the contact line is the only component in the traction power supply installation which cannot be installed redundantly for economic and technical reasons. Hence, to ensure reliable system and to design and review technical OCS design, defined procedure and methodology are necessary for design of railway OCS that particular applicable to Ethiopia.

## **1.3 Objective**

The main objective of this thesis work is focused on one of the major elements of railway electrification, i.e. Customized guideline for designing overhead contact system for Ethiopian Railway.

### **1.3.1 General objective**

- Formulating a clear and simplified OCS design manual which can be as universal as possible to design and review design of overhead contact system for Ethiopia Railway using Indode station as a case study.
- Providing a platform for future works like standard formulation and identifying area for future research works regarding railway OCS in Ethiopia.

### **1.3.2 Specific objective**

- Identify major variable ranges for Indode station
- Determine maximum and minimum acceptable variable for Indode station
- Determine maximum span length
- Determine critical span length
- Determine maximum distance between anchor points
- Calculate OCS traction impedance

- Prepare OCS plan for Indode station using Microsoft Visio
- Station power supply sectioning and feeding arrangement

## 1.4 Thesis Methodology

The work of this thesis used for any place in Ethiopia by taking meteorological factor and site plan of that particular place. The thesis focuses on general OCS design and planning process for Ethiopia Railway.

It is impossible to prepare OCS plan by taking meteorological factor and site plan of different roots of all the current projects in this thesis work. Therefore a particular place selection is obligatory for this thesis work to show OCS design and planning. Station are more complex than main lines (contains many side tracks, crossing, turnouts, depots, etc) and are better to show all consideration in OCS planning process. The current running projects site plan is still updating, we get Indode station site plan from contractor. The reason why Indode station is selected as a case study is because of this and believing the station layout plan complexity could guide the detail works of this thesis.

The Methodology of this thesis involves the following tasks. The first task is data collection.

This was the first task after challenge identification. During this stage; data required for OCS design are collected.

The data collected are:

- Indode station layout plan- from the Sebeta-Meiso railway project contractor
- Meteorological data

The meteorological condition as the base of the design of OCS shall be determined according to the meteorological data along the line being recorded. The designed wind velocity for OCS design shall be taken as the average of maximum value, which is auto-recorded for 10 minutes at the height of 10 m above the ground and in wide region. The maximum wind speed is taken every 15 years and total 50 years return period is required for OCS design [2] [14].

Note: OCS should withstand maximum wind load through its life time and wind speed above the maximum design wind speed is not acceptable. If maximum wind speed that does not consider in

the OCS design is encounter in any time after installation, it may interrupt service temporarily or distract the OCS structure permanently. Therefore maximum wind speed of the root must be properly taken from record data to prevent occurrence of such damage on OCS system.

Maximum and minimum temperature used for OCS design can be taken as the average of the highest and average of the lowest temperature respectively of the area. The temperature data taken for the OCS design must be at least 10 years data and record of the area can be updated for every 10 years.

For this thesis the metrological data of Indode station are taken from Ethiopian Railways Corporation, Addis Ababa~Djibouti Railway, Sebeta~Adama~Mieso Section [5].

Secondly review of various literatures, standards and documents related to railway OCS is undertaken.

After having clear understanding of the literatures and collection of necessary information, Overhead contact system is modeled. During this stage bottom to top approach for modeling various type of overhead contact system is used. Trolley like OCS and simple catenary OCS system modeling are undertaken. The current practice for modeling OCS is based on the dynamics of OCS and it is a complex process which requires complex computer programming. However, such methods are mainly used for high speed lines. In this thesis work, a static modeling is used since it gives a satisfactory level of accuracy for railway lines up to 120km/hr. Finally analysis of data and design process is done. During this stage; source data are analyzed in order to use them for the design.

## **1.5 Literature Review**

During this stage; review of various literatures and documents related to overhead contact system is undertaken.

The challenges at this stages was,

- There are less numbers of literatures which give values for the thesis work
- Similar works are not available

However through intense review of various sources; sufficient material and information were gathered to accomplish this thesis. Some of the literatures are:

Sheilah Frey [1], he presents detailed historical background and development of railway electrification. The evolution of railway OCS from third rail, advantage and disadvantage of each system is discussed.

In [2], the title of the book is “Contact Lines for Electric Railways”. This book describes in detail about traction power supply system, planning, design, implementation, and maintenance of railway OCS. Project design and planning is done using computer software program Sicat Master Program. It also presents protection, safety and electromagnetic interference of OCS.

Arnar Kári Hallgrímsson [3], he investigates in his thesis the dynamic behavior of contact lines for railways with laboratorial model setup according to Norwegian conditions. Dynamic analysis is used for system used for high speed application. He starts with detailed description of OCS components and analysis OCS-pantograph interaction.

In [6], the title of the book is “Power supply system of electrified railways”. This book focuses on impedance modeling of various configurations of traction power supply systems, analysis of parameters of traction power supply systems during various operating modes, system parameter selection and traction system stability analysis during fault conditions. Most of the contents on this book are for the first time developed by the author (Markvart), a prominent railway electrification engineer and Scientist during soviet era, who contributes to the modernization of traction power supply systems in the world. The modeling approach is analytical approach and used electrified railways for speed up 120km/hr. For speed greater than 120km/hr; the modeling need to address modification of parameters.

In [7], the title of the book is “Overhead contact system”. This book describes the details of overhead contact system (OCS) modeling, OCS element structure analysis, physical properties of OCS elements, static modeling of interaction between OCS and pantograph, OCS element static load calculation and element selection. It provides a simplified OCS design approach by abstracting the details of OCS components.

In [8], the title of the book is “Overhead contact system of electrified railway”. This book focuses on the design of overhead contact system (OCS), OCS element structure analysis, based on standardized components of OCS, selection of OCS components, from standardized OCS component pools, design of sectioning and feeding scheme based on operation experience. It provides a simplified OCS design approach and OCS system components selection based on standardized OCS component pools. It is suitable for designing OCS in Russia and similar geographical area, as parameters used on this book considers the metrological states existing only in Russia. In addition, the standardized components are developed for local uses.

## 1.6 Thesis Organization

This thesis is organized in to six chapters including this introduction.

**Chapter two:** In this chapter OCS modeling is presented. It includes derivation of maximum span length; critical span length, maximum sag height, maximum anchoring length and traction impendence are discussed.

**Chapter three:** Analysis of loads on OCS and meteorological data and their effect is discussed

**Chapter four:** In this chapter design OCS parameters based on the modeling and data analysis are calculated. Overhead contact system planning is also discussed in this chapter

**Chapter five:** Conclusion of the thesis work and recommendation is given. By summery of the thesis work and based on standard overhead contact system design manual is preparation is presented in the appendix.

# Chapter Two

## 2. Overhead Contact System Modeling

### 2.1 Overview Railway Traction Power Supply System

Railway traction power supply system is a system which delivers an electrical traction power for locomotive and vehicles operating on the railway corridors. Generally power supply system for the railway has the following scheme shown in the figure 2.1 [6].

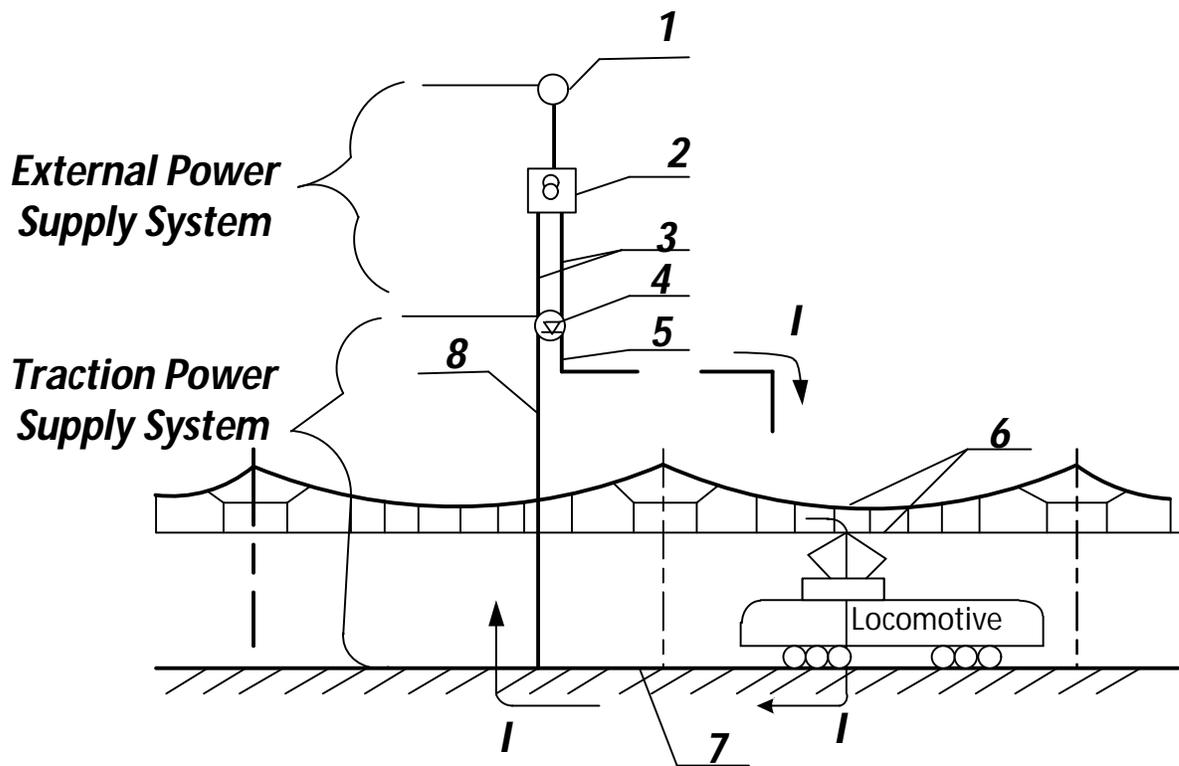
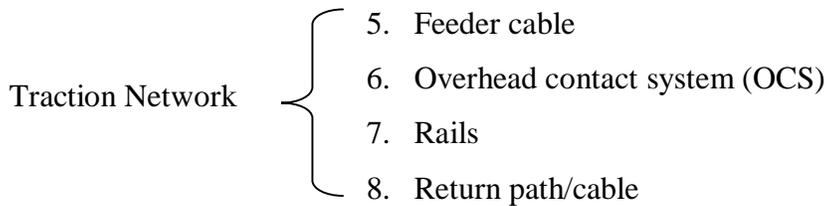


Figure 2.1 General Scheme of railway power supply system and its elements

1. Power generation station
2. Step-UP substation
3. High voltage transmission line
4. Traction substation



**Electric Traction Network:** It is a set of conductors, structures and equipments that enables the transport of electric power from traction substation to a pantograph of locomotive. It includes:

- Feeder and return conductors
- Contact wire and catenary wire
- Insulators
- Rails
- Poles, supporting structures and cantilever assembly
- Other over head Conductors(hangers, bonding wires, return wire...etc)
- Sectionalizing devices
- Disconnects
- Lightening and surge arrester

**Overhead Contact System (OCS):** a part of electric traction network, which includes overhead wires, protecting and sectionalizing devices, insulators, cantilever assemblies. The major requirement of OCS is to insure uninterrupted power supply for locomotives and trains for a given traction load, speed and traffic density along the railway route.

To insure this requirement, designing, construction and operation of OCS are carried out in accordance of standards documents.

## 2.2 Classification of Overhead Contact System

Over contact system broadly classified in to two: [2] [7].

### a) Trolley like contact system

This is a simplest form of overhead contact system. It is mainly used for trolley and tram line and has only contact wire. The maximum speed that can be achieved for this system is 80km/hr.

## b) Catenary contact system

This is a system mainly used in many countries. Using this system speed up to 160km/hr can be achieved. The system has a contact wire hanging on the overhead contact wire using hangers along the line

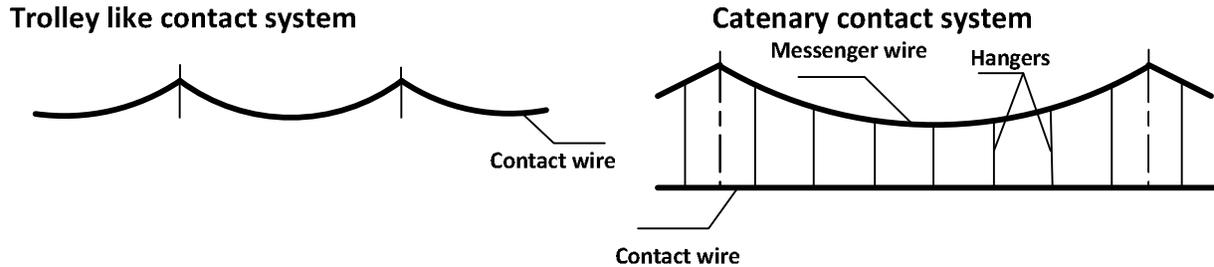


Figure 2.2 Trolley like and catenary overhead contact system

There are various forms of catenary OCS, depending on the number of messenger wire, the stager, zigzag, arrangement, the compensating system, and by the hanger arrangement near OCS mast.

### I. Classification by the Number of Messenger Wire

Depending on the number of messenger wire, catenary OCS is divided in two

#### a) Simple catenary

The contact wire and messenger wire connected directly.

#### b) Compound catenary

Where contact wire hangs with the middle messenger and the middle messenger wire interns hangs over the top messenger wire.

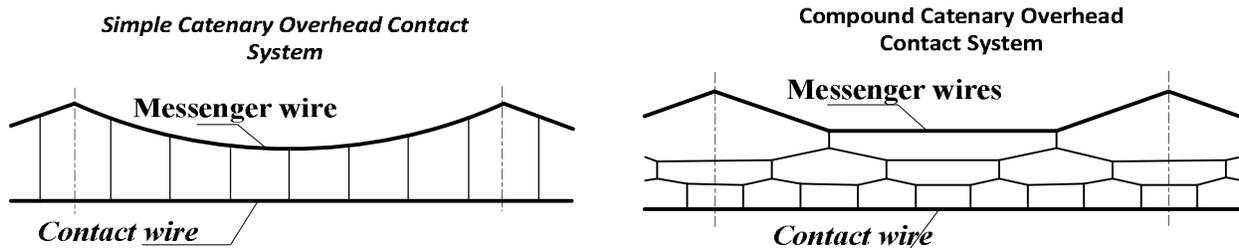


Figure 2.3 Simple and compound catenary overhead contact system

## II. Classification by Compensating System

A compensating system of catenary OCS is a system which compensates the change of tensile force on OCS wire due to temperature change and other factors. It is a weight balancing system which will hang on the wire at the anchoring mast. Based on this system catenary OCS is divided in two three.

### a) *Non-compensated catenary OCS*

The OCS wires are tied on the anchoring masts, without compensators. This system's OCS wire has a variable tension due to change of temperature and other factors.

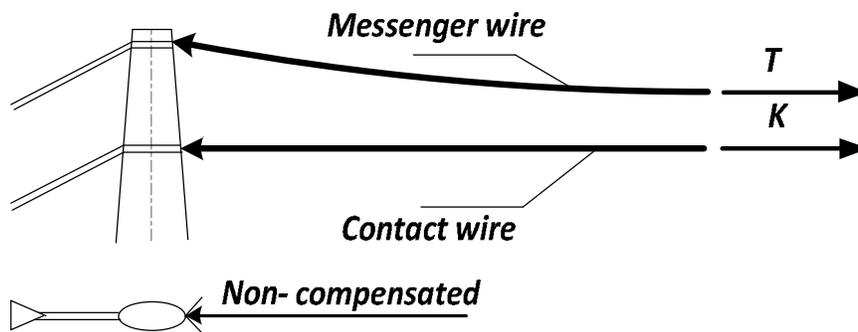


Figure 2.4 Non-compensated catenary OCS

### b) *Semi-compensated catenary OCS, $k=const$ ;*

Only contact wire is compensated with weight compensators at the anchoring mast. The messenger wire is tied to the anchoring mast.

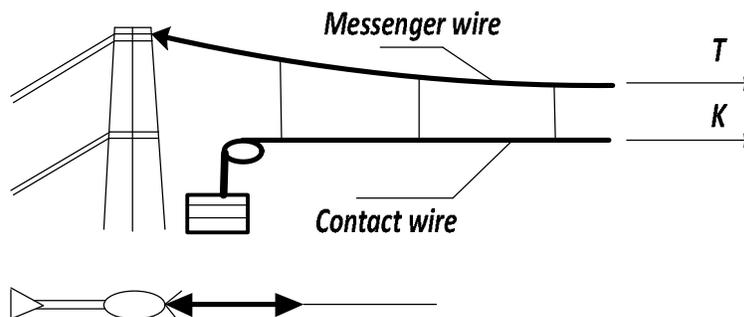


Figure 2.5 Semi-compensated catenary OCS

c) *Auto-compensated catenary OCS,  $k=const, T=const$ .*

Both contact wire and messenger wire are compensated with weight compensators at the anchoring mast.

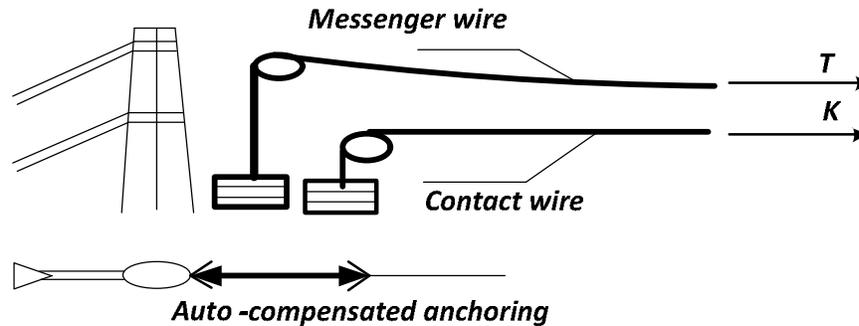


Figure 2.6 Auto-compensated catenary OCS

### III. Classification by Stager of Contact wire and Catenary Wire

To minimize mechanical wear of pantograph plate contact wire is installed with a zigzag layout with respect to the center of railway track. Depending on the layout and arrangement of contact wire and messenger wire zigzag, there are three type of catenary system

a) *Vertical stagger*

Where both contact wire and messenger wire make zigzag together.

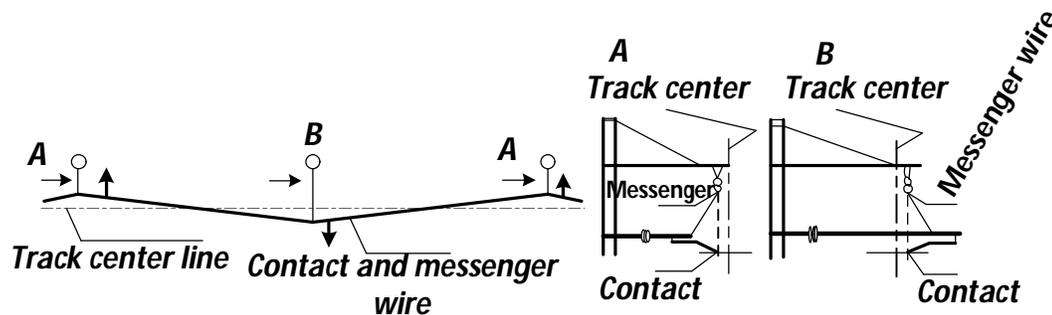


Figure 2.7 Vertical stagger type catenary OCS [7]

### b) *Half-skewed stagger*

Where messenger wire lay straight to the center of the track and contact wire makes zigzag. Since hanger wires are skewed, deflection of contact wire due to wind is minimized when compared with the vertical layout.

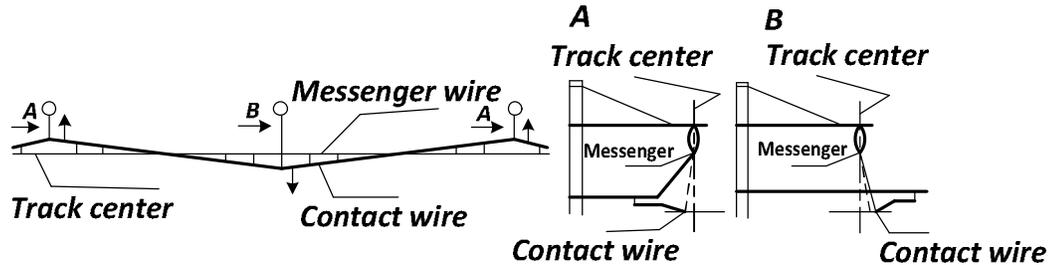


Figure 2.8 Half-skewed stagger type catenary OCS [7]

### c) *Full-skewed stagger*

Where messenger wire and contact wire makes a zigzag in opposite pattern.

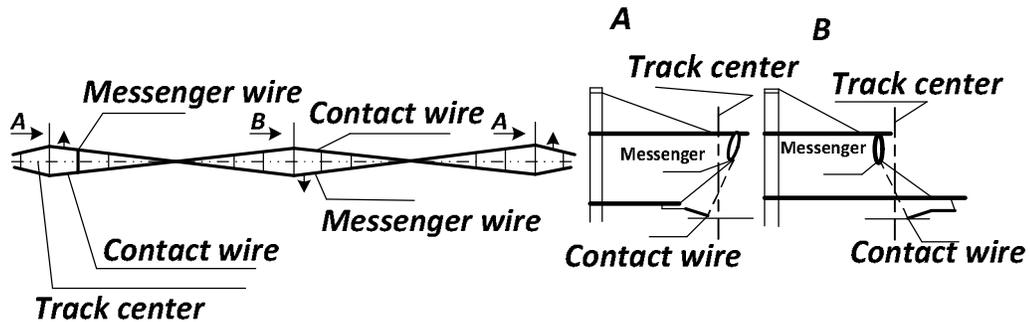


Figure 2.9 Full-skewed stagger type catenary OCS [7]

## IV. Classification by Hanger near OCS Mast

Hangers near OCS mast, determines the dynamical characteristics of OCS wires. Depending on hangers near OCS mast, catenary OCS divides in two three

### a) *Ordinary hangers*

The hanger near the OCS mast hangs directly on the cantilever fixer.

### b) *Displaced hangers*

The hangers near OCS mast hang in displaced fashion.

### c) *Damper hangers*

The hangers near OCS must have damping characteristics.

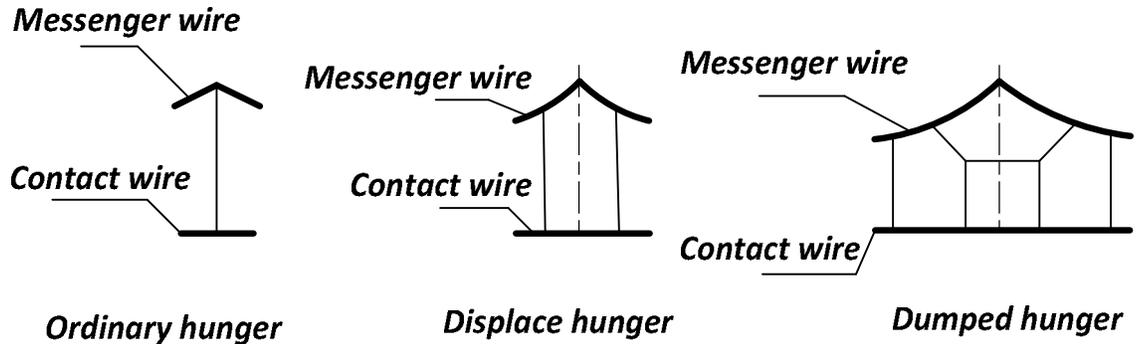


Figure 2.10 Ordinary, displaced and dumped hunger types of OCS

## 2.3 Modeling Overhead Contact System

Any overhead wire is considered to be a stretched bar supported at one or more points and subjected to bend by its own mass or other factors such as wind and ice load. Analysis of such wire takes different approach, depending on its rigidity and the distance between the supporting structures. If the length of the bar is short enough, it is treated like a beam and load analysis takes similar approach as structural analysis.

With increasing distance of the supporting structures, the rigidity of the bar will decrease and sag will occur. This is true for the case of OCS wire, as its supporting structures are distantly separated to each other. For this reason, OCS wire is treated as a flexible bar and the bending moment at any point on the wire is zero. Using this approach for OCS; it is possible to determine the sag at any point (catenary curve), the critical or maximum span length, the anchoring or tensioning length, tensile force on the wire and structures, maximum lateral deflection due to wind and all other design parameters for different OCS types [2] [8].

### 2.3.1 Simple Trolley-Type OCS Model

#### 2.3.1.1 Catenary Curve Equation for Trolley Type OCS

Catenary curve equation for simple trolley-type OCS is derived by taking a differential element of wire, as shown in figure 2.11;

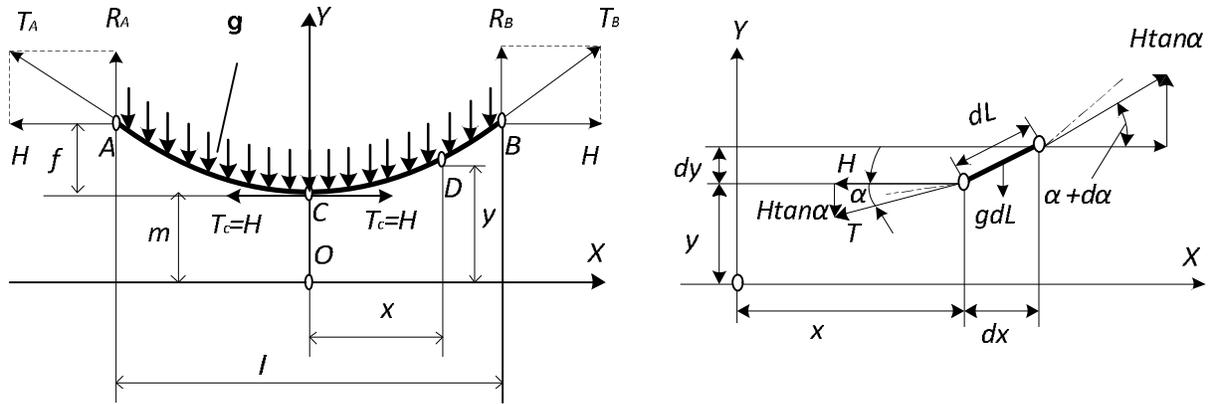


Figure 2.11 Loads on simple trolley type OCS curve and small differential part

As shown in the figure 2.11, the sum of horizontal component of tensile forces, at each end of the differential wire, will be zero. Then

$$T \cos \alpha = T_1 \cos(\alpha + d\alpha) = H \quad (2.1)$$

This means, the horizontal component of the tensile force will not be changed along the differential element. The differences between the resultant tensile forces at each end of the differential wire elements are due to the difference in the vertical components of the tensile forces.

Similarly, the sum of vertical component of tensile forces, at each end of the differential wire, will be zero. Then

$$-H \tan \alpha - gdL + H \tan(\alpha + d\alpha) \quad (2.2)$$

$$\text{Substitute } \tan \alpha = \frac{dy}{dx} = y'$$

$$-Hy' - gdL + H(y' + dy') = 0 \quad (2.3)$$

$$Hdy' = gdL \quad (2.4)$$

However, from fig 2, it can be seen that,

$$dL = \sqrt{dx^2 + dy^2} = dx \sqrt{1 + \frac{dy^2}{dx^2}} = dx \sqrt{1 + y'^2} \quad (2.5)$$

Rewriting equation 2.4 by replacing  $dL$  by equation 2.5

$$Hdy' + gdx\sqrt{1 + y'^2} \quad (2.6)$$

Bringing each variable to one side,

$$\frac{dy'}{\sqrt{1 + y'^2}} = \frac{dx}{m} \quad (2.7)$$

$$\text{Where, } m = \frac{H}{g}$$

After integrating both side,

$$\arcsin hy' = \frac{x + C_1}{m} \quad (2.8)$$

Then,

$$\sinh\left(\frac{x + C_1}{m}\right) = y' \quad \text{Or} \quad \sinh\left(\frac{x + C_1}{m}\right) dx = dy \quad (2.9)$$

Integrating again equation 2.9,

$$y + C_2 = m \cdot \cosh\left(\frac{x + C_1}{m}\right) \quad (2.10)$$

If the origin of the coordinate (0,0) is replaced by  $(-C_1, -C_2)$ , equation 2.10 can be written in the form of,

$$y = m \cdot \cosh\left(\frac{x}{m}\right) \quad (2.11)$$

The equation 2.11 is called, catenary curve.

In some literature, the origin of the coordinates is taken at the point where the sag is maximum, i.e when  $C_1 = 0$  and  $C_2 = m$ , shown in figure 2.12

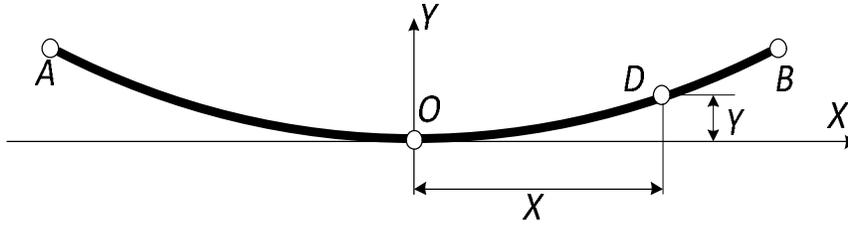


Figure 2.12 Simple trolley OCS curve

Then catenary curve equation becomes

$$y = m \left( \cosh \frac{x}{m} - 1 \right) \quad (2.12)$$

### Approximate catenary curve equation

Catenary curve equation can be written in simplified form if we take the Maclaurin series of equation 2.13.

$$y = m \left( \cosh \frac{x}{m} - 1 \right) = \frac{x^2}{2!m} + \frac{x^4}{4!m^3} + \frac{x^6}{6!m^4} + \dots \quad (2.13)$$

Since the value of  $m$  is large, i.e.  $m \gg 1$ , in the Maclaurin series of catenary curve equation, the terms beyond the first one is negligible. Then,

$$y = \frac{x^2}{2!m} \quad (2.14)$$

Such approximation helps to represent catenary curve equation in the form of parabolic equation rather than hyper-parabolic one, as equation 2.12.

Substitute  $m = \frac{H}{g}$  in equation 2.14, catenary curve equation for simple trolley-type catenary contact line becomes

$$y = \frac{gx^2}{2H} \quad (2.15)$$

### 2.3.1.2 Maximum Sag Height of Trolley Type OCS

If the supporting structure A and B are placed at the same level, then the point where the maximum sag occur is when  $x = l/2$ , then the maximum value of sag is:

$$f = \frac{gl^2}{8H} \quad (2.16)$$

For some cases, it is convenient to writ the equation of curve by shifting the origin of the coordinate at the first supporting structure, as shown in the in fig 2.13,

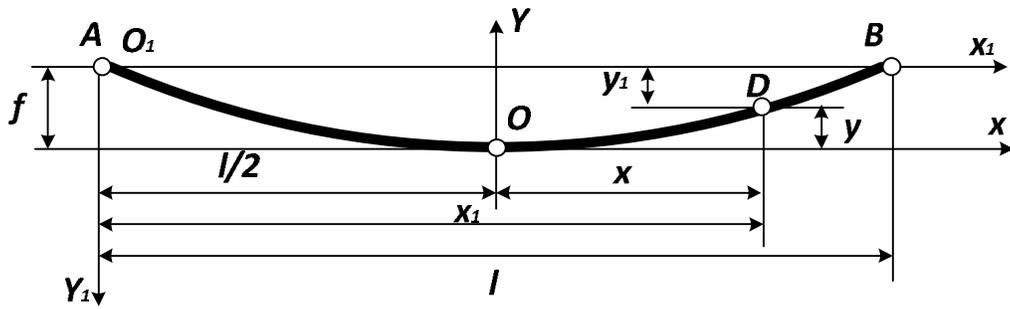


Figure 2.13 Sag of simple trolley OCS curve for masts on the same level

To shift the curve equation to the new coordinate, replacing the variables in equation 2.15 by,

$$x = x_1 - \frac{l}{2} \text{ and } y = f - y_1$$

Then the equation becomes,

$$f - y_1 = \frac{g \left( x_1 + \frac{l}{2} \right)^2}{2H} \quad (2.17)$$

After replace  $f$  in equation 2.17, by equation 2.16,

$$y_1 = \frac{gx_1(l - x_1)^2}{2H} \quad (2.18)$$

The approximate equation of curve in the form of parabolic equation has a very good accuracy for practical use.

The maximum sag height when the supports are at different height as shown in the figure below, can be express in terms of span length  $l$

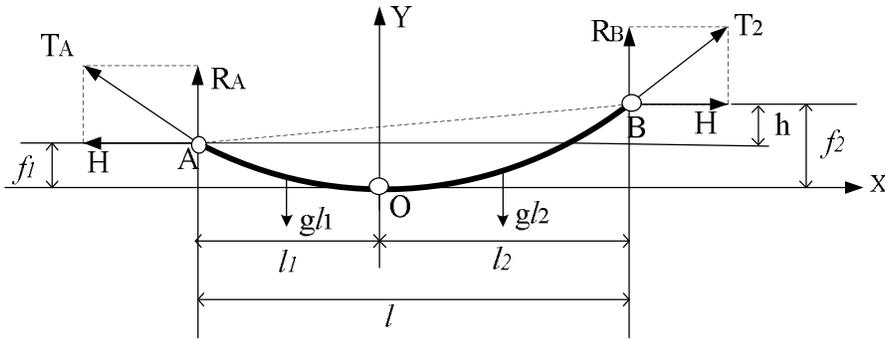


Figure 2.14 Sag of simple trolley OCS curve for masts on the same level

$$f_2 - f_1 = h \quad \text{and} \quad l_1 + l_2 = l \quad \text{where} \quad f_1 = \frac{gl_1^2}{2H} \quad \text{and} \quad f_2 = \frac{gl_2^2}{2H}$$

Where

$f_1$ - sag height to side of mast A

$f_2$ - sag height to the side of mast B

Then

$$\frac{gl_2^2}{2h} - \frac{gl_1^2}{2h} = h$$

After simplification we get

$$l_2 = \frac{l}{2} + \frac{hH}{gl} \quad \text{and} \quad l_1 = \frac{l}{2} - \frac{hH}{gl}$$

And the sag from higher mast B side becomes

$$f_2 = \frac{g \left( \frac{l}{2} + \frac{hH}{gl} \right)^2}{2H} \quad \text{and} \quad f_1 = \frac{g \left( \frac{l}{2} - \frac{hH}{gl} \right)^2}{2H} \quad (2.19)$$

### 2.3.1.3 Conductor Length of Trolley Type OCS

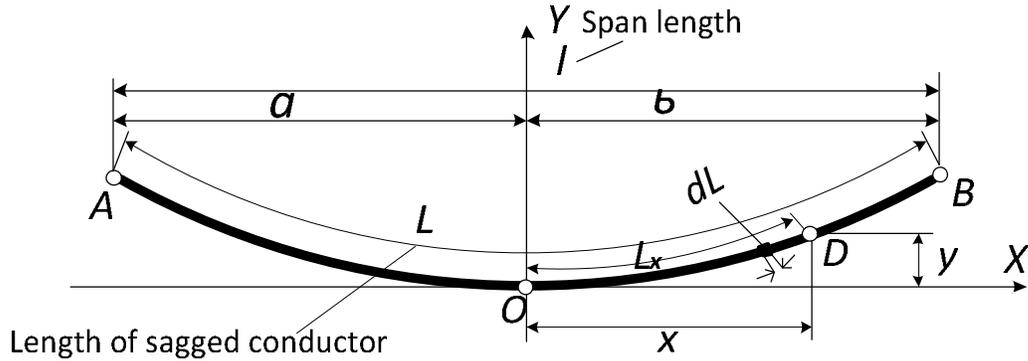


Figure 2.15 Conductor length of simple trolley OCS curve

In the figure above, the equation for differential length of the conductor is given by

$$dL = \sqrt{dx^2 + dy^2} \quad (2.5),$$

After integration, the length of sagged conductor form O to D will be,

$$L_x = \int_0^x \sqrt{1 + y'^2} dx \quad (2.20)$$

Replace  $y'$  by equation 2.9,  $C_1 = 0$  take the origin coordinate to maximum sag point,

$$L_x = \int_0^x \sqrt{1 + \sinh^2 \frac{x}{m}} dx = \int_0^x \cosh \frac{x}{m} dx = m \sinh \frac{x}{m} \quad (2.21)$$

The above formula gives the length of conductor from the center of span, from the maximum sag point, to any point along the two end supporting structure.

The maximum length of conductor is the sum of the conductor length form the center to supporting structure A and from the center to the supporting structure B. i.e.

$$L = m \left( \sinh \frac{a}{m} + \sinh \frac{b}{m} \right) \quad (2.22)$$

If the supporting structures are the same level or height,  $a = b = l/2$ , then the length of sagged OCS conductor will be

$$L = 2m \sinh \frac{l}{2m} \quad (2.23)$$

This formula gives the exact length sagged of conductor modeled in hyper-parabolic curve.

### Approximate equation for conductor length

Formula for sagged conductor length may be approximated with a good accuracy using the parabolic curve equation model.

Integrate equation 2.20 from 0 to  $l/2$ , and multiple the results by 2; the formula for length of conductor becomes,

$$L_x = 2 \int_0^{l/2} \sqrt{1 + y'^2} dx \quad (2.24)$$

According to the approximate equation for catenary curve, equation 2.15,

$y = gx^2 / 2H$ , and  $y' = gx/H$  then,

$$L_x = 2 \int_0^{l/2} \sqrt{1 + \left(\frac{gx}{H}\right)^2} dx \quad (2.25)$$

Since  $\frac{gx}{H} \ll 1$ , then approximate value for the term in the squared root will be,

$$1 + \left(\frac{gx}{H}\right)^2 \approx 1 + \left(\frac{gx}{H}\right)^2 + \frac{1}{4} \left(\frac{gx}{H}\right)^4 = \left(1 + \frac{1}{2} \left(\frac{gx}{H}\right)^2\right)^2 \quad (2.26)$$

Here, the addition of the term  $\frac{1}{4} \left(\frac{gx}{H}\right)^4$  will add significant for the magnitude of result but it will simplify the integration of equation 2.25. Then,

$$L_x = 2 \int_0^{l/2} \left[1 + \left(\frac{gx}{H}\right)^2\right] dx \quad (2.27)$$

Integrating the above equation will give the approximate formula for length of sagged conductor

$$L = l + \frac{g^2 l^3}{24H^2} \quad (2.28)$$

### 2.3.1.4 Equation of Conductor State of Change for Trolley Type OCS

With the change of temperature and change of meteorological load acting on conductors (such as wind load and ice load), the length of conductor and consequently the tensile force on the conductors changes, and the sag height changes. Knowing the value of tensile force and sag height at one meteorological state (at some value of specific temperature and wind load), it is easy to calculate the tensile force and sag height at another meteorological state (other temperature and wind load). This is useful when checking the maximum allowed sag height and allowed maximum tensile force on OCS conductor while the temperature is at its critical minimum or maximum value and wind speed or load is at its critical maximum value [2] [8].

Equation which relates the value conductor tensile force and sag height at one meteorological state to the value of conductor tensile force and sag height at another state is called equation of state of change.

OCS conductor's parameter at the initial or given meteorological state is designated by subscript "1" and the required meteorological state by "i".

- $t_1$  - Temperature at the give state (in  $^{\circ}\text{C}$ );  $t_1$   $q_1$   $H_1$
- $q_1$  - Resultant load per unit length acting on the conductor at the give state (N/m)
- $H_1$  - Tensile force per unit length of the conductor at the give state (N);
- $f_1$  - Sag height along the two supporting structure at the give state (m);
- $L_1$  - Conductor length between the two supporting structure at the give state (m);

For the second state, required state, subscript "i" is used:  $t_i$ ,  $q_i$ ,  $H_i$ ,  $f_i$  and  $L_i$ .

#### a) Conductor length change due to temperature

When air temperature changes from  $t_1$  to  $t_i$ , the length of conductor will changes due to thermal expansion. Then, the length of conductor at  $t_i$  will be

$$L'_i = L_1 [1 + \alpha(t_i - t_1)]$$

(2.29)

Where:

$\alpha$  -Coefficient of thermal expansion ( $^{\circ}\text{C}^{-1}$ );

The above equation assumes that, when temperature changes, the tensile force of conductor remains the same. However, when the temperature changes, the length of conducts will change and consequently the tensile force of the conductor will change due to elastic strain. The change in the tensile force, eventually changes the length of conductor by Hooks law.

### b) Conductor length change due to tensile force change

Hook's law states that, a change in the tensile force of conductor will linearly change the length of conductor. i.e

$$L_i = L'_i \left( 1 + \frac{H_i - H_1}{EA} \right) \quad (2.30)$$

Where:

E- Conductors modulus of elasticity (Young's module), ( $\text{N}/\text{mm}^2$ );

A-Cross-sectional area of the conductor ( $\text{mm}^2$ );

### c) Combined effect of temperature and tensile force change

When the value of temperature and load acting on the conductors at some particular state changes simultaneously to a new value due to state change, the total length change in the conductor is expressed as:

$$L_i = L_1 \left[ 1 + \alpha(t_i - t_1) \right] \left( 1 + \frac{H_i - H_1}{EA} \right) \quad (2.31)$$

Expanding the terms in the parenthesis; equation 2.31 can be rewritten as:

$$L_i = L_1 + L_1 \alpha(t_i - t_1) + L_1 \frac{H_i - H_1}{EA} + L_1 \alpha(t_i - t_1) \frac{H_i - H_1}{EA} \quad (2.32)$$

Eliminating the last term in 2.32, since it has small value, and bringing  $L_1$  to the left side, the equation 2.32 simplified as:

$$\Delta L = L_i - L_1 = L_1 \alpha (t_i - t_1) + L_1 \frac{H_i - H_1}{ES} \quad (2.33)$$

Again, approximating the above equation by assuming  $L_1 \approx l$ ,

$$\Delta L = L_i - L_1 = l \alpha (t_i - t_1) + l \frac{H_i - H_1}{EA} \quad (2.34)$$

Where:  $l$  - Span length, distance between the two supporting structure of OCS

$\Delta L$  - Change in the conductor length

However, as discussed in 2.3.1.3 and equation 2.28, the length of OCS conductor can be written

as  $L = l + \frac{g^2 l^3}{24H^2}$ . Then

$$L_1 = l + \frac{q_1^2 l^3}{24H_1^2} \text{ and } L_i = l + \frac{q_i^2 l^3}{24H_i^2}$$

$$\Delta L = L_i - L_1 = \left[ l + \frac{q_i^2 l^3}{24H_i^2} \right] - \left[ l + \frac{q_1^2 l^3}{24H_1^2} \right] \quad (2.35)$$

Substituting  $\Delta L$  in equation 2.35 by equation 2.34, and rewriting for equating  $t_i$ , equation for OCS conductor state of change will be:

$$t_i = \left( t_1 - \frac{q_i^2 l^2}{24\alpha H_i^2} + \frac{H_1}{\alpha EA} \right) + \frac{q_1^2 l^2}{24\alpha H_1^2} - \frac{H_i}{\alpha EA} \quad (2.36)$$

If the initial temperature and tensile force at arbitrary meteorological state are known, equation 2.35 enables to calculate the temperature or meteorological state at which tensile force of conductor will be  $H_i$ .

Substitute  $H_i$  and  $H_1$  from equation 2.36 by equation 2.16, and rearranging the variables, equation for OCS conductor state of change in terms of sag height at some specific meteorological state is calculated by:

$$f_i^2 - \frac{3q_i l^4}{64EAf_i} = f_1^2 - \frac{3q_1 l^4}{64EAf_1} + \frac{3}{8} l^2 \alpha (t_i - t_1) \quad (3.37)$$

## 2.3.2 Simple Catenary OCS Model

### 2.3.2.1 Semi-Compensated Catenary OCS Model

For semi-compensated catenary OCS, the catenary wire will be anchored directly and the contact will be anchored with a compensated device. Hence, when the temperature varies, the contact wire will not change the sag since the compensation device will keep the tensile force of contact wire unchanged. However, since the catenary wire is with a fixed type anchoring; when the temperature varies, the sag of catenary wire varies and consequently the sag of contact wire [2] [7] [8].

The semi-compensated catenary OCS curve equation modeling follows the same approach as trolley like OCS. However, is somewhat different.

The figure below shows half of a simple semi-compensated catenary system between two OCS masts.

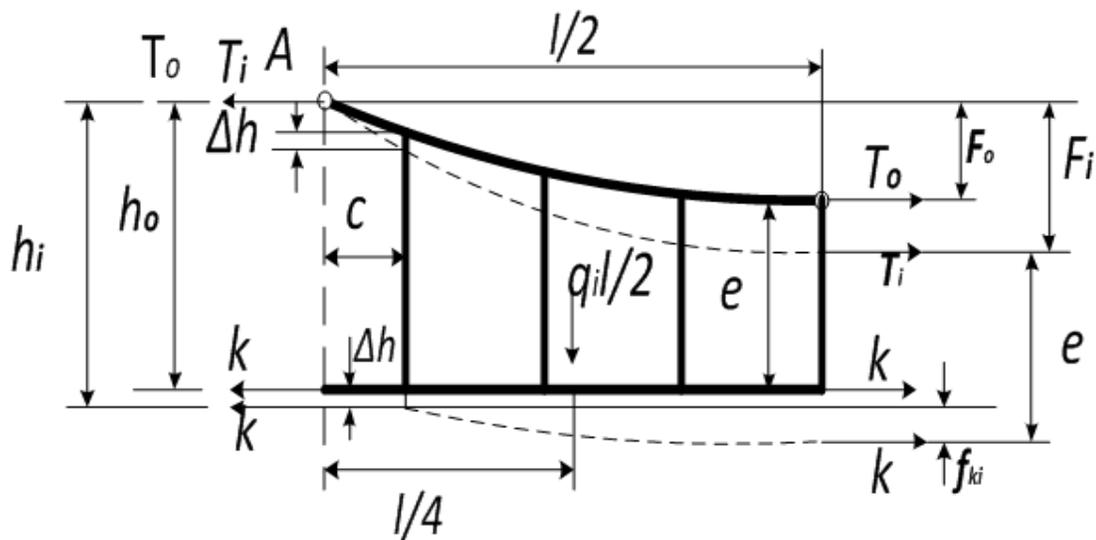


Figure 2.16 Semi-compensated simple catenary OCS curve

As simple catenary are initially installed by making the contact wire horizontal without sag, the initial state for analysis is this state with zero contact wire sag at temperature  $t_0$ . As a standard  $t_0$  is taken as

$$t_0 = \frac{t_{\min} + t_{\max}}{2} \quad (2.38)$$

The other state is taken as  $t_i$ . For simplicity it is assumed that  $t_0 < t_i$ .

At the equilibrium state with temperature  $t_i$ , the sum of moment at A is;

$$T_i F_i + K(F_i + e) - K(F_i + e - f_{ki}) - \frac{q_i l}{2} \cdot \frac{l}{4} = 0 \quad (2.39)$$

Or

$$T_i = \frac{q_i l^2}{8F_i} - K \frac{f_{ki}}{F_i} \quad (2.40)$$

Or

$$F_i = \frac{q_i l^2}{8T_i} - K \frac{f_{ki}}{T_i} \quad (2.41)$$

It can be seen that, sag of the messenger wire  $F_i$ , relates to sag of contact wire  $f_{ki}$ .

Assigning the term in equation 2.41  $\frac{f_{ki}}{F_i - F_0}$  by  $Y_i$  and rearranging; equation 2.41 can be written as;

$$f_{ki} = Y_i (F_i - F_0) \quad (2.42)$$

Where:  $Y_i$  is called the construction coefficient of catenary. This value is constant for particular construction of OCS cantilever. For displaced hanger OCS it is calculated as:

$$Y_i = \frac{(l - 2c)^2}{l^2} \quad (2.43)$$

Where:

C -displacement of the hanger

l -Span length

Substituting  $f_{ki}$  in equation 2.40

$$T_i = \frac{q_i l^2}{8F_i} - K \frac{Y_i(F_i - F_0)}{F_i} \quad (2.44)$$

Or

$$F_i(T_i + Y_i K) = \frac{q_i l^2}{8} + Y_i K F_0 \quad (2.45)$$

Similarly, when the contact wire is at horizontal position without sag at  $t_0$ , the sag equation for messenger wire has the same formula as catenary curve equation of trolley like OCS.

Then, the sag equation for messenger wire is:

$$F_0 = \frac{g_0 l^2}{8T_0} \quad (2.46)$$

Substituting  $F_0$  of the above equation in equation 2.45

$$F_i(T_i + Y_i K) = \frac{q_i l^2}{8} + \frac{g_0 l^2}{8} \frac{Y_i K}{T_0} \quad (2.47)$$

Then,

$$F_i = \frac{\left( q_i + g_0 \frac{Y_i K}{T_0} \right) l^2}{8(T_i + Y_i K)} \quad (2.48)$$

The assigning

$$W_i = q_i + \frac{g_0 Y_i K}{T_0}, \quad Z_i = T_i + Y_i K \quad (2.49)$$

Then, equation for messenger wire sag will be;

$$F_i = \frac{W_i l^2}{8Z_i} \quad (2.50)$$

Where:  $W_i$  is called a referred resultant load of simple catenary OCS and  $Z_i$  is the referred tension force of simple catenary OCS.

The above substitution makes the equation of state of change of simple catenary OCS take similar form as equation of state of change as trolley like OCS. Hence, equation of state of change for simple catenary OCS is:

$$t_i = \left( t_0 - \frac{W_0^2 l^2}{24\alpha Z_0^2} + \frac{Z_0}{\alpha EA} \right) + \frac{W_i^2 l^2}{24\alpha Z_i^2} - \frac{Z_i}{\alpha EA} \quad (2.51)$$

Note: The above method assumes the effect of hangers is negligible. However, to account the effect of hangers, the tensile force of messenger wire is taken as an average and is given by: [2].

$$T_i = 0.7T_{Max} \quad (2.52)$$

### 2.3.2.2 Fully-Compensated Catenary OCS Model

For fully-compensated catenary OCS, the catenary wire and contact wire is anchored with a compensating device. Hence, when the temperature varies, the sag of catenary wire and contact wire will be unchanged since compensating device keep the tensile force of both wire unchanged. However, the sag of contact wire and catenary wire will change when there is a wear on the contact wire. This phenomenon, therefore, changes the height of contact wire from the rail top. This is because; the sag of contact wire depends on weight of the wire, assuming constant tensile force, and hence when contact wire wear occurs; the weight of the contact wire will decrease and consequently the sag of the contact and catenary wire will decrease relative to the amount of wears.

If, during installation, the contact wire is installed with zero sag; then the contact wire will be pulled upward when a wear on contact wire occurs. This is because, the weight decrease on the contact wire  $q_i < q_0$ , because of wear; will decrease the catenary wire sag  $F_i < F_0$  and hence the contact wire sag will be pulled upwards and will have a negative sag value  $-f_k$ , as shown in the figure below, and this is undesirable in the OCS operation point of view.



$$TF_0 + K(f_k + h) - Kh - \frac{q_0 l}{2} \frac{l}{4} = 0 \quad (2.53)$$

Or

$$F_0 = \frac{q_0 l^2}{8T} - f_k \frac{K}{T} \quad (2.54)$$

Where:

T-is constant tensile force in catenary wire

K-is constant tensile force in contact wire

When the contact wire wears, at equilibrium state, the sum of moment at point will be:

$$TF_i + Kh - Kh - \frac{q_i l}{2} \cdot \frac{l}{4} = 0 \quad \text{Or} \quad F_i = \frac{q_i l^2}{8T} \quad (2.55)$$

## 2.4 Maximum Span Length and Anchoring Length Calculation

The maximum design value of span length depends is chosen based on three criteria. These are:

1. For keeping conductor wind deflection within acceptable limit
2. For keeping acceptable OCS conductors vertical clearance limit
3. For reliable and smooth pantograph-OCS interaction, taken 65meter in Chinese standard

The design value of span length will be the minimum from the three span lengths.

### 2.4.1 Determining Maximum Span Length for Permissible Wind

#### Deflection

There are two methods for determining maximum allowable span length that minimize contact wire wind deflection with allowable range [8].

**Dynamic analysis method:** this method assumes the dynamic nature of wind load and gives more accurate span length.

**Static analysis method:** this method assumes wind load on contact wire distributed uniformly along the wire considering various coefficient related to the track area and wind protection measures.

From the above two method; the more advanced and accurate method which needs complex computer modeling is dynamic analysis method. However, in practice, static method is used since it gives results with a reasonable accuracy.

**a) Static analysis method**

To find the maximum span length, which minimizes wind deflection, below in the figures, is shown the horizontal view of contact wire between two masts with a zigzag arrangements where a uniform wind load  $F'_w$  acting horizontally to deflect the contact wire horizontally with a maximum wind deflection length  $b_{kmax}$ . Let assume that, the zigzag in the first mast is away from the mast with a value of  $a$  and the zigzag in the second mast is towards the mast with the same value of  $a$ .

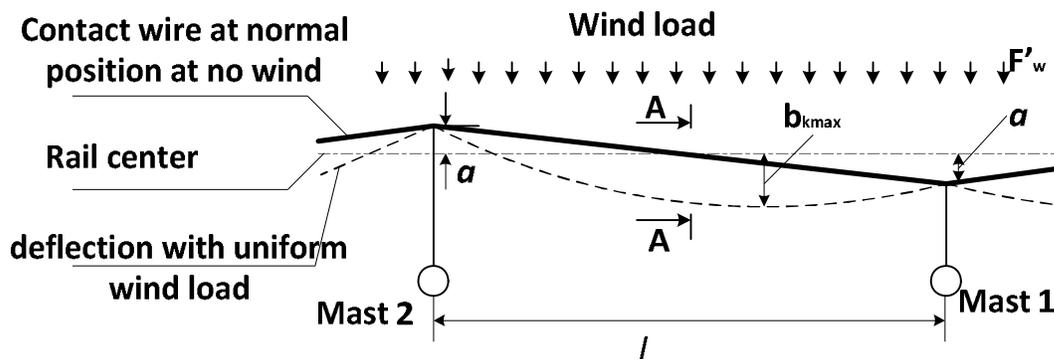


Figure 2.19 Wind load action on OCS

This scenario is similar to a hanging contact wire which was modeled in article 2.3.1.2. The difference is, in figure 2.19 is shown in horizontal view, whereas the hanging wire is in the vertical view. Hence the same approach can be used to model the above scenario by replacing the uniformly acting contact wire weight with the uniformly acting wind load.

As shown in the figure 2.19, a vertical hanging wire with different mast height where a uniform weight acting vertically. The catenary equation for the above hanging wire is:

$$f_A = \frac{g \left( \frac{l}{2} + \frac{hH}{gl} \right)^2}{2H} \quad (2.56)$$

Where; H- tensile strength,  $l$ - span length,  $g$ - weight of contact wire,  $h$ - height difference between the two masts.

Analogously, for horizontal view, with wind deflection, the equation 2.56 is similar to equation 2.19. However, by substituting with the appropriate parameters i.e  $H=k$ ,  $h=2a$ ,  $g= f_w$ .

The required value in this case is  $b_{k \max} = f_A - a$ . Then,

$$b_{k \max} = \frac{F'_w \left( \frac{l}{2} - \frac{2aK}{F'_w l} \right)}{2K} - a \quad (2.57)$$

$$b_{k \max} = \frac{F'_w l^2}{8K} - \frac{2a^2 K}{F'_w l^2} \quad (2.58)$$

The maximum allowable span length will be when the deflection value  $b_{k \max}$  reaches the maximum allowable value,  $b_{k \lim}$  which is limited by the pantograph horizontal working length. Then rearranging the above equation to bring  $l$  to the left, the maximum span length is found.

$$l_{\max} = 2 \sqrt{\frac{K}{F'_w} \left( b_{k \lim} + \sqrt{b_{k \lim}^2 - a^2} \right)} \quad (2.59)$$

From the above equation, it can be seen that, with increasing contact wire tensile strength the maximum span length will increase and similarly with increasing wind load or zigzag, the deflection length will increase.

## 2.4.2 Determining Maximum Span Length for Acceptable OCS Vertical Clearance

### *Semi-compensated OCS*

As discussed above, semi-compensated catenary OCS are initially installed by making the contact with a zero sag value; then the contact wire sag changes when the temperature changes.

The range of change of sag in contact wire can be found from the modeling equation of semi-catenary OCS.

$$f_{ki} = Y_i(F_i - F_0) \quad (2.60)$$

Where:  $Y_i$  - is called the construction coefficient of catenary.

$f_{ki}$  - is the contact wire sag at temperature  $i$

$F_0$  and  $F_i$  - sag of catenary wire at initial installation temperature and at temperature  $i$

$$Y_i = \frac{(l - 2c)^2}{l^2} \quad (2.61)$$

The sag equation for catenary wire is as discussed in section 2.3.2.1 is:

$$F_0 = \frac{g_0 l^2}{8T_0}, \quad F_i = \frac{W_i l^2}{8Z_i} \quad (2.62)$$

Where:  $W_i$  is called a referred resultant load of simple catenary OCS and  $Z_i$  is the referred tension force of simple catenary OCS.

$$W_i = q_i + \frac{q_0 Y_i K}{T_0}, \quad Z_i = T_i + Y_i K \quad (2.63)$$

Then, the sag of contact wire at a temperature  $i$  by substituting appropriate values in equation 2.60 becomes

$$f_{ki} = (l - 2c)^2 \left( \frac{q_i + \frac{q_0 K (l - 2c)^2}{T_0 l^2}}{8(T_i - Y_i K)} - \frac{g_0}{8T_0} \right) \quad (2.64)$$

The sag of the contact wire under semi-compensated and fully-compensated OCS should be not more than 0.25m [14].

$$\Delta h_{ct.wire} = f_{ki} = 0.25m \quad (2.65)$$

Considering vertical clearance limit; the maximum span length, for semi-compensated OCS is calculated with the help of computer program for the equation below:

$$0.25m = (l - 2c)^2 \left( \frac{q_i + \frac{q_0 K (l - 2c)^2}{T_0 l^2}}{8(T_i - Y_i K)} - \frac{g_0}{8T_0} \right) \quad (2.66)$$

### ***Fully-compensated OCS***

As discussed above, fully-compensated catenary OCS are initially installed by making the contact with a positive sag value  $+f_k$  as discussed in section 2.3.2.2, then the catenary wire sag change will be:

$$f_k = F_0 - F_i = \frac{q_0 l^2}{8T} - f_k \frac{K}{T} - \frac{q_i l^2}{8T} = \frac{(q_0 - q_i) l^2}{8(K + T)} \quad (2.67)$$

To keep the contact height within the allowed value; the positive sag value given to the contact wire during installation should be the maximum allowed sag in fully compensated OCS i.e 0.25m [14]:

$$\Delta h_{ct.wire} = f_k = h_{ct.wire}^{\max} - h_{ct.wire}^{\min} = \frac{(q_0 - q_i) l_{\max}^2}{8(K + T)} = 0.25m$$

Considering vertical clearance limit; the maximum span length, for fully-compensated OCS will be:

$$l_{\max} = \sqrt{\frac{2(K + T)}{q_0 - q_i}} \quad (2.68)$$

### 2.4.3 Determining Maximum Anchor Section Length

The length of contact and catenary wire increase when the temperature increases. If the OCS type is a catenary type with a compensated anchoring, then the increment in length on the contact wire will displace the weight aggregate on the anchoring mast as shown in the figure below. Hence, the contact and catenary wire should have some specific maximum value, so that, the weight aggregate would not touch the ground [2] [8].

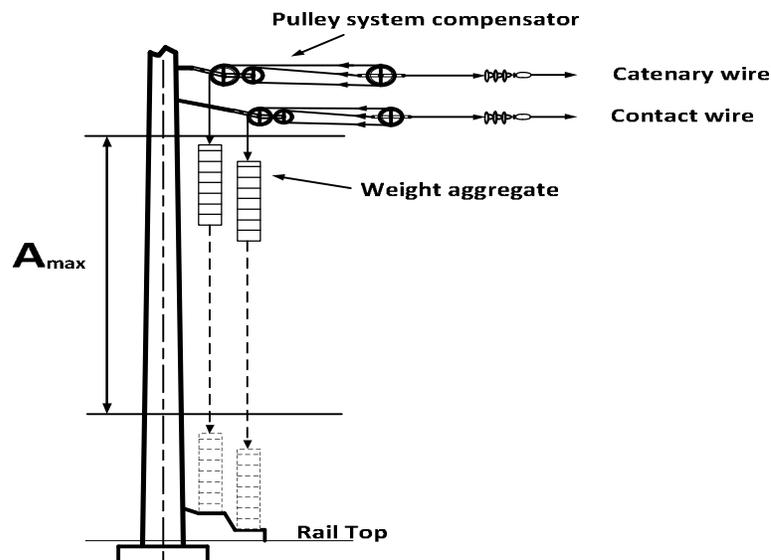


Figure 2.20 Fully-compensated pulley system for temperature variation

The allowed maximum displacement of weight aggregate is governed by thermal expansion of contact and catenary wire.

$$A_{\max} = k\Delta L_{\text{wire}} = k\alpha L_{\text{anchor}_{\max}} (t_{\max} - t_{\min}) \quad (2.69)$$

Then, the maximum anchor length becomes

$$L_{anchor\_max} = \frac{A_{max}}{k\alpha(t_{max} - t_{min})} \quad (2.70)$$

Where:  $A_{max}$  - is maximum displacement of contact wire

$k$  - is displacement ration of the compensator pulley system

$\Delta L_{wire}$  - is the length increment on the OCS wire due to temperature

$L_{anchor\_max}$  - is the maximum anchor length

$\alpha$  - is the liner thermal expansion coefficient of contact/catenary wire

$t_{min}, t_{max}$  - is the maximum and minimum temperature

## 2.5 Application of OCS Model

The major applications of OCS models are when:

- 1 Preparing installation graph and installation table to fix sag height and tensile force when installing new OCS and regulate conductor during temperature change

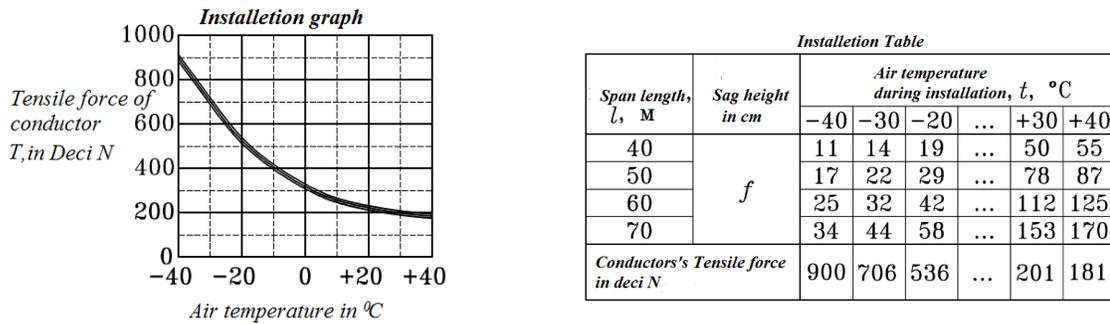


Figure 2.21 Sample installation curve and table [8]

- 2 Checking whether the designed OCS will meet horizontal and vertical clearance requirements, in accordance with the standard or pre-specified limit value, during operation for ever extreme meteorological state (i.e  $S_{tmin}$ ,  $S_{tmax}$  and  $S_{wind}$ ).

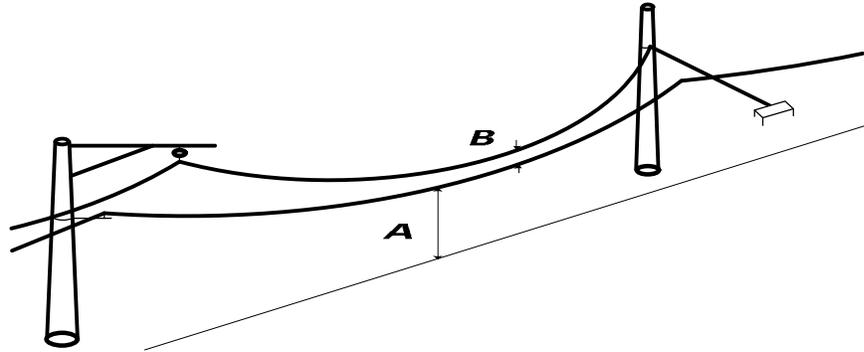


Figure 2.22 Vertical clearance of OCS

For example:

- The vertical clearance from the rail tip till the maximum sag point
  - The clearance between various conductors
- 3 Determining the tensile force of conductors at various meteorological states. This helps to determine the load that will be transferred on various structures and mast of an OCS.

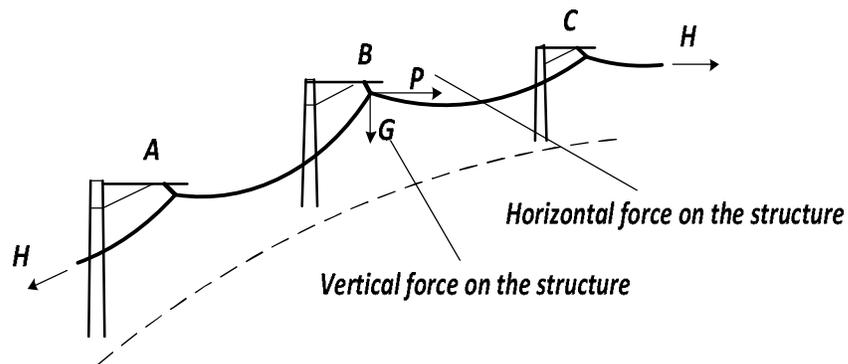


Figure 2.23 Force actions on OCS structure

Hence, to solve such tasks, two equations are used frequently. These are:

1. Equation for sag height (equation 2.16)

$$f_i = \frac{gl_i^2}{8H_i}$$

2. Equation of state of changes (equation 2.36)

$$t_i = \left( t_1 - \frac{q_i^2 l^2}{24\alpha H_i^2} + \frac{H_1}{\alpha EA} \right) + \frac{q_1^2 l^2}{24\alpha H_1^2} - \frac{H_i}{\alpha EA}$$

## 2.5.1 Initial Meteorological State

If, at any one of extreme meteorological state, the values of parameter  $t_1$ ,  $q_1$  and  $H_1$  are known, equation of state of changes is used to determine the tensile force of OCS conductor ( $H_i$ ) at any other meteorological state.

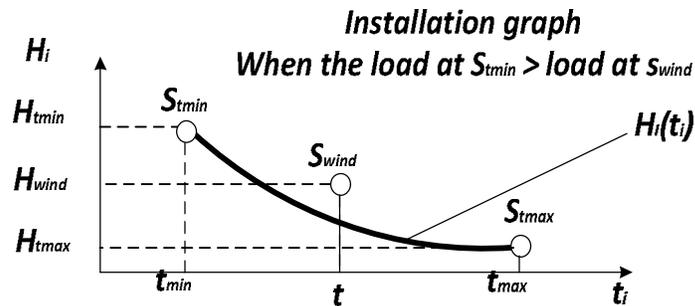
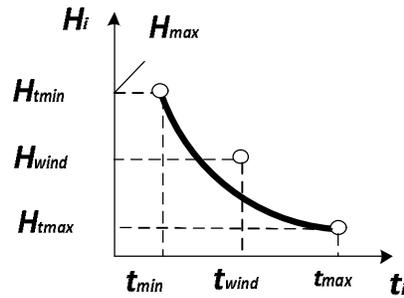


Figure 2.24 Sample installation graph showing critical states

In principle, as an initial state, any meteorological state with known value of  $t_1$ ,  $q_1$  and  $H_1$  can be chosen to determine the parameters at the extreme meteorological state. However, in practice, the preferable meteorological state to be taken as an initial meteorological state is, one of the extreme meteorological states which will exert the maximum tensile force  $H_{max}$  compared to the other extreme meteorological state.

However, tensile force on conductors may reach  $H_{max}$  at any of the two extreme meteorological states i.e when air temperature is at its extreme minimum value or when the wind speed/load is at its extreme maximum value ( $S_{tmin}$  or  $S_{wind}$ ).

**Condition when  $S_{tmin}$  taken as initial state**



**Condition when  $S_{wind}$  taken as initial state**

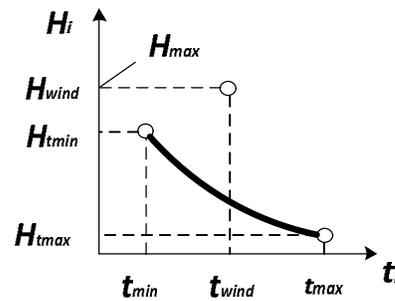


Figure 2.25 Sample installation graph showing  $S_{tmin}$  or  $S_{wind}$  at initial state respectively

## 2.5.2 Determining the Heaviest Extreme Meteorological State

During operation of OCS; tensile force on conductor can reach its maximum value at any of the two extreme meteorological states i.e at  $S_{tmin}$  or  $S_{wind}$ .

In principle, by taking any one of the two extreme meteorological states with known value of  $t_1$ ,  $q_1$  and  $H_1$ , as an initial state; the tensile force of the conductor at the other extreme state is determined using equation of state of change. Then, the tensile force of the conductor at the two extreme meteorological is compared to determine the extreme meteorological state with higher tensile force.

There exists a simpler method to determine the extreme meteorological state which will exerts the highest tensile force. However, to use this method the critical span length and critical load should be calculated first.

## 2.5.3 The Critical Span Length

At some value of span length, one extreme meteorological could be a state with maximum tensile force on the conductors. If the span length increased or decreased, while every other parameter unchanged, the maximum tensile force on the conductors might happen at the other extreme meteorological state different from the first one. This means, the maximum tensile force on the conductors might happen at  $S_{tmin}$  or  $S_{wind}$ , depending on the span length of an OCS system.

For some specific value of span length, the tensile force on the conductor will reach its maximum value ( $H_{wind} = H_{t_{min}}$ ) for both extreme meteorological states i.e for  $S_{t_{min}}$  and  $S_{wind}$ . The value of this span length is called the critical span length.

By arbitrary taking the initial state  $S_{t_{min}}$  and required state  $S_{wind}$ , the relation between span length and the state with highest tensile force could be seen.

$$H_1 = H_{t_{min}}, t_1 = t_{t_{min}}, q_1 = g, H_i = H_{wind}, t_i = t_{wind}, q_i = q_{wind}$$

$$H_{wind} = H_{t_{min}} - \frac{g^2 l^2 EA}{24H_{t_{min}}^2} + \frac{q_{wind}^2 l^2 EA}{24H_{wind}^2} - \alpha EA(t_{wind} - t_{t_{min}}) \quad (2.71)$$

- **Case 1:** When  $l \rightarrow 0$

$$H_{wind} = H_{t_{min}} - \alpha EA(t_{wind} - t_{t_{min}}) \Rightarrow H_{wind} < H_{t_{min}} \quad (2.72)$$

- **Case 2:** When  $l \rightarrow \infty$

Multiply equation 2.71 by  $l^2/2$  and taking the limit  $l \rightarrow \infty$

$$\frac{g}{H_{t_{min}}^2} = \frac{q_{wind}}{H_{wind}^2}, \text{ Since } q_{wind} > g \Rightarrow H_{wind} > H_{t_{min}} \quad (2.73)$$

This means, for very short span length, the highest tensile force will occur when the temperature is at the extreme minimum value, i.e at  $S_{t_{min}}$  state. For very long span length, the highest tensile force will occur when the wind speed/load is at the extreme maximum value, i.e at  $S_{wind}$  state.

Since at critical span length  $H_{wind} = H_{t_{min}}$ , to find the critical span length, we take

$$H_{max} = H_{wind} = H_{t_{min}} \text{ and substitute } H_{max} \text{ in equation 3.38 in terms of } H_{wind} \text{ and } H_{t_{min}}.$$

$$l_{cr} = H_{max} \sqrt{\frac{24\alpha(t_{wind} - t_{t_{min}})}{q_{wind}^2 - g^2}} \quad (2.74)$$

To determine which state exerts maximum tensile force, comparison is done between design values of span length  $l$  with  $l_{cr}$ . Then,

- If  $l < l_{cr}$  then the most extreme state is  $S_{t_{min}}$

- If  $l > l_{cr}$  then the most extreme state is  $S_{wind}$

## 2.5.4 Maximum Sag Height

OCS conductor will have maximum sag height at  $S_{tmax}$ , i.e when temperature is at its extreme maximum value. Then

$$f_{max} = \frac{gl^2}{8H_{tmax}} \quad (2.75)$$

## 2.6 Simple Catenary OCS Model Analysis Steps

- 1 For the given geographical location of station, meteorological factors are analyzed to come up with the designating value of wind speed, minimum temperature and maximum temperature based on given data and standards
- 2 Calculate loads acting on the OCS, horizontal components, vertical components and resultant load during various extreme weather conditions/states such as  $S_{tmin}$ ,  $S_{tmax}$  and  $S_{wind}$
- 3 Set the maximum allowed tension on messenger wire (the load acting on this wire should not create tension on this wire which is greater than this allowed max load).
- 4 Calculate the nominal tension of the contact wire
- 5 Determine the maximum span length and anchor section
- 6 Place the OCS mast on the station plan by considering the maximum span length
- 7 Calculate the critical span length
- 8 Determine the value of tensile force of messenger wire by considering horizontal contact wire without sag
- 9 Determine the weather state that create the highest tension on the messenger wire and adjust the critical span length
- 10 Prepare installation table of the OCS based on the most extreme weather state for trolley and semi-compensated simple catenary

- 11 Determine the change of sag of contact and messenger wire for the most extreme weather condition

## 2.7 Overhead Contact System Traction Impedance

Electrical characteristics such as the impedance, current distribution and current capability determine the energy transmission behavior of an OCS. The electrical characteristics of a contact line and the corresponding protection required for the electric installations and operating equipment are designed in view of the current to be transmitted via the contact line system. Once the transmission characteristics and currents are known, it is possible to evaluate the electromagnetic interferences being emitted by an electric railway line. The contact line system can be assumed to act as a long conductor installed above ground [2] [6] [9]. Figure 2.26 shows the basic supply scheme.

The basic relationships within the contact line system are:

- The substation supplies the electric energy with a source voltage and the current  $I_{\text{traction}}$ .
- The energy is transmitted from the substation to the traction vehicles via the contact line. The line impedance of OCS is designated as  $Z_{\text{eq}}$ .
- The electric power depends on the conditions of the train at the respective time.
- The traction current  $I_{\text{traction}}$  returns to the substation through the return circuit consisting of the rails and return conductors. In OCS, the earth is part of the return circuit.

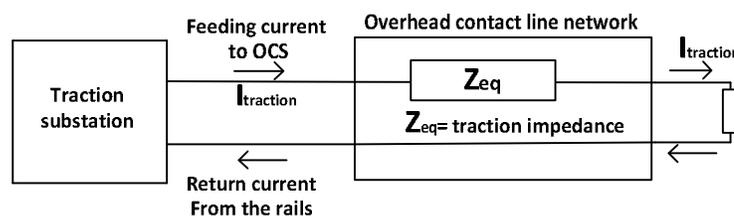


Figure 2.26 Equivalent network of OCS

## 2.7.1 Components of Impedance

The impedance of the loop comprising the contact line and the return circuit is commonly called the line impedance. In DC railway installations, the line impedance is obtained from the resistances of all parallel contact lines, reinforcing feeder conductors or cables and the return circuit comprising the track resistance including all parallel return conductors. The impedances of AC contact line consist of active resistance and internal and external reactance of the conductor, and usually expressed in relation to the length [10] [11].

### 2.7.1.1 Resistance of OCS Conductors per unit Length

The resistance per unit length of conductors, wires, cables and rails is determined by the electrical properties of the materials that these components are made of. The resistance per unit length of wires, conductors, rails and earth is determined in the following.

#### Wires and conductors resistance

The resistance per unit length of wires and conductors is calculated by:

$$R' = \frac{R}{l} = \frac{rl}{Al} = \frac{r}{A} \quad (2.76)$$

Where:

$R'_c$  = per unit resistance of conductor,  $r$  = specific resistivity of the conductor in  $\Omega.m$ ,  $l$  = conductor length

$A$  = cross sectional area of the conductor

#### Running rails

The resistance of steel running rails can be obtained from table below which shows the characteristic properties of commonly used running rails. The resistance of single-track and double-track lines is one half or one quarter, respectively. Where rail joints are used, the resistance  $R'_c$  is increased according to the material and cross section. A commonly accepted value is 0.5% per joint [2].

Table 2.1 Resistances per unit length of conductors at 20 °C and 40 °C, values in mΩ/km [2]

Conductor	A mm <sup>2</sup>	R <sub>c</sub> ' at 20 <sup>0</sup> C		R <sub>c</sub> ' at 40 <sup>0</sup> C	
		New	20 % worn	New	20 % worn
Cu AC-80	80	223	278	240	300
Cu AC-100	100	179	223	193	240
Cu AC 120	120	149	186	160	200
CA BzII	70	422	-	455	-
CA BzII	95	298	-	321	-
CA BzII	120	237	-	255	-

Note: AC contact wire, CA catenary wire, FL feeder line with reinforcing conductor (RL)

Table 2.2 Characteristic properties of commonly used running rail types [2]

Rail type	m'	H	w <sub>f</sub>	A	U	r' <sub>eq</sub> A	R' mΩ/km	R' mΩ/km
	kg/m	Mm	Mm	mm <sup>2</sup>	mm	mm	wear 0 %	wear 15%
R50	50.50	152	132	6450	620	45.31	34,5	40.6
R65	65.10	180	150	8288	700	51.36	25.2	29.9

**Note:** m'-mass per unit length, H-height of rail, w<sub>f</sub>-foot width, A-cross section,

r<sub>eq</sub> - cross section-area-equivalent radius:  $r_{eq} = \sqrt{A/\pi}$

R'-resistance at 20 °C

### Earth return path

Although the differing types of soil show a great variety of resistivity, the resistance of earth to DC currents is zero due to the huge cross section involved. However, in case of AC currents, the earth possesses a resistance. The resistance per unit length of the earth return path  $R'_E$  is a function of the frequency of the power supply [9].

$$R'_E = \left(\frac{\pi}{4}\right) \cdot \mu_0 \cdot f \tag{2.77}$$

**2.7.1.2 Impedance of conductor-earth loop per unit length**

Overhead contact lines differ from the common type of transmission line because of the various asymmetric wire arrangements of OCS. For example, a single trolley type OCS consists of one contact line and two rails to form a three conductor overhead contact line with asymmetric wire arrangement. For single track catenary OCS, there will be one catenary wire, one contact wire and two rails to a four wire overhead contact line with asymmetric wire arrangement. For double track line, similarly, there will be two contact line, two catenary wire and four rails, to form eight conductors overhead contact line with asymmetric wire arrangement.

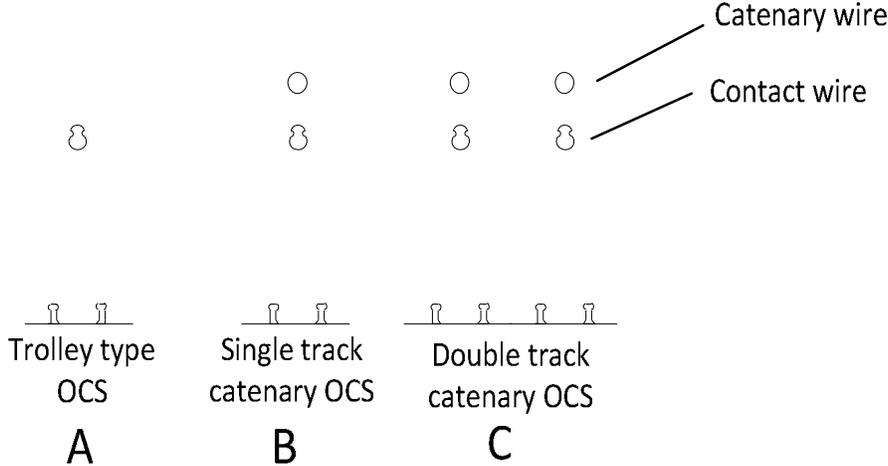


Figure 2.27 Various OCS type conductor arrangements [6]

The current in the overhead contact network distribute unevenly on the contact wire, catenary wire and rails. This is because, not only the three conductor type is different but also their cross section area is different. This makes the overhead contact line very much different and complex than the common transmission line network.

**Trolley type OCS**

To calculate the impedance of OCS, first, it is easy to develop the impedance model for trolley type OCS and analogously develop the model for other type of OCS.

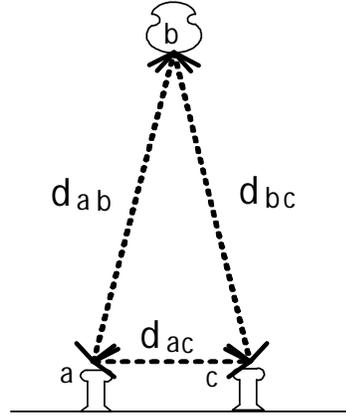


Figure 2.28 Trolley type OCS conductor arrangements

The above trolley type overhead contact line network, consists of a loop containing the contact line **b**, the rail **a**, and rail **c**. The current on each of the rails designated as  $I_a$  and  $I_c$  and the current on the contact line is designated as  $I_b$ .

The current  $I_a$  creates a flux linkage on contact line **b** and this forms a conductor-earth loop **a-b**.

The value is calculated for 1 km of conductor as follows [9],

$$\psi_{ab} = \frac{\mu_0 I_a \cdot 10^3}{2\pi} \int_{R_a}^{d_{ab}} \frac{ds}{\rho} + \psi_a = \frac{\mu_0 I_a \cdot 10^3}{2\pi} \ln \frac{d_{ab}}{R_a} + \psi_a \quad (2.78)$$

Where:

$\psi_{ab}$  - Flux linkage along counter **a-b** due to  $I_a$ , current on rail **a**,

$\psi_a$  -self linkage flux inside the rail **a** due to  $I_a$

$R_a$  -equivalent radius of the rail **a**,

$\mu_0$  -magnetic permittivity of free space,

Then, the voltage drop along the loop **a-b**, created by the current  $I_a$ , on the rail **a**, will be;

$$\Delta V_{ab} = r_a I_a + j\omega \left[ \frac{\mu_0 I_a \cdot 10^3}{2\pi} \ln \frac{d_{ab}}{R_a} + \psi_a \right] \quad (2.79)$$

Where:

$r_a$  - Per unit active resistance of the rail  $a$ , in  $\Omega/\text{km}$

$\omega = 2\pi f$  -Angular frequency in radian per second

Taking  $\mu_0 = 4\pi \times 10^{-7}$  H/m, the above equation can be re-written as:

$$\Delta V_{ab} = \left( r_a + j2\omega \cdot 10^{-4} \ln \frac{d_{ab}}{R_a} + \frac{j\omega\psi_a}{I_a} \right) I_a \quad (2.80)$$

The inner linkage flux creates a self reactance of the rail  $a$ ,  $x_a = \frac{\omega\psi_a}{I_a}$  [9] and since the active resistance is  $r_a$ , then the total self impedance of the rail  $a$  will be:  $Z_a = r_a + jx_a$ . Considering this and re-writing equation 2.80,

$$\Delta V_{ab} = \left( r_a + x_a + j2\omega \cdot 10^{-4} \ln \frac{d_{ab}}{R_a} \right) I_a = \left( Z_a + jm \ln \frac{d_{ab}}{R_a} \right) I_a \quad (2.81)$$

Where:  $m = 2\omega \cdot 10^{-4}$

It is known that, for aluminum and copper wire, irrespective of the conductor length and geometry [6].

$$x_a = 0.25m \quad (2.82)$$

To simplify the above equation, it is represented as:  $\Delta V_{ab} = Z_{ab} I_a$

Then, the impedance of the loop is;

$$Z_{ab} = Z_a + jm \ln \frac{d_{ab}}{R_a} \quad (2.82)$$

Analogously,

The impedance of the loop  $b-a$ ,  $b-c$ ,  $c-b$ ,  $a-c$ ,  $c-a$  will be;

$$\begin{aligned}
Z_{ba} &= Z_b + jm \ln \frac{d_{ba}}{R_b} \\
Z_{bc} &= Z_b + jm \ln \frac{d_{bc}}{R_b}, Z_{cb} = Z_c + jm \ln \frac{d_{cb}}{R_c} \\
Z_{ac} &= Z_a + jm \ln \frac{d_{ac}}{R_a}, Z_{ca} = Z_c + jm \ln \frac{d_{ca}}{R_c}
\end{aligned}
\tag{2.84}$$

Where:  $R_b$  -The radius of contact wire,  $b$  and  $R_c$  equivalent radius of rail  $c$ ,

$Z_b$  -The total self impedance of contact wire,

The two impedance are not equal,  $Z_{ab} \neq Z_{ba}$ , because the rail and the contact wire are not only different on cross section but the type of conductor also.

To calculate the impedance on the loop  $a-b$ , due to the current  $I_c$  on the rail  $c$ ; voltage drop relation is used [6].

$$\Delta V_{ab}^c = \Delta V_{cb} - \Delta V_{ca} \tag{2.85}$$

Since,

$$\begin{aligned}
\Delta V_{cb} &= \left( Z_c + jm \ln \frac{d_{cb}}{R_c} \right) I_c \\
\Delta V_{ca} &= \left( Z_c + jm \ln \frac{d_{ca}}{R_c} \right) I_c
\end{aligned}
\tag{2.86}$$

Then,

$$\Delta V_{ab}^c = jm \ln \frac{d_{cb}}{d_{ca}} I_c \tag{2.87}$$

Representing, the mutual impedance between loop  $a-b$ , due to current  $I_c$  on the rail  $c$ ; by  $X_{ab}^c$

Then,

$$\Delta V_{ab}^c = jX_{ab}^c I_c \tag{2.88}$$

$$X_{ab}^c = m \ln \frac{d_{cb}}{d_{ca}} \quad (2.89)$$

The total voltage drop of along the loop a-b will be,

$$\Delta V_{ab} = Z_{ab} I_a - Z_{bc} I_b + jX_{ab}^c I_c \quad (2.90)$$

### Catenary OCS

Generalizing, the above scenario for catenary OCS with catenary wire and contact wire in addition to the two rails, then, the total voltage drop caused by all conductor current will be,

$$\Delta V_{ab} = Z_{ab} I_a - Z_{bc} I_b + jX_{ab}^c I_c + jX_{ab}^d I_d \quad (2.91)$$

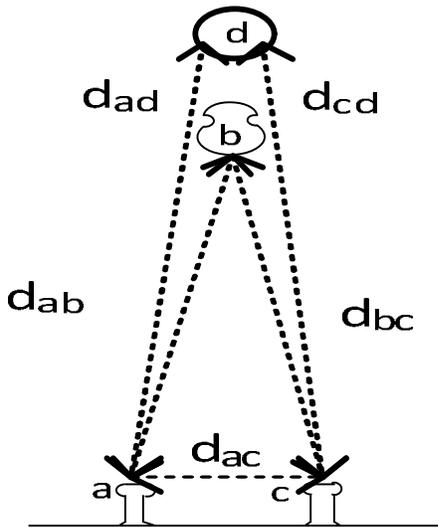


Figure 2.29 Catenary type OCS conductor arrangements

If we take the voltage drop between the loops, **d-b**, i.e the voltage drop between the contact wire and catenary wire, then this value equate to zero, since there is no voltage drop between contact wire and catenary wire. Then,

$$\Delta V_{bd} = Z_{bd} I_b - Z_{bd} I_d + jX_{bd}^c I_c + jX_{bd}^a I_a = 0 \quad (2.92)$$

Where:  $Z_{bd}$  - is the total impedance of the loop between contact wire and catenary wire

$Z_{db}$  - is the total impedance of the loop between catenary wire contact wire

$I_b$  and  $I_d$  - is the current on the contact wire and catenary wire respectively,

$I_a$  and  $I_b$  - is the current on the rail  $a$  and rail  $b$  respectively,

Note: In the above formulas, the magnetic effect of the earth and resistance of the soil, is not considered since, the value is smaller when compared to the other values.

When considering the current on contact wire and catenary wire as a combined current:

$$I_0 = I_b + I_d \quad (2.93)$$

Where:  $I_0$  - is the total current on the contact and catenary wire,

Substituting the above equation in place of  $I_a$  and  $I_b$  in equation 2.92,

Then,

- The total current on contact wire is calculated as:

$$I_b = \frac{Z_{db}I_0 - jX_{bd}^c I_c - jX_{bd}^a I_a}{Z_{db} + Z_{bd}} \quad (2.94)$$

- The total current on catenary wire is calculated as:

$$I_d = \frac{Z_{bd}I_0 - jX_{bd}^c I_c - jX_{bd}^a I_a}{Z_{bd} + Z_{db}} \quad (2.95)$$

Since, the mutual reactance of between the contact and catenary wire caused by the current in rails, rail  $a$  and rail  $c$ , is small due to relatively large distance between rails and overhead lines, then the value of  $x_{bd}^a$  and  $x_{bd}^c$  is approximately zero. Then the above equations, 2.94 and 2.95, can be approximately written as:

$$I_b = \frac{Z_{db}}{Z_{db} + Z_{bd}} I \quad (2.96)$$

$$I_d = \frac{Z_{bd}}{Z_{db} + Z_{bd}} I \quad (2.97)$$

As previously discussed,

- the impedance between total impedance of the loop between contact wire and catenary wire is

$$Z_{bd} = Z_b + jm \ln \frac{d_{bd}}{R_b} \quad (2.98)$$

- the impedance between total impedance of the loop between catenary wire and contact wire is

$$Z_{db} = Z_d + jm \ln \frac{d_{db}}{R_d} \quad (2.99)$$

## 2.7.2 Traction and Equivalent Impedance of OCS

When a current from the traction substations flows to the overhead contact system to feed a locomotive moving along the tracks; there will be some value of voltage drop in the network due to the resultant or equivalent impedance of the network, as shown in the figure 2.26. The resultant impedance which creates, the total voltage drop, is called the traction impedance [2] [6] [12].

### 2.7.2.1 Traction impedance of single track catenary OCS

To calculate the traction impedance of single track catenary OCS; the voltage drops on the loop between the rail  $r_1$  and contact wire  $c$  is need to be calculated.

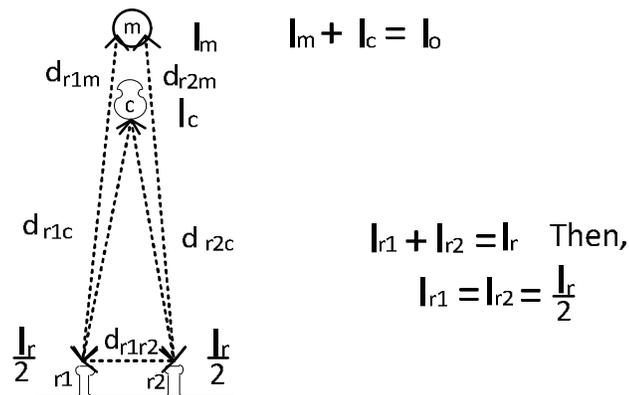


Figure 2.30 Single track catenary type OCS conductor arrangements

Then, using equation 2.92, and the above diagram, the voltage drop on the loop between rail  $r_1$  and contact wire  $c$

$$\Delta V_{cr_1} = Z_{cr_1} I_c + Z_{r_1c} \frac{I_r}{2} + jX_{cr_1}^m I_m + jX_{r_1c}^{r_2} \frac{I_r}{2} \quad (2.100)$$

Then, the substituting the formula for  $I_c$  and  $I_m$  from equation 2.96 and 2.97 to equation 2.100,

$$\begin{aligned} \Delta V_{cr_1} &= Z_{cr_1} \frac{Z_{mc}}{Z_{mc} + Z_{cm}} I_0 + Z_{r_1c} \frac{I_r}{2} + jX_{cr_1}^m \frac{Z_{cm}}{Z_{mc} + Z_{cm}} I_0 + jX_{r_1c}^{r_2} \frac{I_r}{2} \\ \Delta V_{cr_1} &= \frac{Z_{cr_1} Z_{mc} + jX_{cr_1}^m Z_{cm}}{Z_{mc} + Z_{cm}} I_0 + \frac{Z_{r_1c} + jX_{r_1c}^{r_2}}{2} I_r \end{aligned} \quad (2.101)$$

The above equation can be re-written as:

$$\Delta V_{cr_1} = Z_0 I_0 + Z_r I_r \quad (2.102)$$

Where:

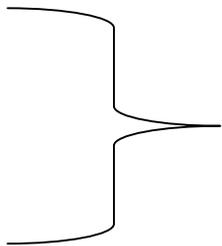
$Z_0$  -is the equivalent impedance of the combined contact and catenary wire.

$Z_r$  -is the equivalent impedance of the both rails.

$$Z_0 = \frac{Z_{cr_1} Z_{mc} + jX_{cr_1}^m Z_{cm}}{Z_{mc} + Z_{cm}} \quad (2.103)$$

$$Z_r = 0.5(Z_{r_1c} + jX_{r_1c}^{r_2}) \quad (2.104)$$

It is assumed that, the total current on the combined overhead lines flows to the combined rails,  $I_0 = I_r = I_{traction}$ . Then, the total equivalent impedance i.e. the traction impedance of a single track catenary OCS will be:

$$\begin{aligned} I_0 &= I_r = I_{traction} \\ \Delta V_{cr_1} &= (Z_0 + Z_r) I_{traction} \\ \Delta V_{cr_1} &= Z_{eq} I_{traction} \\ Z_{eq} &= Z_0 + Z_r \end{aligned} \quad (2.105)$$


Note: In the above equation, it is assumed that, the current flowing in the overhead contact line directly return to the substation through the two rails, without current lose as in side the earth or soil.

### 2.7.2.2 Traction impedance of double track catenary OCS

To calculate the traction impedance of double track catenary OCS; the voltage drops on the loop between the rail  $r_1$  and contact wire  $c_1$  is need to be calculated.

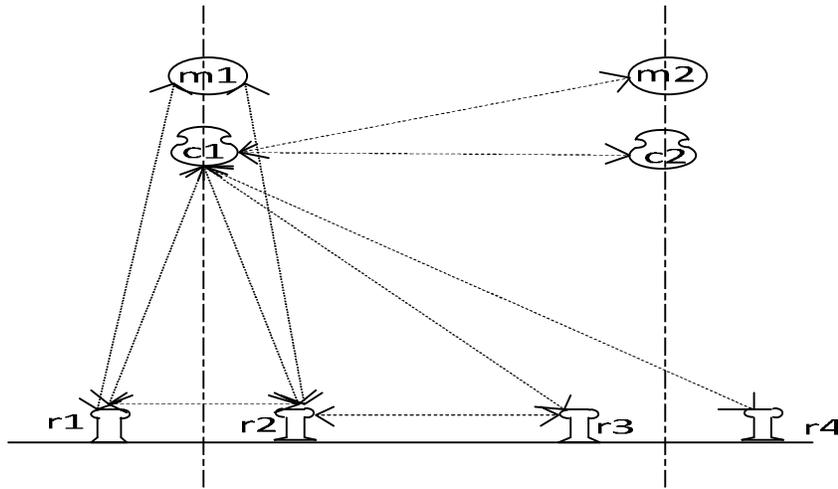


Figure 2.31 Double track catenary type OCS conductor arrangements

Analogously, like single track OCS, the traction impedance for double track OCS, is calculated

by assuming,  $I_1 = I_2 = I_3 = I_4 = \frac{I_r}{4}$

Then, using equation 2.91, and figure 2.31, the voltage drop on the loop between rail  $r_1$  and contact wire  $c_1$ ,

$$\Delta V_{c_1 r_1} = Z_{c_1 r_1} I_{c_1} + jX_{c_1 r_1}^{c_2} I_{c_2} + jX_{c_1 r_1}^{m_1} I_{m_1} + jX_{c_1 r_1}^{m_2} I_{m_2} + Z_{c_1 r_1} \frac{I_r}{4} + jX_{r_1 c_1}^{r_2} \frac{I_r}{4} + jX_{r_1 c_1}^{r_3} \frac{I_r}{4} + jX_{r_1 c_1}^{r_4} \frac{I_r}{4} \quad (2.106)$$

Then, the substituting the formula for  $I_c$  and  $I_m$  from equation 2.96 and 2.97 to equation 2.106,

$$\Delta V_{c_1 r_1} = \frac{Z_{c_1 r_1} Z_{mc} + jX_{c_1 r_1}^{m_1} Z_{cm}}{Z_{mc} + Z_{cm}} I_{0_1} + \frac{jX_{c_1 r_1}^{c_2} Z_{mc} + jX_{c_1 r_1}^{m_2} Z_{cm}}{Z_{mc} + Z_{cm}} I_{0_2} + \frac{Z_{r_1 c_1} + jX_{r_1 c_1}^{r_2} + jX_{r_1 c_1}^{r_3} + jX_{r_1 c_1}^{r_4}}{4} I_r \quad (2.107)$$

Where:  $I_{O_1}$  -is the total current on combined contact and catenary wire of the first track OCS.

$I_{O_2}$  -is the total current on combined contact and catenary wire of the second track OCS.

$I_r$  -is the total current on the parallel connected rails of both tracks

The above equation can be re-written as:

$$\Delta V_{c_1r_1} = Z_{O_1} I_{O_1} + Z_{O_1}^{O_2} I_{O_2} + Z_r I_r, \quad (2.108)$$

Where:

$Z_{O_1}$  is the equivalent impedance of the combined contact and catenary wire of first track OCS

$Z_{O_1}^{O_2}$  is the mutual impedance between the first track and second track combined overhead lines

Then,

$$Z_{O_1} = \frac{Z_{c_1r_1} Z_{mc} + jX_{c_1r_1}^{m_1} Z_{cm}}{Z_{mc} + Z_{cm}} \quad (2.109)$$

$$Z_{O_1}^{O_2} = \frac{jX_{c_1r_1}^{c_2} Z_{mc} + jX_{c_1r_1}^{m_2} Z_{cm}}{Z_{mc} + Z_{cm}} \quad (2.110)$$

$$Z_r = 0.25 \left( Z_{r_1c_1} + jX_{r_1c_1}^{r_2} + jX_{r_1c_1}^{r_3} + jX_{r_1c_1}^{r_4} \right) \quad (2.111)$$

Since double track catenary wire and contact wire are parallel connected, the following relation exists:

$$I_{O_1} = I_{O_2} = \frac{I_0}{2} \quad (2.112)$$

Then equation 2.108 can be re-written as:

$$\Delta V_{c_1r_1} = Z_{O_1} \frac{I_0}{2} + Z_{O_1}^{O_2} \frac{I_0}{2} + Z_r I_r \quad (2.113)$$

$$\Delta V_{c_1r_1} = \left( \frac{Z_{O_1} + Z_{O_1}^{O_2}}{2} \right) I_0 + Z_r I_r \quad (2.114)$$

It is assumed that, the total current on the combined overhead lines flows to the combined rails,

$$I_0 = I_r = I_{traction}$$

Then, the total equivalent impedance i.e. the traction impedance of double track catenary OCS will be:

$$\Delta V_{cr_1} = \left( \frac{Z_{0_1} + Z_{0_1}^{0_2}}{2} + Z_r \right) I_{traction} = Z_{eq} I_{traction} \quad (2.115)$$

$$Z_{eq} = \frac{Z_{0_1} + Z_{0_1}^{0_2}}{2} + Z_r \quad (2.116)$$

Table 2.3 Summary of OCS traction impedance modeling and calculation ( $\Omega/km$ )

<b>Conductor self impedance</b>	$Z_c = R' + j0.5\omega \cdot 10^{-3}$
	$Z_m = R' + j0.5\omega \cdot 10^{-3}$
	$Z_{r_1} = R' + \left( \frac{\pi}{4} \right) \cdot \mu_0 \cdot f \cdot 10^{-3} + j0.5\omega \cdot 10^{-4}$
	$Z_{r_2} = R' + \left( \frac{\pi}{4} \right) \cdot \mu_0 \cdot f \cdot 10^{-3} + j0.5\omega \cdot 10^{-4}$
<b>Mutual impedance</b>	$x_{cr_1}^m = 2\omega \cdot 10^{-4} \ln \frac{d_{mr_1}}{d_{mc}}$
	$x_{r_1c}^{r_2} = 2\omega \cdot 10^{-4} \ln \frac{d_{r_2c}}{d_{mr_1}}$
	$Z_{cr_1} = Z_c + j2\omega \cdot 10^{-4} \ln \frac{d_{cr_1}}{R_c}$

<b>Loop impedance</b>	$Z_{r_1c} = Z_{r_1} + j2\omega \cdot 10^{-4} \ln \frac{d_{cr_1}}{R_{r_1}}$
	$Z_{cm} = Z_c + j2\omega \cdot 10^{-4} \ln \frac{d_{cm}}{R_c}$
	$Z_{mc} = Z_m + j2\omega \cdot 10^{-4} \ln \frac{d_{cm}}{R_c}$
<b>Combined impedance</b>	$Z_o = \frac{Z_{cr_1} Z_{mc} + jx_{cr_1}^m Z_{cm}}{Z_{mc} + Z_{cm}},$
	$Z_r = 0.5(Z_{r_1c} + jx_{r_1c}^{r_2})$
<b>Equivalent or traction impedance</b>	$Z_{eq} = Z_o + Z_r,$

After traction impedance is calculated after current distribution and capability are known, voltage drop, power loss, short circuit condition and protection system on OCS system is determined and safety and electromagnetic emissions issue for OCS system is fully addressed. Therefore all the above remaining tasks must be addressed by future work.

## Chapter Three

### 3. Load on OCS and Data analysis at Indode Station

#### 3.1 Meteorological Factor to be considered for OCS Design

Meteorological factors are one of the major factors that affect design, construction and operation of OCS.

**Major meteorological factors:** The major meteorological factors that affect OCS during operation are: temperature and its changes, wind, ice, dust, suns radiation and corrosive agents. OCS should withstand such factors throughout its lifetime. The major parameters used when designing OCS are wind speed and air temperature near the area where OCS is designed to operate. However, such parameters have a varying nature through the day, month and years. Hence, to account this varying nature of these parameters and come up with a value that reflect the meteorological condition of the area, statistical analysis is used on the data recorded. For temperature more than 10 years return data is required. For wind data is update every 15 years and total return period of 50 years is required for OCS design. The maximum reference speed is recorded at 10m for 10 mints. The data is given with the annual probability of occurrence and the relationship of this annual probability with other the probability. From this probability the required number of future year data can be estimated [2] [14].

##### 3.1.1 Design Value or Wind Speed

OCS must withstand the maximum pressure or load acting on it. This happens when the wind speed riches a maximum value at any unknown specific future time. Hence to determine this value, equation 3.1 is used by considering the characteristics of the area and the record value of wind speed of that particular area [2] [7].

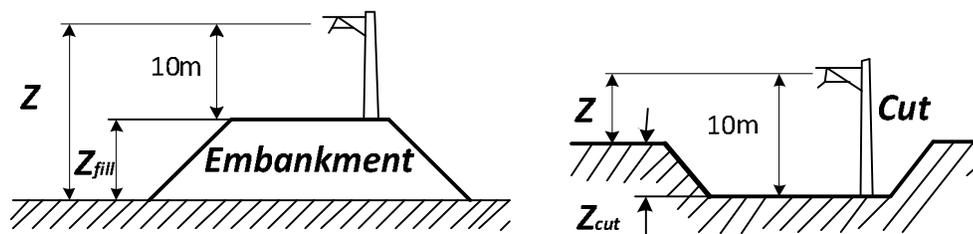


Figure 3.1 OCS in fill and cut section

Maximum design value of wind speed at height Z is calculated as:

$$v_z = v_{ref} \left( \frac{Z}{10} \right)^{z_0} \quad (3.1)$$

Where:

$v_{ref}$  - The reference maximum value of wind speed, 10m above earth surface measure for 10 mints that happed in the area in the past [2].

$z$  - Height above the earth where the air speed is measured

$z_0$  - Surface roughness parameter in which,  $Z_0=0.2$  for hilly, forest and park area

$z$  is determined by,

$$z = z_{pole} + z_{fill} \text{ For embankment (fill) section}$$

$$z = z_{pole} - z_{cut} \text{ For cut section}$$

Where:

$z_{pole}$  - Standard height of the pole of OCS- 10 meter

$z_{Fill}$  and  $z_{cut}$  - Embankment (fill) or cut height for the section

### 3.1.2 Design Value of Minimum and Maximum Air Temperature

The same as wind speed, OCS should withstand the two extreme value of temperature, Max.T and Min.T, for that particular area. Hence, the design maximum and minimum air temperature values are the extreme minimum and maximum temperature for that area. This is because, maximum T determines the maximum allowed sag and minimum T determines the maximum allowed tension on the conductor.

Extreme minimum air temperature is determined by:

$$t_{min} = t_{average} - \Delta t - 6 \quad (3.2)$$

Where:

$T_{\text{average}}$  - the average temperature of the coldest month on that area over a long time

$\Delta T$ - Change of temperature during the coldest day in the past years for that particular area

The extreme maximum air temperature is determined by considering the absolute extreme temperature that exists in the area in the past plus the temperature increment on the conductor because of sun's radiation.

$$t_{\text{max}} = t_{\text{absolute}} + t_{\text{radiation}} \quad (3.3)$$

Where:

$t_{\text{absolute}}$  - The absolute maximum air temperature for that area

$t_{\text{radiation}}$  -The conductor's temperature because of sun's radiation

$$t_{\text{radiation}} = 0.0162\phi_{\text{max}} \quad (3.4)$$

Where  $\phi_{\text{max}}$ - maximum sun's radiation energy in that area in Watt/m<sup>2</sup>

### 3.2 Loads Acting on the OCS

Loads acting on OCS can be divided in to three different type based on the origin of the load as shown below.

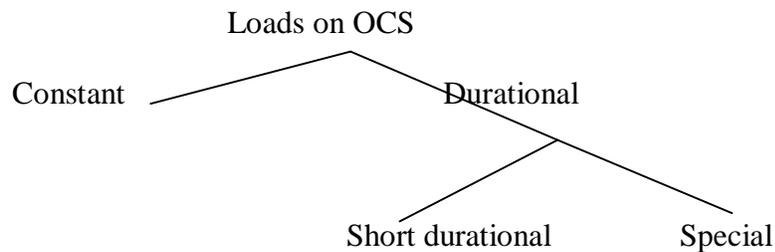


Figure 3.2 Types of loads on OCS

Constant Loads acting on OCS are loads due to:

- weights of wires and structures
- the normal tension on the wires and structures (along the wire or structure)
- Horizontal tension due to change of direction of wires or structure

Short durational Loads on OCS are loads due to:

- Wind
- Ice (at extreme low temperature-not a case in Ethiopia)

Special Loads on OCS are loads due to:

- Wire breakage
- Pole breakage
- Seismic activity
- Etc...

During designing OCS; the maximum value or a combination of maximum value of each types of load acting on OCS should be lower than the load carrying capacity or limit stress value of OCS structure or element, to ensure OCS operates normally.

In addition to their origin, loads acting on OCS can be classified based on their direction, as horizontal and vertical loads, as shown below.

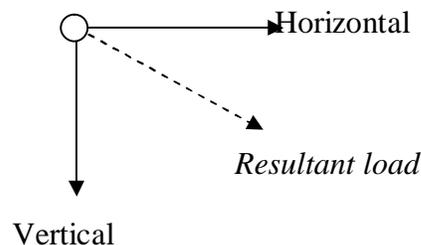


Figure 3.3 Resultant loads on appoint on OCS

### 3.2.1 Vertical Loads

Vertical loads are loads which act vertically downward on the OCS pole. This load is due to weight of wires (contact wire, messenger wires and additive wire), weight of OCS structures (insulators and cantilever) and weight of ice deposited on the wires or structures. Because of the geographical location of the Indode station; vertical load due to ice deposition on the wires and structures is not included in the study.

### 3.2.1.1 Vertical Loads Due to Wires

Weight of a wire is usually treated as uniformly distributed along the wire and it is calculated as:

$$W \cong 9.81.A.\rho.\alpha.10^{-6} \quad (3.5)$$

Where:

$w$  - weight of the wire per unit length, N/m

$A$  - Cross sectional area of the wire, in  $\text{mm}^2$

$\rho$  - Density of the wire,  $\text{kg/m}^3$

$\alpha$  - Coefficient considering the wire manufacturing (for mono-stranded wire  $\alpha=1$ ; for multi-stranded wire  $\alpha=1.025$ )

Hence, the total weights of all wires (contact wires, messenger wire, and additive wires) of an OCS:

$$W_{wires} = W_m + n_c (W_c + 0.1) \quad (3.6)$$

Where:

$w_m$  and  $w_c$  - Weight of the contact wire and messenger wire per a unit length, N/m

$n_c$  - The number of contact wires

0.1 - Weight of approximate value of additive wires per a unit length

### 3.2.1.2 Vertical Loads Due to Structures

This is the total load, due to weight of insulators and cantilever

$$W_{structures} = W_{insulator} + W_{cantilever} \quad (3.7)$$

Where:

$W_{insulator}$  - The total weight of the insulators on the OCS in N

$W_{cantilever}$  - Weight of the cantilever in N

$W_{Structures}$  - The total weight structures on the suspension mast (Pole) in N

### 3.2.2 Horizontal Loads

Horizontal loads are loads which act horizontal on the OCS structure. This load is due force of wind blow and horizontal tension due to change of direction of wires.

#### 3.2.2.1 Horizontal Loads Due to Wind Blow on the Wire

When wind blows in the horizontal direction with respect to OCS wires, it exerts horizontal force on the wire [2] [13]. To calculate this force or load, the design value of wind speed is used as discussed previously.

Wind force exerted per a unit length of wire is given as (N/m) [2]

$$F'_w = q_z G_c C_c d \quad (3.8)$$

Where

$$q_z = \frac{\rho}{2} G_q G_t v_z^2 \text{ and } Q = 1.225 \left( \frac{288}{t} \right) \frac{e^{-1.2 \times 10^{-4} \times \text{altitude}}}{e^{-1.2 \times 10^{-4} \times \text{altitude}}} \quad (3.9)$$

Where:

$q_z$  – The dynamic wind pressure (N/m)

$G_c$ - Structural response factor for the conductor related to wind

$C_c$ - Aerodynamic drag factor of the conductor

$G_q$ - Gust response factor

$d$ - Diameter of the conductor (m)

$G_t$ - Terrain factor taking in to account the protection of the line

$Q$ - Air density ( $\text{kg/m}^3$ )

$v_z$  - design value of wind speed (m/s)

### 3.2.2.2 Horizontal Loads Due to Wire Bend or Horizontal Curves

For a bend (change of direction), if the total bend distance ( $h$ ) is known, the horizontal force on OCS pole is determined by

$$F_s = \frac{Th}{l_2} \quad (3.10)$$

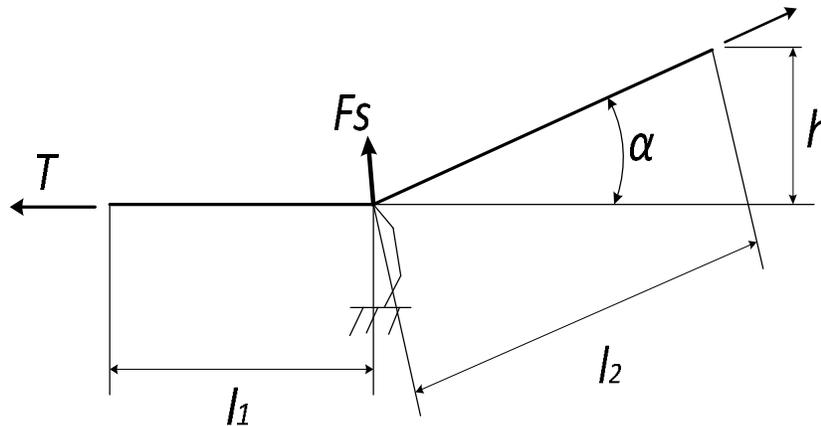


Figure 3.4 Horizontal forces on mast due to bend

Where:

$F_s$  - Force on the OCS structure (pole) due to bend

$h$  -the total bending width

$l_2$  -the bend span length

For a curve, if the curve radius( $R$ ) is known, the horizontal force on OCS pole, located in between two poles inside the curve, is determined by:

$$F_s = \frac{T(l_1 + l_2)}{2R} \quad (3.11)$$

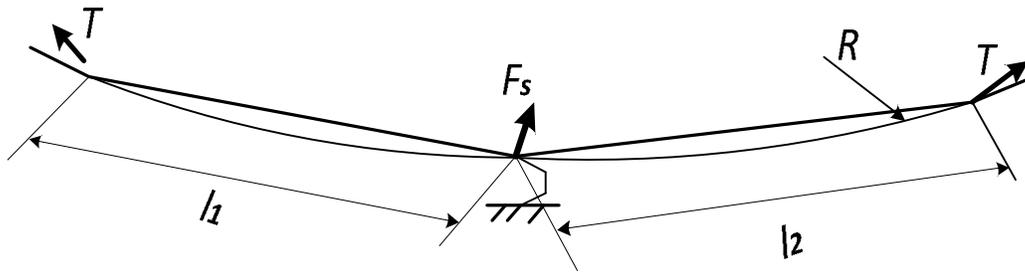


Figure 3.5 Horizontal forces on mast on curve due to masts on both sides

Where:

$F_s$  - Force on the OCS structure (pole) due to bend

$R$  -The radius of curvature

$l_1$  and  $l_2$  - span lengths

### 3.2.3 Resultant Loads on OCS Mast

The total loads acting on a single OCS suspension mast is calculated by considering vertical and horizontal load shared by adjacent masts.

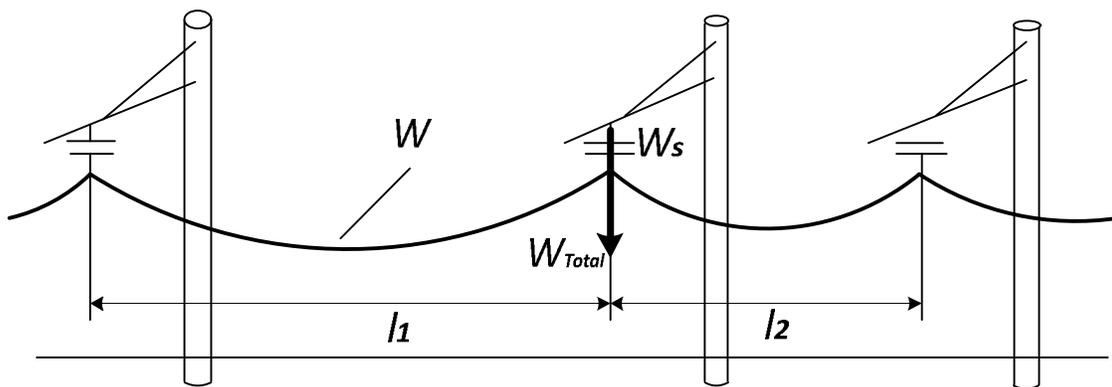


Figure 3.6 Vertical loads on OCS mast

Total vertical weight on the mast is determined by:

$$W_{total} = W_{wires} \left( \frac{l_1 + l_2}{2} \right) + W_{structures} \quad (3.11)$$

Where:

$W_{wires}$  -The total vertical loads/weight on a single OCS suspension mast in N

$W_{structures}$  -Weight of the structures on the OCS suspension mast in N

$W_{wires}$  -Weight per a unit length of all wires on the OCS suspension mast in N/m

$l_1$  and  $l_2$  - the span length between adjacent masts in m

Total Horizontal loads on the mast are determined by:

$$F_{total} = F'_w \left( \frac{l_1 + l_2}{2} \right) + F_s \quad (3.12)$$

Where:

$F_{Total}$  - The total horizontal loads on a single OCS suspension mast in N

$F_s$  - Force on the OCS suspension mast due to curve or bend in N

$f_w$  - Force per a unit length, due to wind force on OCS wires in N/m

$l_1$  and  $l_2$  - the span length between adjacent masts in m

The resultant load on a single OCS suspension mast is the vector sum of horizontal and vertical loads.

$$\bar{G} = \bar{F}_{total} + \bar{W}_{total} \quad (3.13)$$

### 3.3 Methods of Analyzing Loads Acting on OCS

Generally there are two approaches that are used to analysis load acting on OCS. The two approaches are used on for different scenarios during designing OCS.

These are:

- Maximum allowable stress calculation
- Limiting state calculation

### 3.3.1 Maximum Allowable Stress Value Method

For this calculation, all the external loads that are directly acting on the single element of OCS are accounted, by considering their maximum value in the past 10 years. When all external loads (Constant, short durational or specials) during their maximum value are directly acting on OCS wires, cantilever and structures; the stress on that particular OCS element should not exceed its maximum allowed value considering safety factors. Chinas and Europeans use different formula for this computation. Here both of them are presented but this thesis use Europeans approach since it observes different factors separately and assign appropriate constants for each factor according to the situation.

According to Chinas standard [14],

Stress  $\sigma$  on any element on OCS is determined by:

$$\sigma = \frac{T}{A} \quad (3.14)$$

Where

$T$  - Force acting on the element

$A$  - Cross sectional area of the element

The maximum allowed values of stress on a particular OCS element are calculated by multiplying and dividing coefficients on the limit stress value i.e.

$$\sigma_{Max} = \frac{\sigma_{limit}}{k_3} k \quad (3.15)$$

Where

$\sigma_{limit}$  - The limit stress value for that particular object elasticity limit

$k$  - Correction coefficient to account the possible change of  $\sigma_{limit}$  during operation

$k_3$  - Strength safety coefficient

Hence, to ensure the safe operation of OCS, the actual stress  $\sigma_{actual}$  on any of OCS element of, should not exceed the above maximum allowed stress. i.e.

$$\sigma_{actual} \leq \sigma_{Max}$$

This calculation is convenient when checking stress on OCS wire, cantilever and selecting span length of OCS.

For contact wires and messenger wires, instead of maximum stress value check, maximum allowed tension on the wire could be used i.e.

$$T_{Max} = \sigma_{Max} \cdot A = \frac{\sigma_{limit}}{k_3} k \cdot A \quad (3.16)$$

Note: for contact and messenger wire the Chinese standard use  $k = 1$ ; for safety strength coefficient  $k_3$  not less than 2 for and additive wires (hangers, and other wires on OCS)  $k_3$  not less than 2.5 [14].

The above formula does not account the possible cross sectional area decrement of contact wire during operation due to wearing of contact wire by the pantograph. In the Chinese standard, this is accounted by considering the maximum allowed wear on the contact wire to be 25% of the total cross section area of contact wire.

$$T_{Maxcontactwire} = \frac{\sigma_{limit}}{2} \cdot A \cdot 0.75 \quad (3.17)$$

Since there is no wear on messenger wire, the formula for maximum tension of messenger wire is

$$T_{Maxcatenarywire} = \frac{\sigma_{limit}}{2} \cdot A \quad (3.18)$$

According to Europeans standard [2] [15],

The calculated grooved contact wire working tensile stress shall not exceed 65 % of the minimum tensile stress of the grooved contact wire. The minimum tensile stress of the grooved contact wire shall be multiplied by the product of these factors to get the maximum permissible working tensile load [15].

$$\sigma_{per} = \sigma_{min} \times 0.65 \times k_{temp} \times k_{wear} \times k_{load} \times k_{eff} \times k_{clamp} \times k_{jo\ int} \quad (3.19)$$

Whereas the maximum allowed stress value on the catenary wire in which wear is not concerned is given by [15]

$$\sigma_{per} = \sigma_{min} \times 0.65 \times k_{temp} \times k_{wind} \times k_{eff} \times k_{clamp} \times k_{load} \quad (3.20)$$

Where

$\sigma_{min}$  -is the minimum breaking stress of the contact line

$K_{temp}$  -factor which relate maximum working temperature and permissible working stress

$K_{wear}$  -permitted maximum wear

$K_{load}$  -factor which express the effect of wind

$K_{eff}$  -tensioning equipment efficiency

$K_{clamp}$  -Tensioning clamp characteristics

$K_{joint}$  -factor which describe reduction of tension due to joint

The maximum working (permissible) tensile force for both contact and catenary wire becomes

$$T_{per} = \sigma_{per} \times A \quad (3.21)$$

### 3.3.2 Limiting State Calculation

Unlike the allowable maximum stress calculation, which accounts the individual elements strength; limiting state calculation accounts the total OCS structure, such as pole, strength and factors that affect the structure so that above a particular total loads on the elements of OCS should be limited in order to OCS to operate safely.

The limiting state calculation could be used to accounted one, two or three limiting states. The first limiting state accounts the carrying capacity of OCS structure, i.e. the strength, durability and stability. The second limiting state accounts the possible deformation (displacement and vibration) of the structure while the third state accounts the liability of the structure due to cracks (especially for structures made from concrete)

- When calculating based on the first limiting state, the structure is checked for [7]

$$\sum N_{Max} \leq \varphi_{Min}$$

Where:

$\sum N_{Max}$  - The sum of all maximum loads acting on the structures

$\varphi_{Min}$  - The minimum load carrying capacity of the structure

➤ When calculating based on the second state, the structure is checked for

$$\Delta_{Max} \leq \Delta_{Min}$$

Where:

$\Delta_{Max}$  - Maximum displacement of the OCS structure such as wire, cantilever, etc

$\Delta_{Min}$  - Allowed displacement of the OCS structure such as wire, cantilever, etc

For metallic structure, most of the times only the first limiting state is considered, for some case the second limiting state. However, for concrete made structure, in addition to the other states, the third limiting state (fracture strength) is considered.

The major characteristics of this calculation is that, instead of using single strength coefficient (as the first method), it use various strength coefficients based on the adopted standard [7].

- 1 Strength coefficient considering the material,  $k$ , characterize the possible decrees in the strength of material  $k \geq 1$
- 2 Strength coefficient considering acting loads,  $n_i$ , characterize the possible increment in the loads during operation  $n_i \geq 1$
- 3 Coefficient of condition of operation,  $m$ , accounts the conditions of the working environment of that structure  $m \leq 1$
- 4 Combined coefficients,  $n_c$ , accounts noncoincidence of maximum value for all simultaneously acting loads  $n_c \leq 1$

Note: All the above coefficient values are statistical by nature are found on standards.

When determining the sum of maximum acting load and the allowed carrying capacity of structures; the above coefficients are used in the following ways

$$\sum N_{\max} = n_c \sum (n_c \cdot N_{\text{standard}}) \text{ and } \varphi_{\min} = \frac{m \varphi_{\text{standard}}}{k} \quad (3.22)$$

And the structure should be checked for

$$\sum N_{\max} \leq \varphi_{\min}$$

Where:

$N_{\text{standard}_i}$  - The standard load of the OCS element (found in the standard of manufacturer data)

$\varphi_{\text{standard}}$  - Allowed carrying capacity of the structure (found in the standard of manufacturer data)

### 3.4 Extreme Weather States

To performer load analysis on OCS based on any of the above two calculation methods, the extreme weather conditions should be taken in to account. However, at extreme weather all meteorological factors are not at their extreme value. For example, it known that, maximum and minimum air temperature could not exist at some place simultaneously. The same is true for wind and air temperature, they do not exist at their extreme value simultaneously. Hence, during designing OCS, meteorological factors are accounted by considering a weather state in which one extreme weather condition exists.

Through long year experience; different countries list the following weather state as adverse weather state in which one meteorological factor is at its extreme value and are used as scenarios during OCS designing.

- $S_{\text{tmin}}$ - Weather state when the air temperature is at its extreme low value (No wind)
- $S_{\text{tmax}}$ - Weather state when the air temperature is at its extreme high value (No wind)
- $S_{\text{storm}}$ - Weather state when there is ice deposition on wires and structures (not a scenario that should be studied in the case of Ethiopia due to geographical location)

- $S_{wind}$ - Weather state when the wind speed is at its extreme high value ( Chinese standard states that at maximum wind, temperature is considered to be 10°C)

### 3.5 Data to Design OCS for Indode Station

All the basic data used for the design listed below in the following tables are taken from Ethiopian Railways Corporation, Addis Ababa~Djibouti Railway, Sebeta~Adama~Mieso Section [5].

#### 3.5.1 Basic Design Parameters

Table 3.1 General information of Indode station from ERC [5]

No.	Type of data	Value	
1	Station layout plan	Given	
2	Meteorological data	Maximum reference wind speed	$v_{ref} = 25\text{m/s}$
		Minimum temperature in °C	0
		Maximum temperature in °C	+40
3	Embankment height, m	0.5	
4	Comprehensive soil strength , Mpa	0.20	
5	Characteristics of the region where station located	Hilly with trees and park	
6	Maximum speed of locomotive inside the station	On main tracks	120 km/hr
		On side tracks	50 km/hr
7	Traction power supply system	AC-25kV, 50Hz	
8	Type of pantograph	----	
9	Mark, cross section and quantity of conductors	Overhead wires on the main tracks	CTSH-120 + JTMH-95
		Overhead wires on side/station tracks	CTSH-85 + JTMH-70
		Traction in-feed line conductor	LBGLJ-185/25
		Return conductors	LBGLJ-185/25
		Arial earthing conductors	LBGU-70/10

### 3.5.2 Meteorological Conditions for Design

Table 3.2 Meteorological data of the root Sebeta to Adama [5]

Starting and ending points Item	Sebeta-Adama
Max. calculation temperature (°C )	60
Max temperature (°C)	40
Min. temperature (°C)	0
Maximum reference wind velocity (m/s)	25
Structural designed wind velocity (m/s)	30
Air temperature (°C) at max. wind velocity	10
Air temperature (°C) when the steady arm is at normal position	30
Number (N) of thunderstorm days	20<N<40

### 3.5.3 Physical and Mechanical Characteristics of Conductors used for OCS

Table 3.3 The mechanical strength of conductors [5]

TYPE		Model	Tension (kN)
Contact wire	Mainline	CTSH-120 (high strength)	20
	Station track	CTSH-85	9
Messenger wire	Main line	JTMH-95	15
	Station track	JTMH-70	15
	Feeder or line feeder	LBGLJ-185/25	12
Additive wire	Return wire	LBGLJ-185/25	12
	Aerial earthing wire	LBGU-70/10	6.5

Table 3.4 Specification of contact wire [18]

Style of contact line(no specification)	Resistivity (20°C),no more than $\Omega$ mm <sup>2</sup> /m	Electrical conductivity (20°C),no less than %IACS
CT	0.01777	97
CTA, CTAH	0.01777	97
CTM	0.02240	77
CTS	0.02395	72
CTMH	0.02573	67
CTMT	0.02653	65

Table 3.5 Specification of catenary wire [19]

Material number	W(Cu)	W(Mg)	other impurities no more than	Single wire resistivity (20°C)no more than $\Omega$ mm <sup>2</sup> /m	Single wire electrical conductivity(20°C)no less than %IACS
T	99.95	-	0.05	0.01777	97
TM	over-measure	0.1-0.3	0.30	0.02240	77
TMH	over-measure	0.4-0.7	0.30	0.02778	62
TMT	over-measure	0.1-0.3	0.30	0.02240	77

### 3.5.4 Classification of Polluted Area

According to the specific conditions of the line, it is determined that the Overhead Contact Line System (OCS) of the whole line shall be designed as per the conditions of heavily polluted area and the insulator leakage distance is not less than 1200mm.

### 3.5.5 Height above Sea Level

The maximum Height above Sea Level (ASL) of the whole line is 2350m and insulation design is subject to adjustment according to the ASL.

### 3.5.6 Suspension Type OCS

All autotensioned simple messenger suspension is used for the line and the structural height is 1.4m.

## Chapter Four

### 4. Design Result analysis and Plan Preparation of OCS for Indode Station

Design results are obtained from modeling and design data analysis by taking appropriate data and from Ethiopia Railway Corporation Sebeta – Adama - Mieso section [5] and referring different standards such as Chinas Railway Standard TB1 0009-2005 [14], European Standard EN 1991-1-4 [13] and EN 50119 [15] accordingly to our situation of Indode station.

#### 4.1 Temperature

The extreme maximum and minimum temperature are given by

$$t_{\max, \text{calculated}} = t_{\text{absolute}} + t_{\text{radation}} \quad \text{and} \quad t_{\min} = t_{\text{averagemin}} - \Delta t - 6$$

But from ERC document [5] maximum and minimum temperature are given 0°C and 40°C respectively. From Chinas Railway Standard [14]

$$t_{\max, \text{calculated}} = 1.5t_{\max} \rightarrow t_{\max, \text{calculated}} = 1.5 \times 40^\circ\text{C}$$

Hence the temperature range considered is 0°C to 60°C.

#### 4.2 Wind Speed

The maximum wind speed at height Z is given by the formula

$$v_z = v_{\text{ref}} \left( \frac{z}{10} \right)^{z_0}$$

Where:

$v_{\text{ref}}$  - is the maximum reference wind speed at a height of 10m which is 25 m/s as given in ERC document [5]

$Z_0$ - surface roughness parameter depends on surrounding area

Table 4.1 The roughness parameter of a terrain are given from European standard as: [4],

Environment type	Town center	Suburban district and forest area	Open terrain with obstacle	Flat land and costal area
Z <sub>0</sub>	0.28	0.20	0.16	0.12

Since the Indode root is hilly and trees with parks z<sub>0</sub>=0.2 and height Z is given by

$$z = z_{pole} + z_{fill}$$

But Z<sub>pole</sub>=10m (taking standard pole height) and Z<sub>fill</sub>=0.5m taken from [5]. Therefore

$$v_z = v_{ref} \left( \frac{z}{10} \right)^{z_0} = 25 \left( \frac{10.5}{10} \right)^{0.2} = 25.25 \text{ m/s}$$

Is the maximum wind speed of Indode station used to calculate wind load.

### 4.3 Wind Load per Unit Length (F'<sub>w</sub>)

The wind load per unit length on OCS conductor is given by

$$F'_w = q_z G_c C_c d \quad \text{and} \quad q_z = \frac{Q}{2} G_q G_t v_z^2$$

Where:

q<sub>z</sub> – The dynamic wind pressure (N/m)

G<sub>c</sub>- Structural response factor for the conductor related to wind

C<sub>c</sub>- Aerodynamic drag factor of the conductor

G<sub>q</sub>- Gust response factor

d- Diameter of the conductor (m)

G<sub>t</sub>- Terrain factor taking in to account the protection of the line

Q- Air density (kg/m<sup>3</sup>)

$v_z$ - design value of maximum wind speed (m/s)

$$Q = 1.225 \left( \frac{288}{t} \right) e^{(-1.2 \times 10^{-4} h)} / e^{(-1.2 \times 10^{-4} \times 600)}$$

Where:

T- Absolute temperature at high wind (°K)

H- Is the altitude of the area (m)

Table 4.2 The Coefficients value of wind load per unit length for Indode station [15]

$G_q$	$G_t$	$G_c$	$C_c$	T(°K)	H(m)	Q(kg/m <sup>3</sup> )
2.05	0.8	0.75	1	280	2350	1.01051

The dynamic wind load per unit length is simplified to

$$F'_w = 0.621 v_z^2$$

Table 4.3 Calculated wind load per unit length on OCS conductors

Type of Conductor	Contact wire		Catenary wire	
	Main line	Station line	Main line	Station line
	CTAH 120	CTAH 85	JTMH 95	JTMH 70
	D=12.34m	10.80m	12.5m	10.5m
$F'_w$ (N/m)	5.107	4.276	4.949	4.157

#### 4.4 Permissible Tensile Force (Maximum Working Tensile Loads)

The permissible maximum working tensile stress of grooved contact line is given by [15],

$$\sigma_{per} = \sigma_{min} \times 0.65 \times k_{temp} \times k_{wear} \times k_{load} \times k_{eff} \times k_{clamp} \times k_{jo\ int}$$

Where:

$\sigma_{\min}$  -is the minimum breaking stress of the contact line

$K_{\text{temp}}$  -factor which relate maximum working temperature and permissible working stress

$K_{\text{wear}}$  -permitted maximum wear

$K_{\text{load}}$  -factor which express the effect of wind

$K_{\text{eff}}$  -tensioning equipment efficiency

$K_{\text{clamp}}$  -Tensioning clamp characteristics

$K_{\text{joint}}$  -factor which describe reduction of tension due to joint

Table 4.4 Appropriately selected coefficients for contact wire [15]

	$K_{\text{temp}}$	$k_{\text{wear}}$	$k_{\text{load}}$	$k_{\text{eff}}$	$k_{\text{clamp}}$	$k_{\text{joint}}$
Fully-compensated	0.9	0.8	1	0.95	1	0.95
Semi-compensated	0.9	0.8	0.95	0.95	1	0.95

The permissible working tensile stress of catenary wire is given by

$$\sigma_{\text{per}} = \sigma_{\min} \times 0.65 \times k_{\text{temp}} \times k_{\text{wind}} \times k_{\text{eff}} \times k_{\text{clamp}} \times k_{\text{load}}$$

Table 4.5 Appropriately selected coefficients for catenary wire [15]

	$K_{\text{temp}}$	$K_{\text{wind}}$	$K_{\text{eff}}$	$K_{\text{clamp}}$	$K_{\text{load}}$
Fully-compensated	0.95	1	0.95	1	0.8
Semi-compensated	0.95	0.95	0.95	1	0.8

The permissible tensile force ( $T_{\text{per}}$  or  $H_{\text{max}}$ ) becomes

$$T_{\text{per}} = \sigma_{\text{per}} A$$

Table 4.6 Calculated permissible tensile force

Type of Conductor	Contact line				Catenary wire			
	Main line		Station line		Main line		Station line	
	CTAH120		CTAH85		JTMH 95		JTMH 70	
	$\sigma_{\min}=360\text{Mpa}$		$\sigma_{\min}=375$		$\sigma_{\min}=587\text{Mpa}$		$\sigma_{\min}=587\text{Mpa}$	
	Fully-comp	Semi-comp	Fully-comp	Semi-comp	Fully-comp	Semi-comp	Fully-comp	Semi-comp
Tensile force (kN)	18.246	17.334	13.463	12.790	18.319	17.404	13.498	12.823

## 4.5 Maximum Span Length

Conductor displacement caused by wind is the decisive governing factor that determines overhead contact line longitudinal span length. As can be derived in the modeling part the maximum span length is given in section 2.4.1 equation 2.59 by

$$l_{\max} = 2 \sqrt{\frac{K}{F'_w} \left( b_{k \text{ limit}} + \sqrt{b_{k \text{ limit}}^2 - a^2} \right)}$$

Where:

K- is contact line tensile strength

$P_k$ -is the wind load per unit length (N/m)

$b_{k \text{ limit}}$ - the maximum working range of pantograph (m)

a- contact line stagger (m)

From chine's standard

$$b_{k \text{ limit}} = 450\text{mm} = 0.45\text{m} \text{ and } a = 250\text{mm} = 0.25\text{m}$$

For simple catenary system K is the sum of contact and catenary conductor tensile strength

Table 4.7 Calculated maximum span length for trolley type OCS for wind load

	Main line	Station line
H <sub>max</sub> (kN)	17.334	12.790
F'(N/m)	5.107	4.276
<i>l</i> <sub>max</sub> (m)	105.780	99.301

Table 4.8 Calculated maximum span length of simple catenary OCS for wind load

	Main line		Station line	
	Fully-comp	Semi-comp	Fully-comp	Semi-comp
K(kN)	36.565	34.737	26.961	25.613
F' <sub>w</sub> (N/m)	10.056		8.433	
<i>l</i> <sub>max</sub> (m)	109.486	106.714	102.663	100.122

The maximum span length of fully-compensated OCS for vertical clearance requirement is given in section 2.4.2 by equation 2.68:

$$l_{\max} = \sqrt{\frac{2(T + K)}{q_0 - q_i}}$$

Table 4.9 Maximum span length of fully-compensated OCS for vertical clearance

	Main line	Station line
T(kN)	18.246	13.463
K(kN)	18.319	13.498
q <sub>0</sub> -q <sub>i</sub> (N/m)	2.0954	1.4842
<i>l</i> <sub>max</sub> (m)	186.816	190.606

## 4.6 Critical Span Length

Critical span length is the span length in which the governing state can be determined. As derived in the modeling part is given in section 2.5.3 equation 2.74 by

$$l_{cr} = H_{\max} \sqrt{\frac{24\alpha(t_{wind} - t_{\min})}{q_i^2 - g^2}} = H_{\max} \sqrt{\frac{24\alpha(t_{wind} - t_{\min})}{(F_w'^2 + g^2) - g^2}}$$

Where:

$H_{\max}$ - is the maximum tensile force on the contact wire (kN)

$\alpha$ - Thermal expansion of the contact wire (1/°C)

$q_i$ - resultant force of wind load and conductor weight per unit length (N/m)

$g$  -Weight per unit length of conductor

$t_{\min}$  -minimum temperature

$t_{wind}$  -the temperature when the wind speed is very high

From [5] and specification of conductor

Table 4.10 Thermal expansion coefficient and temperature data [2] [5]

$\alpha(1/^\circ\text{C})$	$t_{\min}$	$t_{wind}$
$1.7 \times 10^{-5}$	$0^\circ\text{C}$	$10^\circ\text{C}$

By substitute the appropriate values the critical span length becomes

Table 4.11 Calculated critical span length

	Main line	Station line
$F_w'(N/m)$	5.107	4.267
$H_{\max}(kN)$	18.246	13.463
$l_{cr}(m)$	228.209	201.534

We can conclude from this as the critical span length is greater than the maximum span length. The initial state that creates maximum tensile force on OCS conductor is the minimum temperature. Since the maximum span length is 65m, wind load has no effect to create maximum tensile force on OCS conductor.

## 4.7 Double track OCS traction impedance calculation result

Equivalent impedance of double track from Summary of OCS traction impedance modeling and calculation can be determined by first listing constants, known line parameters and space distribution of OCS conductor from each other.

Track gage is standard track gage=1435mm=1.435m and distance between track center line=5m.

Assume OCS is above the center line of the Track. The minimum and maximum contact line height is from the rail is 5.75m and 6.5m respectively [14]. From this value contact wire height is taken an average value of 5.9m. The distance between catenary and contact wire at the mast (system height) is 1.4m [5] and minimum dropper length is 0.5m [14]. From this the distance between contact and messenger line is taken an average value of 1m.

### 1. Conductor self impedance

a. Contact line CTAH 120,  $Z_c = R' + j0.5\omega \times 10^{-3} \Omega/km$

$$\rho = 0.01777 \Omega mm^2/m, \omega = 2\pi f = 2\pi \times 50Hz$$

$$R' = \frac{\rho}{A} = \frac{0.01777}{120} = 1.481 \times 10^{-4} \Omega/m = 0.1481 \Omega/km$$

$$Z_c = 0.1481 + j0.1571 \Omega/km$$

b. Messenger line JTMH 95  $Z_m = R' + j0.5\omega \times 10^{-3} \Omega/km$

$$\rho = 0.02778 \Omega mm^2/m$$

$$Z_c = 0.2924 + j0.1571 \Omega/km$$

c. Rails R50  $Z_{r_1} = Z_{r_2} = R' + \left(\frac{\pi}{4}\right) \cdot \mu_0 \cdot f \cdot 10^{-3} + j0.5\omega \times 10^{-4} \Omega/km$

$$R' = 0.0345 \Omega/km, \mu_0 = 4\pi \times 10^{-7} H/m = 4\pi \times 10^{-4} H/km$$

$$Z_{r_1} = Z_{r_2} = 0.03455 + j0.01571 \Omega/km$$

2. Mutual impedance  $X_{cr_1}^m = 2\omega \times 10^{-4} \ln \frac{d_{mr_1}}{d_{mc}}$ ,  $X_{r_1c}^{r_2} = 2\omega \times 10^{-4} \ln \frac{d_{r_2c}}{d_{mr_1}}$

$$d_{mr_1} = \sqrt{0.7175^2 + 6.9^2} = 6.937m, d_{mc} = 1m$$

$$d_{r_2c} = \sqrt{0.7175^2 + 5.9^2} = 5.943m$$

$$X_{r_1c}^m = 0.122 \Omega/km$$

$$X_{r_1c}^{r_2} = -0.00097 \Omega/km$$

3. Loop impedance

i.  $Z_{cr_1} = Z_c + j2\omega \times 10^{-4} \ln \frac{d_{cr_1}}{R_c}$

$$d_{cr_1} = 5.943m \text{ and equivalent radius of the rail } R_c$$

$$R_c = 0.0453m$$

$$Z_{cr_1} = 0.1481 + j0.4639 \Omega/km$$

ii.  $Z_{r_1c} = Z_{r_1} + j2\omega \times 10^{-4} \ln \frac{d_{cr_1}}{R_{r_1}}$

$$Z_{r_1c} = 0.03455 + j0.3221 \Omega/km$$

iii.  $Z_{cm} = Z_c + j2\omega \times 10^{-4} \ln \frac{d_{cm}}{R_c}$

$$Z_{cm} = 0.1481 + j0.3515 \Omega/km$$

iv.  $Z_{mc} = Z_m + j2\omega \times 10^{-4} \ln \frac{d_{cm}}{R_c}$

$$Z_{mc} = 0.2924 + j0.3515 \Omega/km$$

4. Combined impedance

$$I. Z_0 = \frac{Z_{cr_1} Z_{mc} + jX_{cr_1}^m Z_{cm}}{Z_{mc} + Z_{cm}}$$

Substituting each value from above we get

$$Z_0 = 0.0876 + j0.2467 \Omega/km$$

$$II. Z_r = 0.5(Z_{r_1c} + jX_{r_1c}^{r_2})$$

$$Z_r = 0.03455 + j0.1562 \Omega/km$$

5. Equivalent or Traction impedance

$$Z_{eq} = Z_0 + Z_r$$

$$Z_{eq} = 0.12215 + j0.4029 \Omega/km$$

Table 4.12 Summary of calculated traction impedance ( $\Omega/km$ )

<b>Conductor self impedance</b>	$Z_c = R' + j0.5\omega \cdot 10^{-3} = 0.1481 + j0.1571$
	$Z_m = R' + j0.5\omega \cdot 10^{-3} = 0.2924 + j0.1571$
	$Z_{r_1} = R' + \left(\frac{\pi}{4}\right) \cdot \mu_0 \cdot f \cdot 10^{-3} + j0.5\omega \cdot 10^{-4}$ $= 0.03455 + j0.01571$
	$Z_{r_2} = R' + \left(\frac{\pi}{4}\right) \cdot \mu_0 \cdot f \cdot 10^{-3} + j0.5\omega \cdot 10^{-4}$ $= 0.03455 + j0.01571$
<b>Mutual impedance</b>	$x_{cr_1}^m = 2\omega \cdot 10^{-4} \ln \frac{d_{mr_1}}{d_{mc}} = 0.122$
	$x_{r_1c}^{r_2} = 2\omega \cdot 10^{-4} \ln \frac{d_{r_2c}}{d_{mr_1}} = -0.0097$

<b>Loop impedance</b>	$Z_{cr_1} = Z_c + j2\omega \cdot 10^{-4} \ln \frac{d_{cr_1}}{R_c} = 0.1481 + j0.4639$
	$Z_{r_1c} = Z_{r_1} + j2\omega \cdot 10^{-4} \ln \frac{d_{cr_1}}{R_{r_1}} = 0.03455 + j0.3221$
	$Z_{cm} = Z_c + j2\omega \cdot 10^{-4} \ln \frac{d_{cm}}{R_c} = 0.1481 + j0.3515$
	$Z_{mc} = Z_m + j2\omega \cdot 10^{-4} \ln \frac{d_{cm}}{R_c} = 0.2924 + j0.3515$
<b>Combined impedance</b>	$Z_o = \frac{Z_{cr_1} Z_{mc} + jx_{cr_1}^m Z_{cm}}{Z_{mc} + Z_{cm}} = 0.0876 + j0.2464$
	$Z_r = 0.5 (Z_{r_1c} + jx_{r_1c}^{r_2}) = 0.03455 + j0.1562$
<b>Equivalent or traction impedance</b>	$Z_{eq} = Z_o + Z_r = 0.12215 + j0.4029$

## 4.8 OCS Layout Plan Preparation

The objective of planning task is to create plan document for a specific electrification project based on specified conditions and parameters. This document permits the installation and operation of overhead contact line system to a defined operational specification for a specific line [2]. In this thesis work OCS plane of Indode station (case study station) is prepared based on planning standard and rules which is presented below.

On station plan layout the following futures are depicted [2] [7].

- Center line or axis of existing track
- The station buildings
- Overpass bridges and Culverts
- Crossings and other simple surrounding structures...

For the case of electrification, Station layout plan are usually has 1:1000 scale. The station layout center is taken at the station building axis, and every 100 meters, pegs is placed in the station layout plan, taking positive to the right direction and negative in the left direction. In addition, on the plan, the distance between the center-lines of adjacent track, the distance between any structure from the tracks and signaling posts are shown.

Station layout plan preparation begins, first by placing bold vertical line every 100 meter, pegs, from both side of the center axis of station balding which will be taken as a zero or start location of station plan.

**Drawing center-line of the tracks:** Tracks in station are represented by the center-line of the track. At the turnout, the axis of the diverging and through track will be represented by the intersection of both tracks center line called point intersection or point center (PC). The number of the turnout and the distance between the point centers from the station building axis is also shown on the plan e.g. **PC-10**. The number of the track is also shown at some distance along the station plan. In addition, on the plan, the arrangements of the tracks which are planned to be implemented in futures are also shown, usually using broken lines.

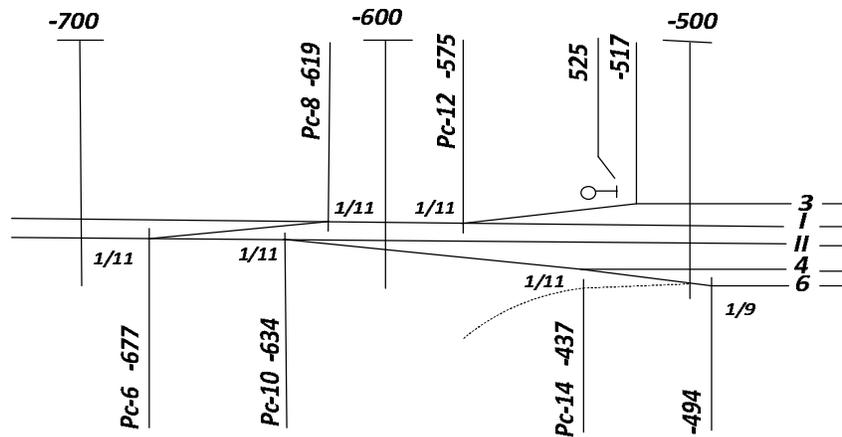


Figure 4.1 OCS section with PC, track types and reference locations

Turnout are drawn using the parameters of the turnout. Every turnout is represented by the tangent angle between the branching and through track center lines and also using the slop ration of the branching and through track center line Eg. 1/11.

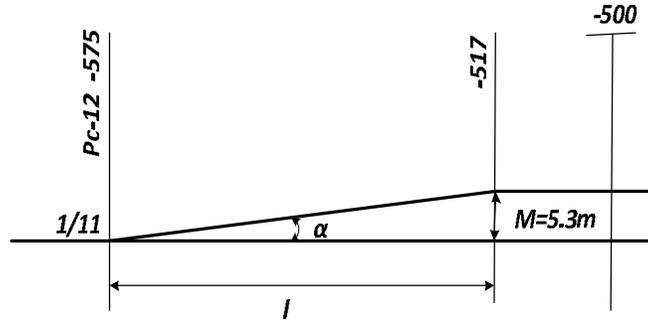


Figure 4.2 OCS section with showing turnout

$$\tan \alpha = \frac{m}{l},$$

#### 4.8.1 OCS Mast Location Determination near Track Turnouts

Above track points or turnouts, OCS wires will cross each other. OCS above track points, are the most critical point of OCS system, where the reliability and durability of the whole OCS system largely determined by the reliability of wiring at this points. Hence, branching and through track OCS wires, which intersect at this point, should be correctly and carefully fixed.

To fix the OCS wires at track points and OCS wires that change directions; there should be an OCS mast with fixing structures at those particular locations. Such locations are concentrated at entrance and departure end of the stations and hence, fixing mast locations begins at the entrance or departure end of the station.

For simple turnout, the most preferable position of OCS mast near this turnout is at a distance “C” from the track intersection point, **PC**.

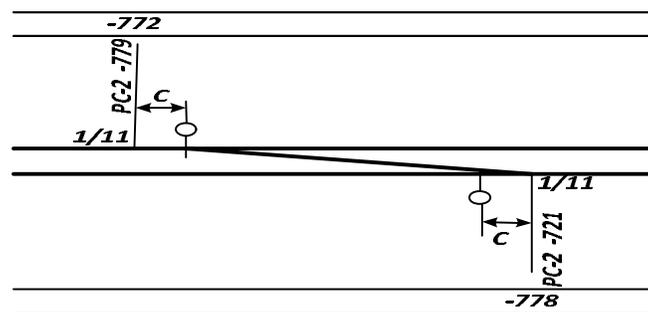


Figure 4.3 OCS plan section showing location of mast from PC

Table 4.13 Type of turnout and optimum distance from of the mast from PC

Type of turnout	1/22	1/8	1/11	1/9
Optimal distance of the mast from the track intersection point (meter)	12.5	11	6	5

Note:

- The above length might be taken smaller considering the actual scenarios, however the distance between the point center to the mast must not be less than that 4-6 meter [8].
- The above distance might be increased considering site conditions but not more than 1 meter [8].

For the diamond crossing; OCS mast are placed at the center point of the crossing and if necessary the mast can be displaced 1 or 2 meter to either sides of the center point of the diamond crossings [8].

For a curve after the crossing turnout found at the far end of station tracks; the mast location should be chosen to be at the center of the curve. For example, in the figure below, the convenient place to place mast is at -517 and -494 and if it is necessary to displace the mast position, it might be displaced by 1-5 meter to either direction [8].

At location where the mast location is determined, the symbol of a mast and the distance of this mast from the station building center-line should be indicated on the plan.

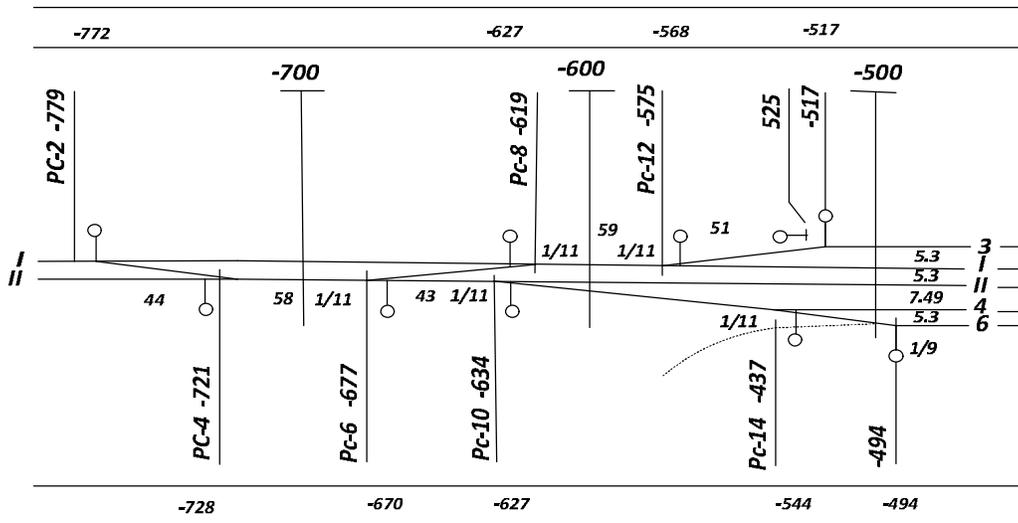


Figure 4.4 OCS plan section showing location of masts on curved points

## 4.8.2 OCS Mast Location Determination at the Locations in the Station

The most common type of structures used at station for fixing OCS is a portal structure across three to eight tracks supported by one or two metallic or concrete mast. At the departure and entrance end of station, where the number of track not greater than two; a metallic or concrete mast with one or two cantilever structures are used. Near station area with more than 8 tracks; head-span structures are used which is supported by metallic or concrete mast.

## 4.8.3 Placing Poles at Turnouts and Side Track Curve Area

Selecting OCS mast location in the station, as discussed above, usually starts near station entrance or departure area, where turnout and curve are concentrated. At this location, depending on the number of track or OCS wires needed to be supported; the supporting structure can be head-span or portal. Usually at such location, the distance between consecutive masts might be much less than the maximum allowable span length, and there might be a lot of mast concentrated at small distance in such locations.

Since, standards recommend that, the maximum difference in span length between adjacent span lengths should not be greater than 25% of the next span length [8], the concentrated masts at station entrance and departure area might have span length with a difference of more than 25%. Hence to avoid short span length, a mast above track points could have a pull of structure rather

than a supporting structure, if only if the OCS wire did not change direction at this point and the turnout or track point is at side tracks rather than main track. In such way, the span length become the distance between mast with the supporting structure located before the track turnout and the mast after the track turnout as shown in the figure 4.5.

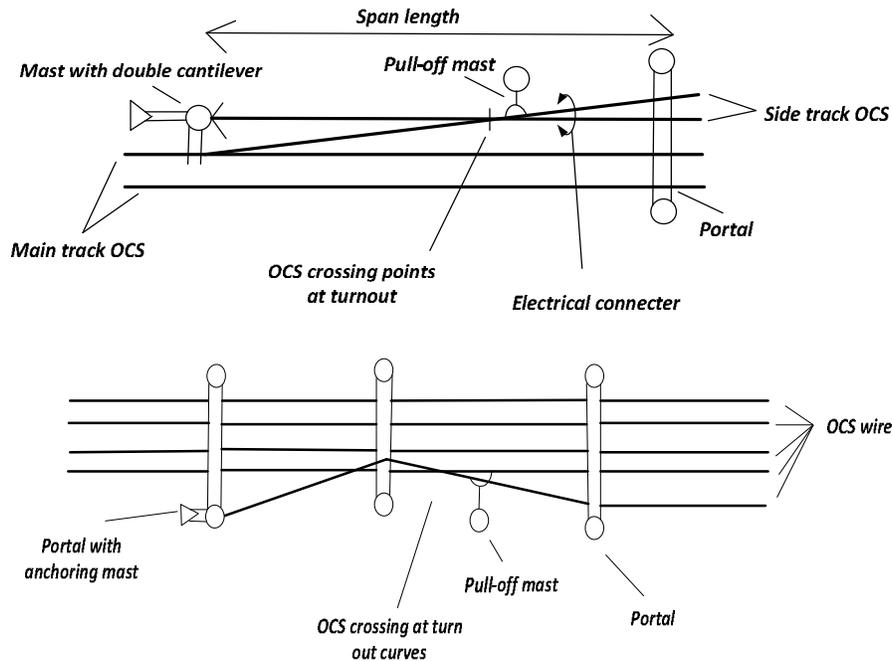


Figure 4.5 OCS plan section showing pull-off mast and portal structure

Generally, OCS mast placement at station; should be done in accordance with the following requirements:

1. Near the center of turnouts of main tracks; mast with supporting structure should be placed.
2. To avoid short span length, a mast above track points could have a pull of structure rather than a supporting structure, if only if the OCS wire did not change direction at this point and the turnout or track point is at side tracks rather than main track.
3. For simple turnout, the most preferable position of OCS mast near this turnout is at a distance “C” from the track intersection point, **PC**.
4. Masts supporting portal structure are used to support OCS wire across three to eight tracks

5. At the departure and entrance end of station, where the number of track not greater than two; a metallic or concrete mast with one or two cantilever structures are used
6. Near station area with more than 8 tracks; head-span structures are used which is supported by metallic or concrete mast.
7. In any case, the span length, or distance between two masts with supporting structure, should be lower that the calculated maximum allowable span length.
8. In multiple track section of stations, with parallel main track and side tracks, where head-span or portal are used; the span length between two consecutive head-span or portal, should be selected as the minimum of allowable span length calculated for main track and side track.
9. The maximum of span length should be 65 meter and the minimum should be 30 meter [14] [8].
10. The difference between two adjacent span lengths should be lower that 25% of the next span length [8].
11. Independent masts in opposite tracks should be place facing of each other.
12. Considering site conditions and layout conditions, the mast location could be shifted within 1-or 2 meter from the first selected position at point center of the turnout [12].

Example:

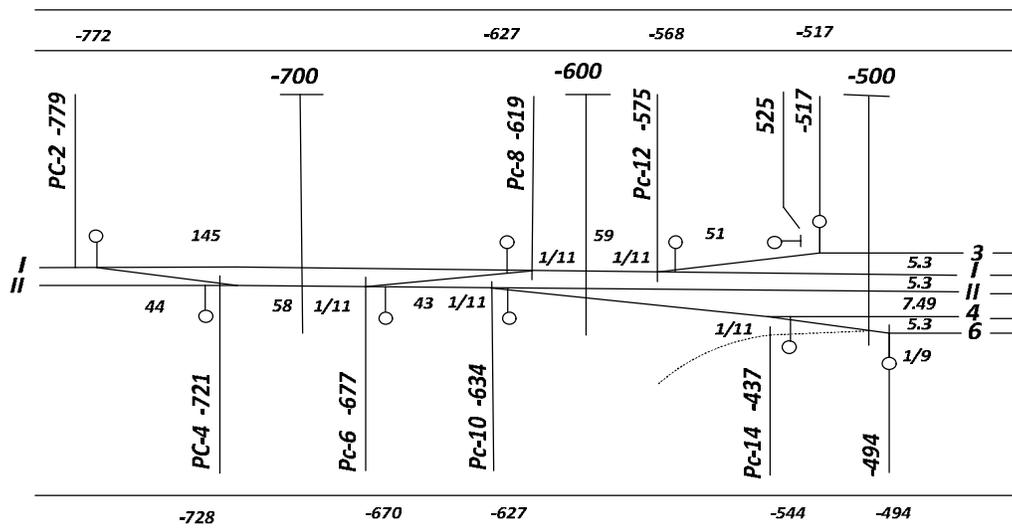


Figure 4.6 OCS plan section to show how to fix mast location

In figure 4.6, to fix turnout of main track number II PC-4, PC-6 and PC-10, the mast are placed in accordance with mast displacement “C” given in table 4.12. The distance between the masts, span lengths, become 58 and 43 respectively.

Next, to fix turnout of main tracks I PC-2, PC-8 and PC-12, the mast are placed in accordance with mast displacement “C” given in table 4.12. The distance between the masts, span lengths, become 145, 59 and 51 respectively. If the maximum allowable span length is 65m, then span length between PC-2 and PC-8 exceeds the calculated allowable span length. Hence this span length could be divided into three, so that, the span lengths could fall to the allowable span length. Using requirement 6 of section 4.8.3; the span length 145, is divided into 44, 58, and 43 by placing mast in front of the respective mast placed for main track number II turnouts. The final span length for track I, become 44, 58, 43, 59 and 51.

Then, the span length difference will be checked, weather it fulfills requirement 5 of section 4.8.3. Checking this, span length between PC-8 and PC-10, violets this requirements and hence, using criteria 7, mast can be shift, to keep span length difference within 25% of the next span length.

To do this, mast of PC-4 is shifted one meter to the right and also masts of PC-10 & PC-8 shifted 1 meter to the right. Finally, the adjusted span length becomes 45, 57, 44, 58 and 51 as shown in the figures 4.7.

A portal structures supported by masts is used at (-568), (-517), (-457), (-397), (-337) in figure 4.7, as the tracks in between opposite mast at these points exceeds 2 tracks. In addition on mast number 19 and 20, supporting structures will be portal structures, as at mast 20, there is a need to fix three groups of OCS wires. To fix the turnouts at side tracks, PC-14 and PC-16, the supporting structures for the crossing OCS wire will be a pull off type, as per requirement 2.

All other masts will have a cantilever supporting structures. However, on mast number 13, 15, 18, 21 and 22, the single mast will have two cantilevers to support the double OCS wires.

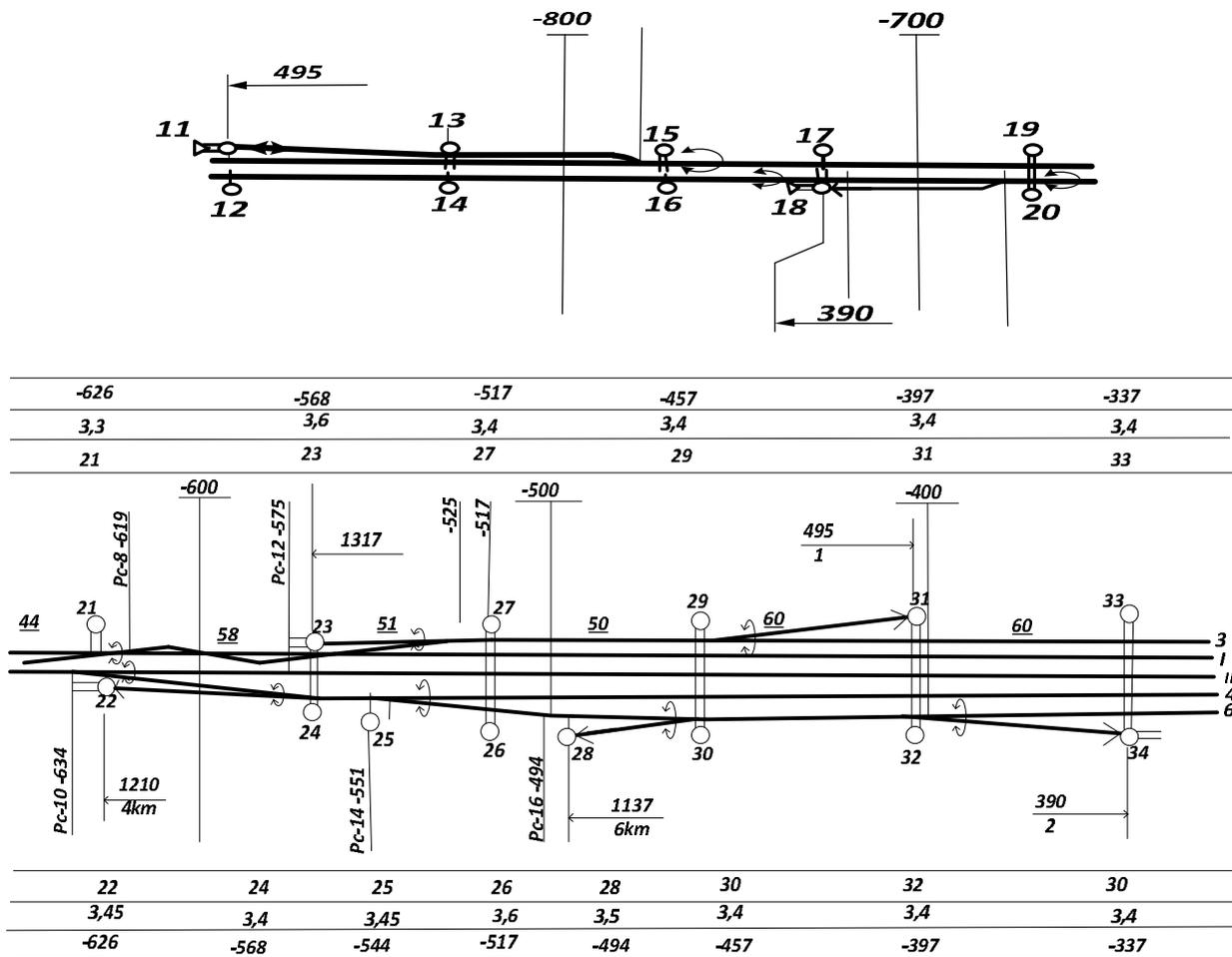


Figure 4.7 OCS plan parts after mast are fixed and showing mast number and distance

#### 4.8.4 Placing Masts in Between Station Departure and Entrance Area

In between station departure and entrance area, there exists long section where pole must be placed.

Normally the numbers of tracks in this section are greater than 3; hence the typical supporting structures used in this section are a portal or head span OCS supporting structures.

In most passenger stations, there exists a bridge or over pass for passenger to inter in to the middle track platform or leave the platform in the middle of tracks. The standard height between the top of rails to the bottom of the bridge is 7-7.5 meter [8]. The standard contact wire height above rails is 6.5 meter and in harsh condition the height could be 5.75 meter but not less than this [14].

The following are a general rule of guide when placing OCS supporting structures in between station departure and entrance area.

- Placing OCS supporting structures opposite to public entrances, exits area, station building doors, platform or passenger overpass bridge staircases, gang ways and signaling & interlocking equipments shall be avoided. In general, OCS supporting structures shall be placed not in a way that hinders people's movement as well as freight loading and unloading.
- OCS supporting structures can be placed on station platform. However, the *setting of masts*, i.e. the distance between the mast and the rail track center line, on platforms shall not be less than 4.75 m [8]. As far as possible, masts shall be located in line with other masts or obstructions on platform and shall be of minimum possible dimensions and fit in with the architectural pattern prevailing in the vicinity.
- For separate group of tracks or track groups other than tracks grouped together with main tracks; a separate OCS supporting structures or portal shall support the OCS wires.
- To pass OCS under the passenger overpass bridge; there shall be OCS supporting structures placed at the left and right side of the bridge with equal distance separation to keep the bridge at the center of the span.
- Mostly, the middle of the anchor section of fully compensated or half compensated OCS systems falls at the middle station area. Hence, the span length of two spans, in the middle of the anchor section of fully compensated OCS, shall be lower by 10% of the maximum span length calculated in order to accommodate the middle anchoring [8]. For semi-compensated OCS only one span, found in the middle of anchor section, should be lower by 10% of the maximum span length calculated.
- If there exist turnout at the middle of station, OCS above track points or point center shall be fixed by portal supporting structures. If this is not possible, other mast which will fix OCS above track point shall be provided.
- There shall not be anchoring and tensioning device near the station platform area to avoid the risk of breakage on passengers/people on the platforms.

- Head-span or portal OCS supporting structures permit the termination of overhead contact lines. It can however be expedient to provide separate termination anchor poles in order to limit the overhead contact line length or to avoid sharp bends and intersections.
- The standard length of portal type mast is 44 meters (for 8 tracks), and if the number of track is greater than 8, there shall be another portal supporting mast in between tracks. In this case, the setting of masts shall be at least 3.1. In difficult conditions, the setting of masts shall be placed at 2.5 meter from but not less than this [8].
- No live conductor should be run over platforms.

#### **4.8.5 Placing Masts before Station Entrance and after Station Departure Area**

As a rule of thumb, station section is feed by independent feeder from traction substation. Hence, the station OCS should be separated or isolated from OCS of non-station section. The arrangement used to separate station section from non-station section is called an insulated overlap.

#### **4.8.6 Types of Overlaps**

**There are two types of insulated overlaps:**

These are single overlap and double overlap (neutral section) arrangement. The phase of station feeder and non station feeder are different for safety reasons. The first insulated overlap (single overlap) is located at one end of station. This insulated overlap at this end will isolate electrically the station area feeder zone from the non-station area feeder zone. Since at this end the feeders are from the same phase, phase A or B or C; the overlap type is a single overlap with insulation because there is no risk of phase to phase shorting. Here the phases are in 27.5kV side which feed to OCS.

The second insulated overlap (double overlap) located at the other end of station. This insulated overlap at this end will isolate electrically the station area feeder zone from the non-station area feeder zone. Sine at this end the feeders are from different phase, one can be phase A and other phase B or C; there is a risk of phase to phase shorting in case pantograph exists in between the

two feeders. To avoid this, the overlap in this section is a double overlap with a neutral section between the two overlaps. Such overlap is also called a neutral section overlap [2] [16] [17].

### ***Single overlap arrangement***

The subdivision of the overhead line into deferent feeder zones, with feeders having the same electrical phase, is required at the boundaries of stations and non-station section. Even if the two feeder zones are from the same phase; there are cases in which a voltage difference exists between the station and non-station feeder zones.

Voltage difference between the station feeder zone and non-station feeder zone may exist because of two rezones.

1. There may be more locomotive operating in the non-station zone and relatively less locomotive in the station zone. This will create more voltage drop in non-station zone when compared to the station zone.
2. The station zone may be temporally de-energized or has earthed faults. When this condition happens and there is a locomotive inside the overlap section; the pantographs of the locomotive will get two different voltage level

When voltage difference occurred based on the above two facts in the presence of locomotive in the overlap section; there will be high current flowing through the pantograph in contact with the non-station feeder zone and the pantograph in contact with the station feeder. This high current might create a spark or electric arc. These phenomena might create OCS wire melt or damage if the locomotive moves at this section with a low speed.

To avoid this, the insulated overlapping sections planned there need to be protected by warning signals, in order to protect the overheating of wires in the overlap span section because of voltage difference between the two feeder zones or fault at one of the zone. This signal tells the driver the existence of an overlap ahead and also recommends the speed to pass that overlap. The distance  $a$ , shown in figure 4.8, shows the positioning of the overlapping span relative to the signal and represents the distance  $a$  between the signal and the first pole of the overlapping with two cantilevers. The higher the length  $a$ , the more the locomotives gain speed or accelerant and hence swiftly pass the overlap section without long overheating.



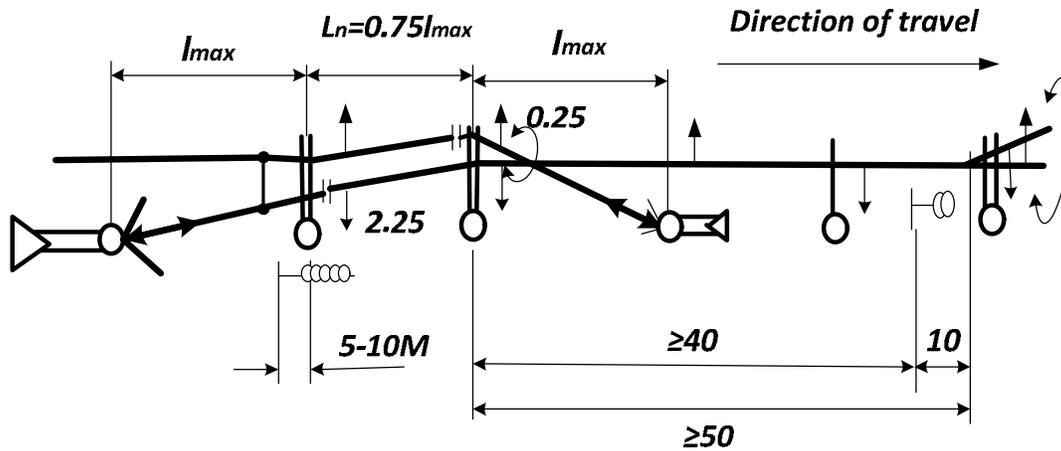


Figure 4.9 Distance of signals from overlaps

**Neutral section or double overlap arrangement**

Phase separation sections must ensure that trains can move from one section to an adjacent one without bridging the adjacent phases as shown in the figure below. Adequate means need to be provided to allow a train that is stopped within the phase separation section to be restarted. Therefore, the neutral section needs to be connectable to the adjacent sections by remotely controlled disconnectors. The dimensions essential for the design of phase separation sections are shown in Figure below

The neutral section arrangement should consider that, all the pantographs of the longest trains can be accommodated within the neutral section. The length of the neutral section ( $D$ ) has to be at least 142 m in this case. The maximum spacing between the outer pantographs is 140 m. reserve of 2 m leads to a spacing of 142 m [2].

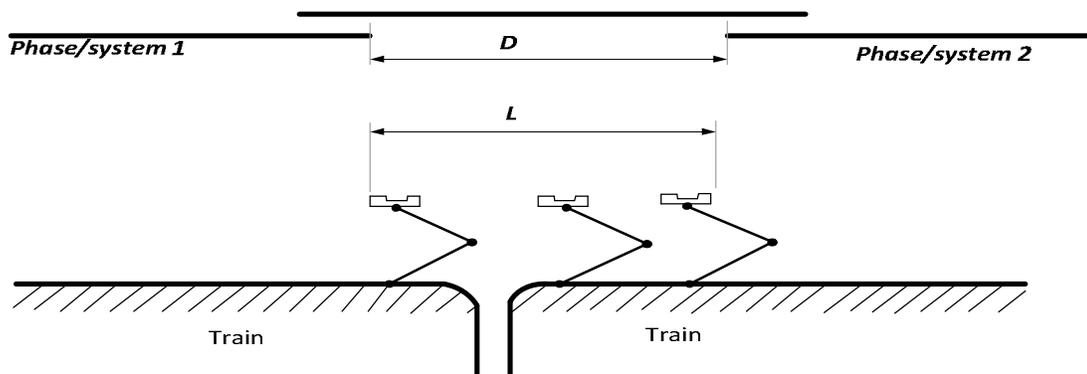


Figure 4.10 Neutral section arrangement

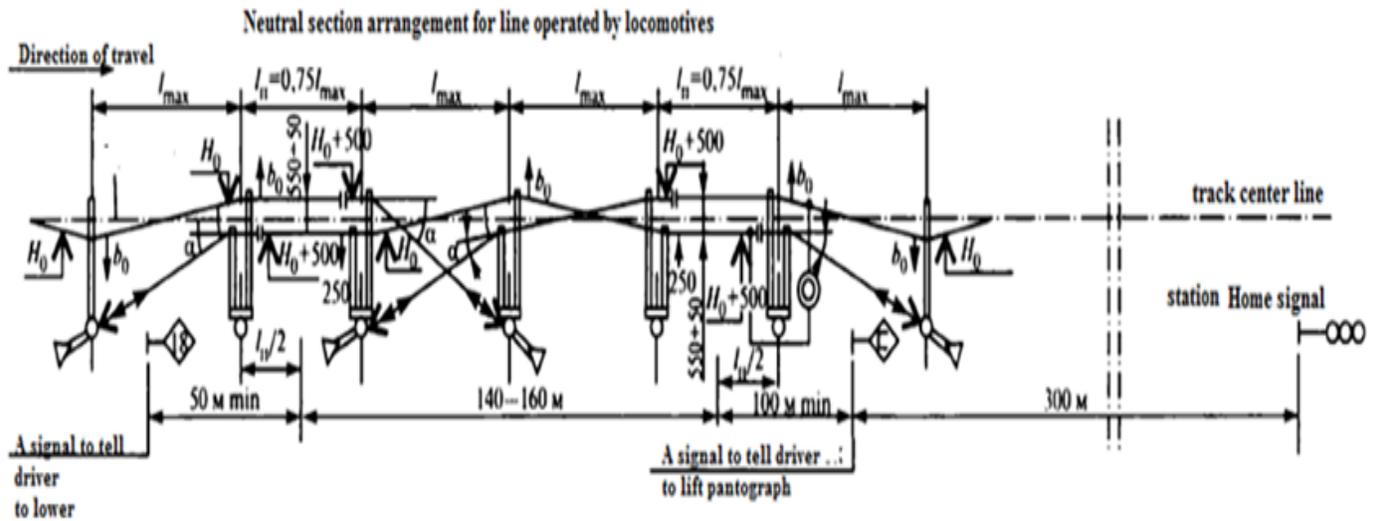


Figure 4.11 OCS plan section with insulated overlap [8]

The following are the requirements of neutral section arrangement

1. Neutral section of overhead contact line system shall be located in traction substation, sectioning post, and at the boundary between railway bureaus.
2. The location of the neutral section of overhead contact line system shall fulfill the requirements of the operation mode of electric locomotive, convenience for shunting operation, reasonable arrangement of power supply line, as well as the requirements of the position and display of home signal etc.
3. The location of the neutral section of overhead contact line system shall be more than 300m away from home signal or the first turnout of the station

#### 4.8.7 Tracing OCS Wires along the Masts

After placing OCS masts at track departure section, entrance section, in-between station departure and entrance section; the OCS wire should be traced or installed on the OCS masts.

The maximum anchor section length during compensation at both sides of the main line should not be more than  $2 \times 800\text{m}$ ; the anchor section length during compensation at single side shall be 50% of the above value and it should not be greater than  $2 \times 900\text{m}$  in case of difficult conditions [14].

The maximum anchor section length of the station/side track should not be greater than  $2 \times 850\text{m}$  or should not be greater than  $2 \times 950\text{m}$  in case of difficult conditions [14].

Anchor sections of main tracks are traced starting from the overlap at one end of station and ending on the overlap or neutral section at the other end of station. For ever side tracks, independent anchor section should be installed with fully compensated OCS.

Turnouts of main tracks and curved turnout of side tracks can have their own anchor section, with one side non-compensated anchoring and other side fully compensated anchoring. However to minimize the number of anchor section (the cost of OCS); Curved turnout OCS and side track OCS can be grouped in one anchor section.

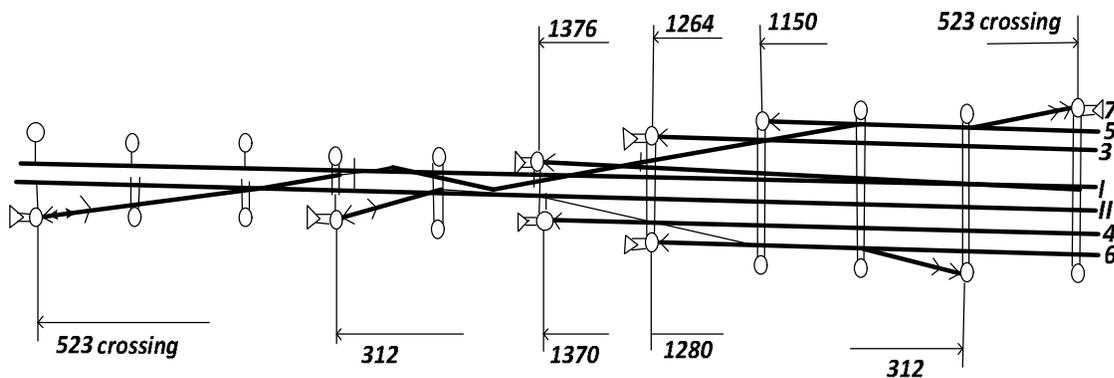


Figure 4.12 Different anchor section for curved turnout and side track OCS

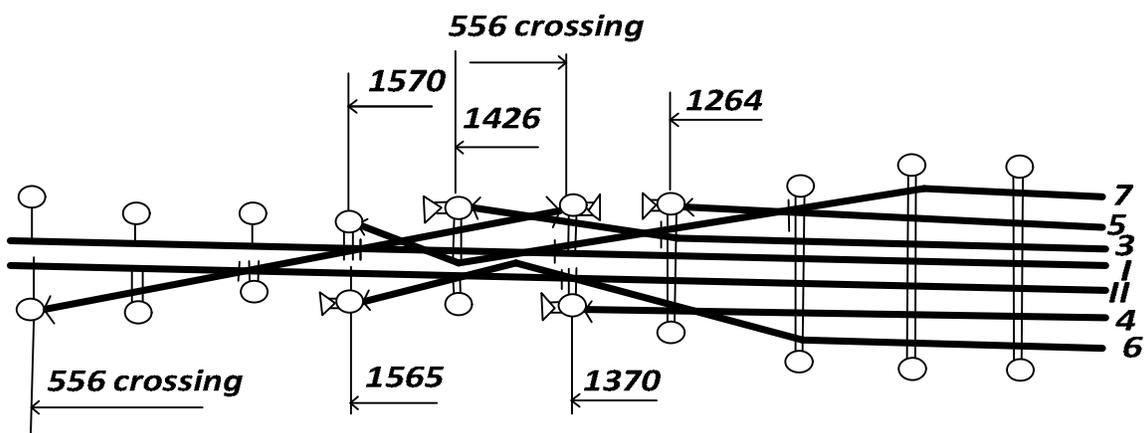


Figure 4.13 The same anchor section for curved turnout and side track OCS

It is preferable to anchor turnout's OCS on the mast located one span before the point center or turnout center. If this is, difficult to implement this, anchoring turnout's OCS wire on the mast located two spans before the point center or turnout center is recommended.



Figure 4.14 One span anchoring

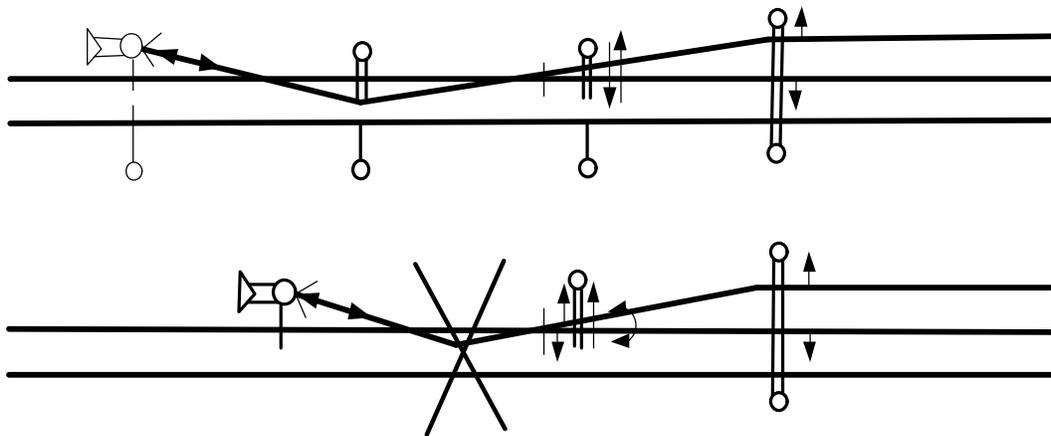


Figure 4.15 Two spans anchoring, recommended and not recommended

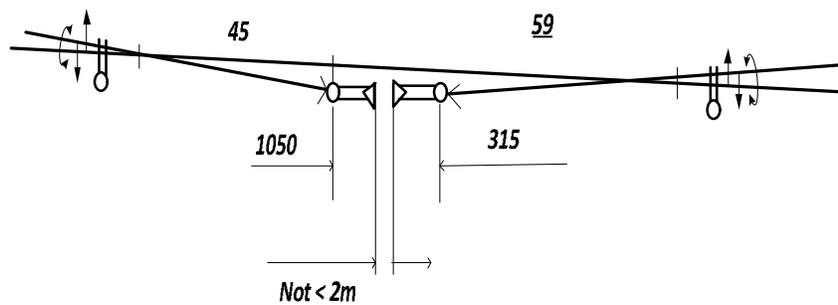


Figure 4.16 Space between anchoring mast

After tracing all anchor section in the station; the length of anchor section needed to be check. If the distance between the two station end's overlaps is greater than 1600 meter (the maximum

allowed anchor section length); the anchor section of the main tracks will be divided in to two or three by using 3 or 4 span overlap at preferable or suitable area along the section as shown in the figure 4.17.

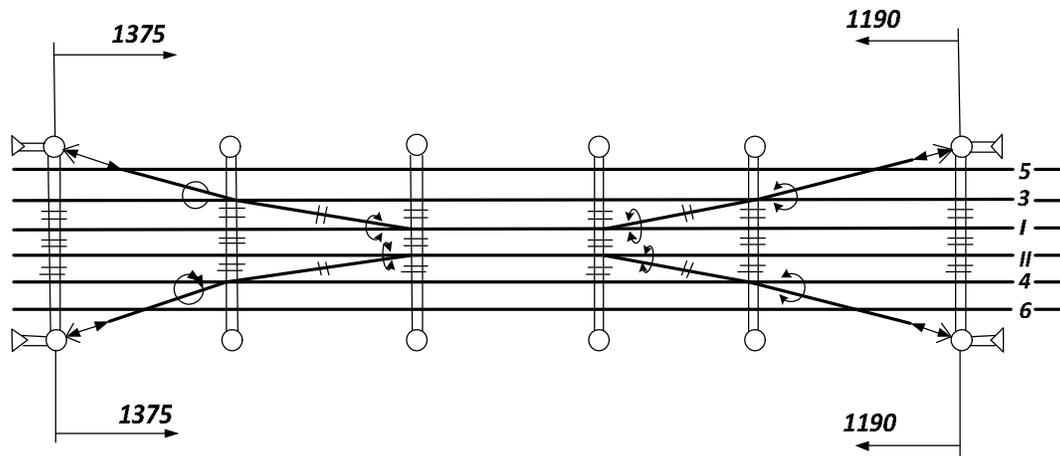


Figure 4.17 OCS plan section with anchoring mast

If any anchor section has a length greater than 800 meter [14], there should be a middle anchoring. If the mast placed in the first steps, could not fall to the middle of the anchor, masts should be rearranged so that, the middle of anchor coincides with the mast. It is recommended to have span length at the middle anchor 10% less than the maximum span length calculated [8].

A separate anchor section for branching track at the turnout should be provided as discussed previously. Hence, most of the time, the anchor length of the turnout OCS will be smaller than 800 meter. For this case, one side of the anchor section will be fully compensated anchoring and the other end non-compensated anchoring. To have a uniform displacement of contact wires of the trough and branching tracks, at turnout, due to temperature; the non compensated anchoring side of the branching track should be at the same side with the middle anchoring of the through or main tracks, looking from the track turnouts.

The final work of tracing will be naming the anchor section and specifying the length of the anchor section in the OCS layout plan as shown the previous figures.

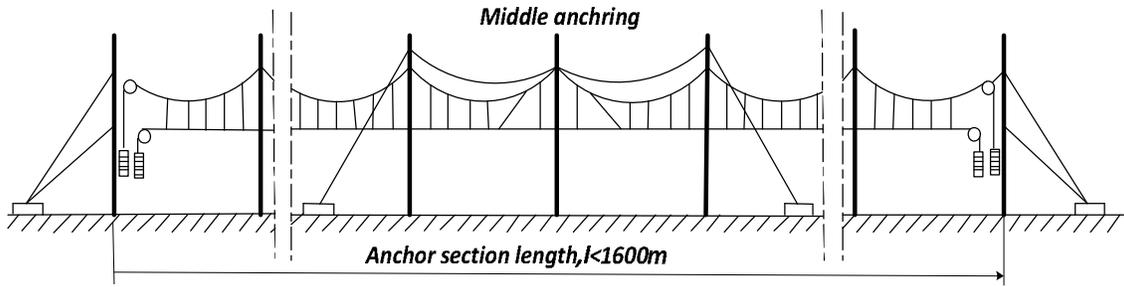


Figure 4.18 Side view of typical anchor section of main track with middle anchoring

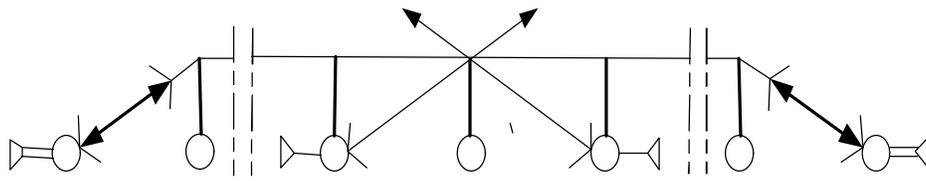


Figure 4.19 Anchor section of main track OCS with middle anchoring in the layout plan

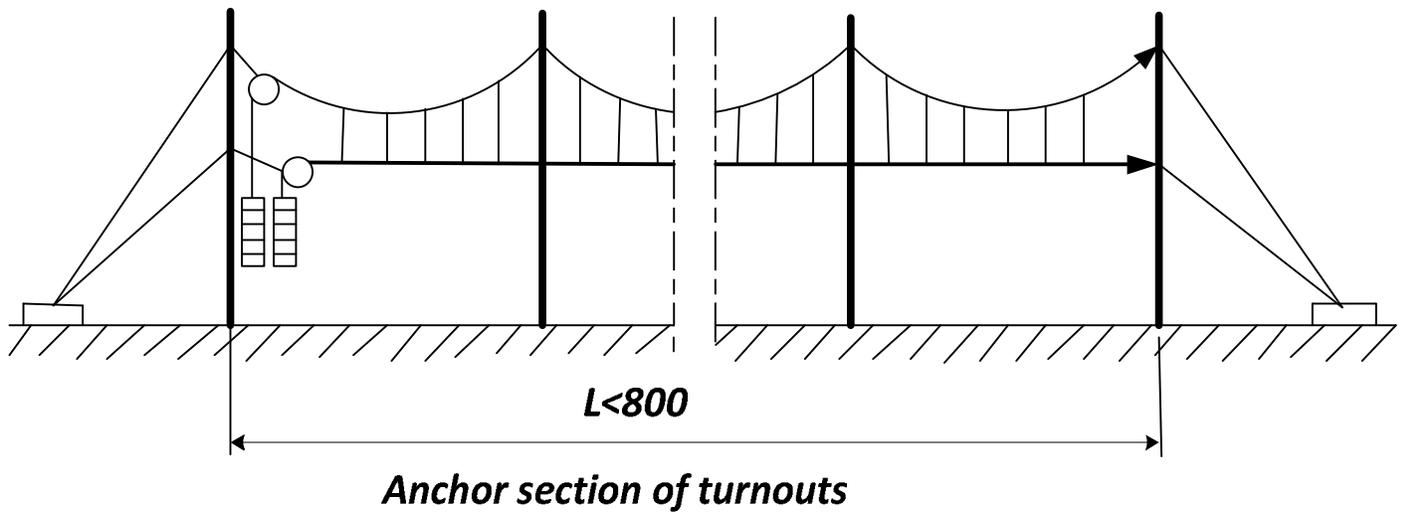


Figure 4.20 Side view of typical anchor section of OCS with one side full-compensated

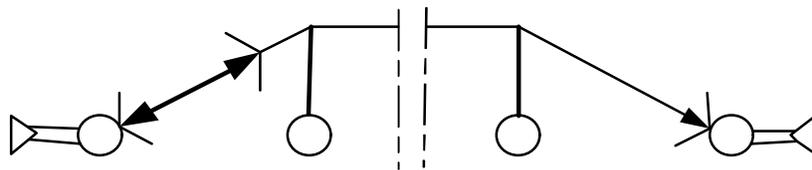


Figure 4.21 Representation of anchor section of turnout track OCS

## **4.8.8 Sectioning Arrangements and Tracing OCS Feeders**

Overhead contact system in station area, are separately fed from a traction substation or sectioning post located in the station compound. This requirement is arise because of the existence of more locomotives and trains in station at some moment when compared to non-station sections and because of this there is a need for more loads. In addition, inside stations; there are more tracks and hence there is a need for more loads and hence more separate feeders.

Inside stations, it is practical to provide a switchable section in order to facilitate the maintenance of OCS by switching only some section of OCS and hence avoids wide area black out and effects train operation or operation schedule. Furthermore, sectioning minimize electric traction energy loss since small section-length means small voltage drop.

### **4.8.8.1 Sectioning and Feeding Schema Design**

When designing feeding and sectioning scheme of station OCS; the following connection types are considered and included in the scheme.

- Feeders, from traction substation or sectioning posts, connections to the OCS
- Longitudinal sectioning
- Parallel sectioning
- OCS sections with a mandatory earthing disconnecter

Sectioning is realized with sectioning insulators, insulated overlaps or neutral section ions. Feeder switching or section connections are realized with disconnectors.

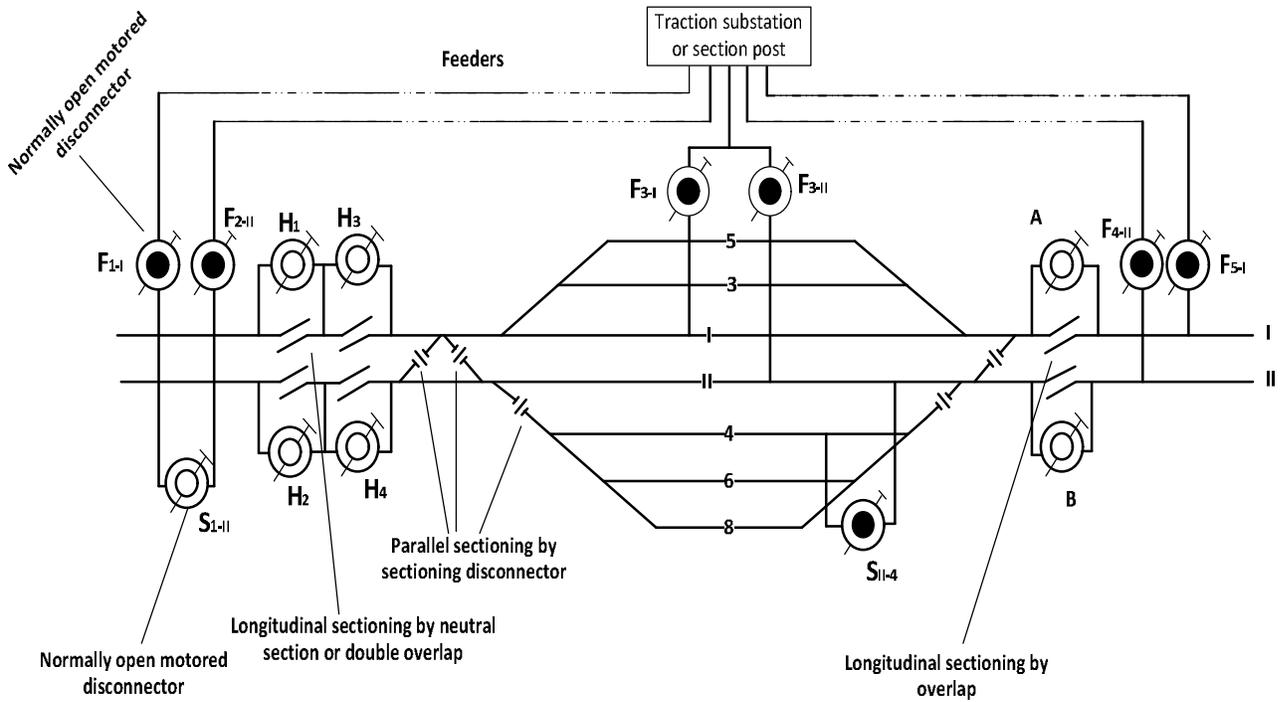


Figure 4.22 OCS sectioning and feeder schema

#### 4.8.8.2 Feeder Connections to the OCS

Station area and non station area; are feed from a separate feeder from traction substation or section post. The station and non station section is separated by overlap and neutral section at each end of station.

Separate sub-feeder from one feeder; feeds each groups of tracks in the station. The feeders are connected to the OCS through a motorized disconnector, so that in case of maintenance, faults and damage of OCS, the track OCS are de-energized or disconnected from the substation feeders.

#### Longitudinal Sectioning

Longitudinal sectioning is provided in the station in order to separate station OCS from the non-station section OCS. The separation is realized with insulated overlap at one end of the station and neutral sections at the other end of station as shown in the figure above.

Each longitudinal section is provided with dedicated feeder from traction substation or section post. At the point of connection of the feeder to the section; a disconnector are provided in order to provide a switching or bypassing capability of sections as shown in the figure above.

In the figure 4.22 normally opened disconnector,  $H_1$ ,  $H_2$ ,  $H_3$  and  $H_4$  above a neutral section and normally opened disconnector A and B; provide a longitudinal sectioning arrangement for the station, in order to separate the station with the non station OCS. The disconnectors also have a bypassing capability when they are closed in order to feed all station section and non station sections from one feeder from the substation or section post.

### **Parallel Sectioning**

Parallel sectioning is provided in double or multi track lines and stations. Even if station area tracks are feed from one feeder from substation or post sections; each station main track and group of side tracks are separated electrically/sectioned parallel from each other by sectioning insulators but, under normal conditions, a normally closed disconnector  $S_{II-4}$  in figure 4.22 provide electrical connection to all station parallel section.

Parallel sectioning is required in stations, in order to electrically sectionalize or separate OCS of group of side tracks and, if exists, OCS of a separate group of tracks in stations during maintenance, inspection and faults or damage of OCS at some section. This is done by opening disconnector  $S_{II-4}$  in figure 4.22, when there is a need for maintenance or during faults or damage of OCS of track number 4, 6 and 8.

### **4.8.9 OCS Sections with Mandatory Earthing Disconnector**

OCS sections, above the following tracks, are sectioned with a mandatory earthing disconnector to provide earth connection to the OCS when there is some king of routine operation at that tracks or section.

- Depot tracks
- Parking tracks
- Fright loading and unloading tracks

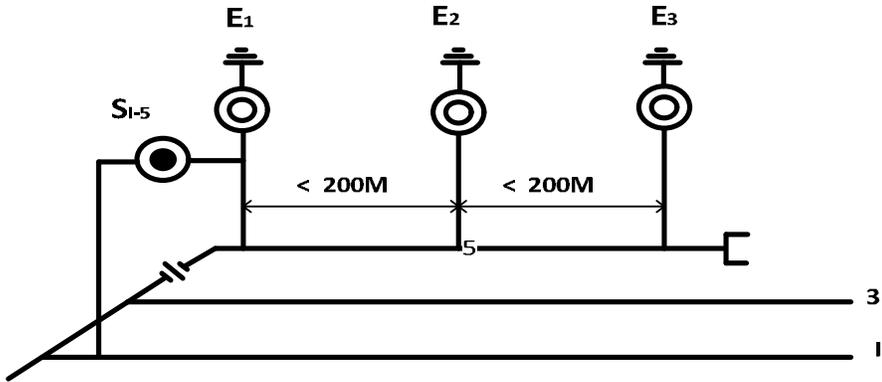


Figure 4.23 OCS section with earthing disconnector

In the above figure, tracks 5 which is a parking, need to be provided with earthing disconnector. This is because, during locomotive parking, there might be a minor locomotive maintenance or inspection and for safety reason, S<sub>1-5</sub> should be disconnected and E<sub>1</sub>, E<sub>2</sub> and E<sub>3</sub> OCS should be earthed.

By using the above OCS planning steps and rules, OCS pane for Indode station is done using Microsoft Visio. Since the size of the plan is large, it is difficult to submit with hard copy with this paper. Hence the proposed Indode station OCS plan is attached at the last of document with plan paper.

# Chapter Five

## 5. Conclusion and Recommendation

### 5.1 Conclusion

The main purpose of this thesis work was to develop a generalized Overhead Contact System design process for Ethiopia Railway. It was achieved by statically modeling of OCS using bottom to top approach. Even if simple catenary system is used for Indode station having root speed of 120 km/hr, trolley type OCS model is included which may be used in case of roots having speed restriction up to 80 km/hr.

From the model and meteorological data, all the parameters i.e max span length, critical span length, anchoring length is determined. Based on this value OCS plan is prepared for Indode station using Microsoft Visio from station site plan. Since the critical span length is greater than the maximum span length, it can be concluded that temperature variation is the extreme meteorological state than the maximum wind load. Traction impedance also modeled and computed for double track system which determines the energy transmission behavior of OCS.

The main contribution of this thesis is OCS design guideline to Ethiopia railway Corporation.

This thesis does not review the design for Indode station because the design is updating until now and review unfixed design and put the document for future literature may lead wrong conclusion. OCS pantograph interaction for smooth current collection must also be done for fully review the design as it affects the parameters of OCS.

Overall this thesis work use as starting point in the area of OCS design and planning for Ethiopia railway for the progress project and future work.

The manual for overhead contact system design is presented in appendix A and Indode station OCS plan is attached at the last of document with plan paper.

## 5.2 Recommendation

As have been discussed, this thesis tried to present OCS design for Ethiopia which is applicable to roots up to 160 km/hr. This thesis used as bench mark and gives direction for further works as

- This thesis use conductor specification from china's document of Ethiopia railway corporation [5], but if the material is selected based on electrical characteristics and current capacity it is possible do bill of quantity and review the design cost wise
- OCS pantograph interaction for smooth current collection must be worked for optimum elasticity at the mid span which in turn has effect on span length and all the parameters. In this case it is fully possible to review designs.
- This work can be extended for modeling compound catenary OCS (for high speed application) and the evaluation of the dynamic performance of compound catenary with compared to other OCS type, in Ethiopia Railway, can be a possible research point which can base this thesis work and thesis result
- The manual included in the Appendix A, can be further developed and tested to be a standard OCS design guide for Ethiopia Railway.
- Voltage drop, harmonic and interference can be different depending on the type of OCS; hence a further study can be undertaken study electrical performance of different type of OCS in Ethiopia Railway.

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# Appendix A

## MANUAL FOR OVERHEAD CONTACT LINE SYSTEM DESIGN FOR ETHIOPIA RAILWAY

### Introduction

This design manual is compiled from the thesis work and aims to give recommendations and standardization of the design as well as construction process of AC 25kV overhead contact system in Ethiopia.

As electrified railway and electrification are new to Ethiopia; there are no standards and specification tailored to Ethiopian economical, environmental, geographical and demographical conditions. The main features, which makes the design and construction of 25kV overhead contact system in Ethiopia a unique scenario, can be broadly categorized in to three. These are:

- The unique climatic condition of Ethiopia, i.e. a single main line railway may crosses two or more climatic zone and also absent of snow, storms and other extreme low weather conditions
- Relatively less freight traffic and less need of high speed transport (speed greater than 160km/hr) for the current and near future, and need of upgrade to higher freight traffic accommodation and higher speed transport for the future; which will give a room for relaxed design, at this stage, and consideration of upgradability for the future
- The main railway lines are currently being built by different country with different standards and specifications. Hence, the need for system inter-operability and integration

Generally, the design of overhead contact lines follows the following main principles:

- Consideration of OCS operation life cycle
- Consideration of safe construction, operation and maintenance
- Consideration of minimum initial investment and resources utilization
- Consideration of economical feasibility
- Consideration of upgradability

- Consideration of system inter-operability and integration
- Consideration of system maintainability

Hence, overhead contact system design in Ethiopia needs to fulfill the above general design principles by following a customizing design approach which meet the three features that makes the OCS design process, in Ethiopian, a unique scenario.

## **1. Load acting on OCS**

**1.1** Loads acting on any overhead contact system are classified in to two: *Constant short durational* where the last can also classified in to short durational and special.

**1.2** *Constant Loads acting on OCS* are Loads due to:

- weights of wires and insulators and structures on OCS mast
- the normal tension on the wires and structures (along the wire or structure)
- Horizontal tension due to change of direction of wires or structure

**1.3** *Short durational Loads on OCS* are Loads due to:

- a. Wind
- b. Change of temperature from the average temperature
- c. Loads during installation and maintenance of OCS

**1.4** *Special Loads on OCS* are Loads due to:

- OCS Mire breakage
- OCS mast breakage
- Seismic activity

**1.5** Calculation of OCS acting loads should be done by considering the sum of the constant loads and the durational loads when a basic extreme condition or compound extreme conditions appears.

The basic extreme conditions can be:

- When the maximum value of wind pressure for that particular area appears
- When the maximum value of temperature for that particular area appears
- When the minimum value of temperature for that particular area appears

The combined of extreme conditions can be:

- Maximum/minimum temperature with a maximum wind and special durational loads such as breakage of mast appears

### Vertical loads

**1.6** Weight of a wire is usually treated as uniformly distributed along the wire and it is calculated as:

$$w \cong 9.81 \cdot m \cdot \alpha ; \quad m = A \cdot \rho$$

$$w \cong 9.81 \cdot A \cdot \rho \cdot \alpha \cdot 10^{-6}$$

Where:

$w$  -weight of the wire per unit length, N/m

$A$  - Cross sectional area of the wire, in  $\text{mm}^2$

$\rho$  - Density of the wire,  $\text{kg/m}^3$

$\alpha$  - Coefficient considering the wire manufacturing (for mono-stranded wire  $\alpha = 1$ ; for multi-stranded wire  $\alpha = 1.025$ )

$m$  -Mass of the wire per unit length,  $\text{kg/m}$

Hence, the total weights of all wires (contact wires, messenger wire, and additive wires) of an OCS:

$$W_{wires} \cong W_m + n_c (W_c + 1)$$

Where:

$w_m$  and  $w_c$  -Weight of the contact wire and messenger wire per a unit length, N/m

$n_c$  - The number of contact wires

1 - Weight of approximate value of additive wires per a unit length

**1.7 Vertical loads due to structures:** This is the total load, due to weight of insulators and cantilever

$$W_{Structures} = W_{insulators} + W_{cantilever}$$

Where:

$W_{insulators}$  - The total weight of the insulators on the OCS in N

$W_{cantilever}$  - Weight of the cantilever in N

$W_{Structures}$  - The total weight structures on the suspension mast (Pole) in N

### Horizontal loads

**1.8 Loads due to wind pressure:** when wind blows in the horizontal direction with respect to OCS wires, it exerts horizontal force on the wire. To calculate this force or load, the design value of wind speed is used as discussed previously.

**1.9** According to Chinese Design Code of Railway Traction Feeding TB10009-2005 [14], the basic wind pressure, acting on any OCS elements, is calculated by:

Wind force exerted per a unit length of wire is given as (N/m)

$$W_0 = 0.625 V_0^2,$$

Where:

$W_0$  -Basic wind pressure (N/m<sup>2</sup>)

$V_0$  -Design value of wind speed, m/s

Then the wind load in OCS wire is calculated by:

$$W_x = \mu_z \cdot \mu_s \cdot W_0 \cdot d \times 10^{-3},$$

Where:

$d$  - Diameter of the conductor, *mm*

$W_x$  - The standard wind load wire on unit length of OCS wire (N/m)

$\mu_z$  - The height variable factor of wind pressure, Table 1 below.

$\mu_s$  - The shape factor of wire under wind pressure, Table 2 below.

Table 1: Height variable factor of wind pressure,  $\mu_z$

Height from Ground Surface (m)	Classification base on Ground Roughness			
	A	B	C	D
5	1.17	1.00	0.74	0.62
10	1.38	1.00	0.74	0.62
15	1.52	1.14	0.74	0.62
20	1.63	1.25	0.84	0.62
30	1.80	1.42	1.00	0.62
40	1.92	1.56	1.13	0.73

Notes:

1. For flat or slightly undulate landform, height variable factor of wind pressure can be determined according to the classification of the ground roughness. The ground roughness is divided into A, B, C and D categories:
  - Category A: indicates inshore area, island, coastline, lakeshore and desert;
  - Category B: indicates the areas such as field, countryside, jungle, hill, township where there are less buildings and city suburbs
  - Category C: indicates urban areas with dense buildings;
  - Category D: indicates urban areas with dense and high buildings.
2. For mountain area, height variable factor of wind pressure shall be defined by not only the ground roughness in flat area listed in Table 5. 5. 9—1 but also the correction of landform condition.

3. For the valley mouth, mountain pass in the same direction with wind direction, the coefficient of correction shall be 1.20~1.50.

Table 2: Shape coefficient under wind load,  $\mu_s$

No.	Category	Shape	Coefficient $\mu_s$
1	Concrete OCS mast	Circular cross-section	0.6
2		Rectangular or H-shaped cross-section	1.3
3	Solid web OCS steel mast	Circular cross-section	0.9
4		H shaped cross-section	1.3
5	OCS Wire	suspension with stitch wire	1.25
6		suspension without stitch wire (including additive wire)	1.2

According to European standard [2], wind load per unit length on OCS conductor is given by

$$F'_w = q_z G_c C_c d \quad \text{and} \quad q_z = \frac{\rho}{2} G_q G_t v_z^2$$

Where:

$q_z$  – The dynamic wind pressure (N/m)

$G_c$ - Structural response factor for the conductor related to wind

$C_c$ - Aerodynamic drag factor of the conductor

$G_q$ - Gust response factor

$d$ - Diameter of the conductor (m)

$G_t$ - Terrain factor taking in to account the protection of the line

Q- Air density (kg/m<sup>3</sup>)

v<sub>z</sub>- design value of wind speed (m/s)

$$Q = 1.225 \left( \frac{288}{t} \right) e^{(-1.2 \times 10^{-4} h)} / e^{(-1.2 \times 10^{-4} \times 600)}$$

Where:

T- Absolute temperature at high wind (°K)

H- Is the altitude of the area (m)

The value of the above coefficients taken based on EN 50119 [15] [2] and Indode station accordingly is

## 2. The meteorological conditions and design values

**2.1** The meteorological condition as the base of the design of overhead contact line system shall be determined according to the meteorological data along the line being recorded recently for at least 20 years and combining with the operation experience of existing electrified railways or high-voltage overhead transmission lines.

### Extreme wind velocity

**2.2** OCS must withstand the maximum pressure or load acting on it. This happens when the wind speed reaches a maximum value at any unknown specific future time.

**2.3** **The maximum wind velocity** causing wind deflection in overhead contact line system shall be taken as the maximum value in every 15 years, which are auto-recorded for 10 minutes at the height of 10 m above the ground and in wide region. The designed wind velocity of structure in overhead contact line system shall be taken as the average maximum value in every 50 years, which are auto-recorded for 10 minutes at the height of 10 m above the ground and in wide region. It shall be converted according to the stipulation if the value recorded in the observatory does not meet the above mentioned requirements.

**2.4** **The design wind velocity:** If the actual structure of OCS located at a height other than 10 meter, then the design wind velocity is calculated by considering the characteristics of the

area and the record value of wind speed of that particular area.

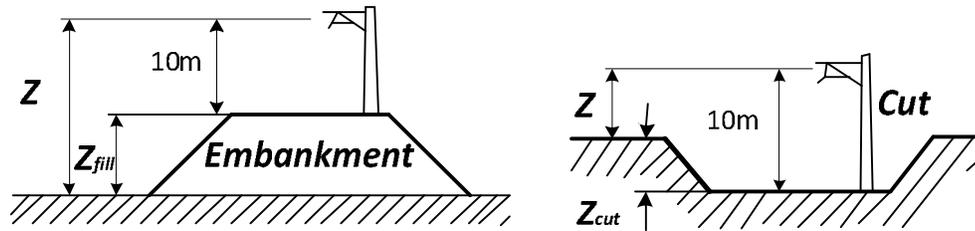


Figure: OCS in fill and cut section

The design value of wind is calculated as:

$$v_z = v_{ref} \left( \frac{Z}{10} \right)^{z_0}$$

Where:

$v_{ref}$  - The reference maximum value of wind speed, 10m above earth surface that happened in the area in the past 10 year.

$z$  - Height above the earth where the air speed is measured

$z_0$  - Surface roughness parameter in which,  $Z_0=0.2$  for hilly, forest and park area

$z$  is determined by,

$$Z = Z_{pole} + Z_{Fill} \text{ for embankment (fill) section}$$

$$Z = Z_{pole} + Z_{cut} \text{ for cut section}$$

Where;

$Z_{pole}$  - Standard height of the pole of OCS- 10 meter

$Z_{fill}$  and  $Z_{cut}$  - Embankment (fill) or cut height for the section

### Extreme temperature

**2.5 Extreme temperature:** The same as wind speed, OCS should withstand the two extreme value of temperature, maximum and minimum. for that particular area. Hence, the design maximum and minimum air temperature values are the extreme minimum and maximum

temperature for that area.

**2.6** Various temperatures in the design of overhead contact line system shall be determined according to the following principles:

1. 40 °C should be taken as the highest temperature. The highest calculated temperature should be 1.5 times the highest temperature.
2. The lowest temperature shall be determined as the average of the lowest temperatures in every 15 years.
3. The temperature under the maximum wind velocity shall be determined combining the actual value under the maximum wind velocity with the mean monthly temperature in the coldest month of strong wind season.
4. The temperature under which droppers and steady arms are in normal positions shall be taken as the mean of the highest calculated temperature and the lowest temperature.
5. The temperature under which contact wire has no sag under the mode of semi-tensioning shall be 5 °C lower than the mean of the highest calculated temperature and the lowest temperature.

**2.7** *Extreme minimum air temperature is determined by:*

$$t_{\min} = t_{\text{average}} - \Delta t - 6$$

Where:

$t_{\text{average}}$  – the average temperature of the coldest month on that area over a long time

$\Delta t$ - Change of temperature during the coldest day in the past years for that particular area

**2.8** *The extreme maximum air temperature* is determined by considering the absolute extreme temperature that exists in the area in the past plus the temperature increment on the conductor because of sun's radiation.

$$t_{\max} = t_{\text{absolute}} + t_{\text{radiation}}$$

Where:

$t_{\text{absolute}}$  - The absolute maximum air temperature for that area

$t_{\text{radiation}}$  -The conductor's temperature because of sun's radiation

$$t_{\text{radiation}}=0.0162\varphi_{\text{max}}$$

Where:

$\varphi_{\text{max}}$ - maximum sun's radiation energy in that area in Watt/m<sup>2</sup>

**2.9 The average temperature:** When determining, the state where the OCS wire hangs with zero sag as well as and calculating the maximum anchor section length by considering range that tensioning device displace due to temperature change; the average temperature of the area is used.

$$t_0 = \frac{t_{\text{min}} + t_{\text{max}}}{2}$$

### 3. System definition and requirements

#### Types of OCS

**3.1 Trolley-type contact lines:** The term trolley-type contact line is applied to systems that do not have a continuous catenary wire and thus have a simple structure. In comparison to catenary-type overhead contact line installations, the contact wire sag of systems of this kind is large, and the distance between supports must be kept short in order to meet the requirement that the height of contact be as nearly constant as possible. The running speed of these systems, 80 km/h at the most, restricts their application to tramways, trolley-buses, industrial railways and turn-outs and sidings of main railway lines.

**3.2 Overhead contact lines with catenary suspension:** are characterized by one, or in some cases two, supporting catenary wires located above the contact wires. The catenary wires support the contact wires by means of droppers. Because of their relatively simple design and favorable running characteristics, overhead contact line installations of the catenary design have become commonly used world-wide. They permit longer support spacing's than trolley-type contact lines and reduce the wear on contact components. They are also being more frequently installed in urban mass transit transportation systems.

Table 3: OCS property and application

Type	Design	Properties	Application
1	Simple overhead contact line without continuous catenary wire, fixed termination or flexible tensioning, horizontal registration arrangements	Contact wire height changes with temperature, limited span length and currents carrying capacity	Light rail systems (tramways) with low electrical load, sidings on mainline railways, speed up to 100 km/h
2	Vertical contact line without stitch wire, tensioned contact wire, catenary wire fixed or tensioned	Contact wire height independent of temperature, span lengths up to 80 m are possible, current-carrying capacity can be adapted by selecting suitable catenary wire and contact wire cross sections, large variation of elasticity between mid-span and support	Tramways with high electrical load, main-line railways at speeds up to 120 km/h, two parallel contact wires are often employed with DC traction supplies
3	As (2), but with or without stitch wire, automatically high tensioned contact wire and catenary wire	As (2), however lower elasticity differences between mid-span and support	Main-line railways with high electrical loading and speeds up to 350 km/h
4	Vertical contact line with auxiliary catenary wire automatically tensioned	As (3), however higher current-carrying capacity and more uniform elasticity	Main-line railways with very high electrical loading and very high speeds

**3.3** It is possible to classify overhead contact lines according to the design of the tensioning system used. A distinction is made between completely compensated contact lines with either combined or separate contact wire or catenary wire tensioning mechanisms and semi-compensated contact lines which have fixed, uncompensated catenary wires and compensated, i. e. automatically tensioned, contact wires. Usually a single contact wire is used for single-phase AC railways. For DC railways with heavy current load requirements,

the associated large currents often make it necessary to use twin contact wires.

**3.4 Suspension type of overhead contact line system:** simple overhead contact line system with automatically tensioned contact wire and messenger wire (contact wire and messenger wire are always at the same vertical plane) shall be adopted in station and section; the suspension type in other area shall be dependent on comprehensive comparison of technology and economy as well as operation condition. The allowable operation speed of overhead contact line shall not be less than the maximum operation speed of line.

### OCS wire physical property and strength requirements

**3.5** Components and structural elements of overhead contact system have to possess adequate mechanical and electrical strength.

**3.6 Copper alloy or copper** should be selected as the material of contact wire. Contact wire made of the same material should be used within the same locomotive routing.

The tension of contact wire on mainline shall not be less than; 10 kN ( $v \leq 120$  km/h); 13 kN ( $120$  km/h  $< v \leq 160$  km/h). For electrification railway with speed more than 120 km/h, pre-sag shall be set for contact wire.

**3.7 Stranded wire made of copper alloy, copper or other material** should be used as messenger wire. The material of current-carrying messenger wire should be the same as that of contact wire.

**3.8 Physical property of OCS wire used in European Union (EU) and China** are shown in the tables below. They are more or less the same but differ at some physical property.

Table 4: Physical property of contact wires according to EU standards [2]

Property	Unit	Cu	Contact wires		Origin
			CuAg0,1	CuMg0.5	Application
Ultimate strength $\sigma$	$10^6$ N/m <sup>2</sup>	355	360:100 mm <sup>2</sup>	510:100 mm <sup>2</sup>	EN 50149
		330	350:120 mm <sup>2</sup>	490:120 mm <sup>2</sup>	EN 50149

Modulus of elasticity $E$	kN/mm <sup>2</sup>	120	120	120	EN 50149
Coefficient of thermal expansion $\alpha$	10 <sup>-6</sup> K <sup>-1</sup>	17	17	17	EN 50149
Coefficient of resistivity $\sigma_{20}$	10 <sup>-3</sup> K <sup>-1</sup>	3.93	3.81	3.85	EN 50149
Resistivity $\rho_{20}$	$\Omega \cdot \text{mm}^2/\text{m}$	0.01777	0.01777	0.02778	EN 50149
Conductivity $k_{20}$	$S \cdot \text{m}/\text{mm}^2$	56.3	56.3	36.0	EN 50149
Specific mass $\gamma$ (density)	kg/dm <sup>3</sup>	8.9	8.9	8.9	DIN 43 140;
Specific heat $c$	Ws/(kg.K)	380	380	380	EN 60865-1
Coefficient of thermal conductivity $\lambda$	W/(K .m)	377	375	59	

Table 5: Physical property of contact wires according to Chinese standards

Property	Unit	Cu	Contact wires		Origin Application
			CTAH (China)	CTMH (China)	
Ultimate strength $\sigma$	10 <sup>6</sup> N/m <sup>2</sup>	355	375: 85 mm <sup>2</sup>	525:110mm <sup>2</sup>	TB/T2829: 2005
		330	360: 120 mm <sup>2</sup>	520:120mm <sup>2</sup>	TB/T2829: 2005
Modulus of elasticity $E$	kN/mm <sup>2</sup>	120	120	120	TB/T2829: 2005

Coefficient of thermal expansion $\alpha$	$10^{-6}K^{-1}$	17	17	-	TB/T2829: 2005
Resistivity $\rho_{20}$	$\Omega \cdot mm^2/m$	0.01777	0.01777	0.02573	TB/T2829: 2005
Conductivity $k_{20}$	$S \cdot m/mm^2$	56.3	56.3	38.9	TB/T2829: 2005
Specific mass $\gamma$ (density)	$kg/dm^3$	8.9	8.9	8.9	TB/T2829: 2005
Specific heat $c$	Ws/(kg.K)	380	380	380	TB/T2829: 2005
Coefficient of thermal conductivity $\lambda$	W/(K .m)	377	375	-	TB/T2829: 2005
Diameter of wire	mm	-	For $85mm^2=10.8$ For $120mm^2=12.9$	-	TB/T2829: 2005

Table 6: Physical property of catenary wires/stranded wire/ according to EU standards

Property	Unit	Catenary wire	Origin Application
		BzII	
Ultimate strength $\sigma$	$10^6 N/m^2$	589	DIN 48 200: BzII: 7-wire; steel II
Modulus of elasticity $E$	$kN/mm^2$	113	DIN 48 203:7-wire
Coefficient of thermal expansion $\alpha$	$10^{-6}K^{-1}$	17	DIN 48203
Coefficient of resistivity $\sigma_{20}$	$10^{-3}K^{-1}$	4	DIN 48203;EN 60865-1
Resistivity $\rho_{20}$	$\Omega \cdot mm^2/m$	0,02773	DIN 48203;EN 60865-1
Conductivity $k_{20}$	$S \cdot m/mm^2$	36	DIN 48203; EN 60865-1

Specific mass $\gamma$ (density)	kg/dm <sup>3</sup>	8.9	DIN 48 200
Specific heat $c$	Ws/(kg.K)	380	EN 60865-1
Coefficient of thermal conductivity $\lambda$	W/(K .m)	59	

Table 7: Physical property of catenary wires /stranded wire/ according to Chinese standards

Property	Unit	Catenary wire	Origin
		JTMH	Application
Ultimate strength $\sigma$	10 <sup>6</sup> N/m <sup>2</sup>	589	TB/T2829: 2005
Modulus of elasticity $E$	kN/mm <sup>2</sup>	113	TB/T2829: 2005
Coefficient of thermal expansion $\alpha$	10 <sup>-6</sup> K <sup>-1</sup>	17	TB/T2829: 2005
Coefficient of resistivity $\sigma_{20}$	10 <sup>-3</sup> K <sup>-1</sup>	4	TB/T2829: 2005
Resistivity $\rho_{20}$	$\Omega \cdot \text{mm}^2/\text{m}$	0.02773	TB/T2829: 2005
Conductivity $k_{20}$	$S \cdot \text{m}/\text{mm}^2$	36	TB/T2829: 2005
Specific mass $\gamma$ (density)	kg/dm <sup>3</sup>	8.9	TB/T2829: 2005
Specific heat $c$	Ws/(kg.K)	380	TB/T2829: 2005
Coefficient of thermal conductivity $\lambda$	W/(K .m)	59	TB/T2829: 2005
Diameter of wire	Mm	For 70mm <sup>2</sup> =10.5 For 95mm <sup>2</sup> =12.5	TB/T2829: 2005

**3.9 Designed strength safety coefficient** for overhead contact line system shall conform to the following stipulations;

1. Under the situation that maximum allowable wear area is 20%, the strength safety coefficient of copper or copper alloy contact wire shall not be less than 2.0.

2. The strength safety coefficient of various messenger wire; not less than 2.0 for copper or copper alloy wire, not less than 3.0 for steel stranded wire, not less than 2.5 for steel aluminum stranded wire. Al-coated steel stranded wire or Cu-coated steel stranded wire.
3. For head span structure, the strength safety coefficient of the head span wire shall not be less than 4.0; that of registration wire shall not be less than 3.0.
4. As for additive wire such as feeder, reinforcing feeder, positive feeder cable, return wire, etc., their strength safety coefficient shall not be less than 2.5.

**3.10 Stress  $\sigma$**  on any element on OCS is determined by:

$$\sigma = \frac{T}{A}$$

Where

$T$  - Force acting on the element

$A$  - Cross sectional area of the element

**3.11 The maximum allowed values of stress** on a particular OCS element are calculated by multiplying and dividing coefficients on the limit stress value i.e.

$$\sigma_{Max} = \frac{\sigma_{limit}}{k_3} k$$

Where

$\sigma_{limit}$  - The limit stress value for that particular object - *elasticity limit*

$k$  - Correction coefficient – to account the possible change of  $\sigma_{limit}$  during operation

$k_3$  - Strength safety coefficient

Hence, to ensure the safe operation of OCS, the actual stress  $\sigma_{actual}$  on any of OCS element of, should not exceed the above maximum allowed stress. i.e.

$$\sigma_{actual} \leq \sigma_{Max}$$

**3.12 For contact wires and messenger wires**, instead of maximum stress value check, maximum allowed tension on the wire could be used i.e.

$$T_{Max} = \sigma_{Max} \cdot A = \frac{\sigma_{limit}}{k_3} k \cdot A$$

When considering the maximum allowed wear on the contact wire to be 20% of the total cross section area of contact wire; the maximum tensile force is calculated as.

$$T_{Max.contactwire} = \frac{\sigma_{limit}}{2} \cdot A \cdot 0.75$$

Since there is no wear on messenger wire, the formula for maximum tension of messenger wire

$$\text{is } T_{Max.catenarywire} = \frac{\sigma_{limit}}{2} \cdot A$$

According to EN 50119:2001 [15],

The calculated grooved contact wire working tensile stress shall not exceed 65 % of the minimum tensile stress of the grooved contact wire. The minimum tensile stress of the grooved contact wire shall be multiplied by the product of these factors to get the maximum permissible working tensile load.

$$\sigma_{per} = \sigma_{min} \times 0.65 \times K_{temp} \times K_{wear} \times K_{load} \times K_{eff} \times K_{clamp} \times K_{jo\ int}$$

Whereas the maximum allowed stress value on the catenary wire in which wear is not concerned is given by

$$\sigma_{per} = \sigma_{min} \times 0.65 \times K_{temp} \times K_{wind} \times K_{eff} \times K_{clamp} \times K_{load}$$

Where

$\sigma_{min}$  -is the minimum breaking stress of the contact line

$K_{temp}$  -factor which relate maximum working temperature and permissible working stress

$K_{wear}$  -permitted maximum wear

$K_{load}$  -factor which express the effect of wind

$K_{eff}$  -tensioning equipment efficiency

$K_{clamp}$  -Tensioning clamp characteristics

$K_{\text{joint}}$  -factor which describe reduction of tension due to joint

The maximum working (permissible) tensile force for both contact and catenary wire becomes

$$T_{\text{per}} = \sigma_{\text{per}} \times A$$

All the above coefficients are given and selected according to the situation.

### **OCS clearance and insulation gap requirements**

**3.13** The maximum distance between contact wire and rail top shall not be more than 6500 mm. Min. distance shall conform to the following stipulations.

1. In station yard and section (including tunnel), the heights of contact wire to rail top shall be the same, of which the minimum value shall not be less than 5700 mm; in marshalling stations and section stations which are equipped with shunting unit, the height can be not less than 6200 mm under normal conditions and shall not be less than 5700 mm under difficult conditions.
2. In existing tunnel (including the area outside the tunnel where tunnel height is decreased as stipulated and inside the buildings crossing track), the height of contact wire shall not be less than 5 700 mm under normal conditions, not less than 5650 mm under difficult conditions, and not less than 5 330 under special conditions.
3. For the line on which double-deck container train runs, the lowest height from contact wire to rail top shall not be less than 6330 mm.

**3.14** When the height at the suspension point of incoming wire (working wire) is changed, the gradient should not be bigger than 2% , and bigger than 4% under difficult conditions. At the spans of both ends of the section where the gradient varies, the gradient change of contact wire should not be bigger than half of the greatest gradient in the section with gradient varying.

**3.15** The shortest dropper length should not be less than 500 mm on main line within the section and in station yard, and not less than 400 mm in tunnel.

**3.16** The sag of contact wire under each suspension mode should not be more than 250 mm. Within low-speed section where running speed is not more than 45 km/h, the sag of contact

wire can be 350 mm.

**3.17** The insulation level of overhead contact line system shall accord with the stipulation and table as follows:

1. The creep age distance shall not be less than 960 mm in lightly polluted area and not be less than 1200 mm in heavily polluted area.
2. If there is no detailed pollution data, then the creepage distance shall be determined according to the requirement of heavily polluted area.
3. The air insulation gap shall not be less than the stipulations listed in the table below
4. Within double-track section, the distance between the live parts of up and down track shall not be less than 2000 mm under normal circumstances; not be less than 1600 mm under difficult conditions.
5. The elevation correction factor is:  $K = 1/[1.1 - (H/1000)]$  and the requirements for the air insulation gap and the installation gap are as shown in the following table:

Table 8: Values of Air Insulation Gap(mm)

No	Relevant Circumstances	Value: (Normal Condition)	Value: (Difficult Condition )	
1	Gap between two suspension points of insulated overlap	Normal circumstance (applicable to any elevation)	450	—
		Booster transformer location	3C0	—
2	Gap from live parts of auto transformer feeder cables to live parts of overhead contact line or feeders	500	450	
3	Gap from 25 kV live parts to fixed earthing body	300	240	
4	Gap from 25 kV live parts to rolling stock or loaded goods	350	—	
5	Instantaneous gap from limit position caused by pantograph vibration and the highest position of uplifted conductor to earthing part	200	160	

6	Gap from leading wire of isolator, electric connecting wire (including that crosses another branch of suspension), feeder cables of automatic transformers or jumper wire for feeder to earthing bodies	330	—	
7	Gap from 25 kV live parts to the neutral wire or protective wire of auto transformer when the wind is flowing oppositely and the wind speed is 13 m/s	250	—	
8	Gap from the shed on the earthing side of insulating elements to earthing parts (applicable to any elevation)	Porcelain and toughened glass insulators	100	75
		Insulating elements made of synthetic materials	50	—
9	The static gap from 25 kV live parts to the bottom of buildings or crossing track	500	300	

Notes on the table:

- 1 When the creepage distance in polluted area is increased, the values of the air insulation gap listed in table above may not be increased;
- 2 In the area where the elevation is more than 1 000 m, the values of the air insulation gap listed in Table above shall be modified.
- 3 When it is very difficult to adopt the normal gap within the existing structures such as tunnel with low clearance, Overpass Bridge etc. and the corresponding lightning protection measures have been adopted, the difficult values listed in Table above may be used thereafter. It is forbidden to adopt the difficult values in the heavy thunderstorm area and in the area less than 10km far away from coastline.

### **OCS Protective earthing requirements**

**3.18** The masts of overhead contact line system and metal structures close to live part of overhead contact line system shall be earthed according to the following principles.

- 1 Working earth

- a) A Centralized earthing mode should be adopted for masts of overhead contact line system by using the return cables and protective wires as flashover protective earthing wires.
- b) Aerial earthing wire can additionally be erected to realize the centralized earthing for the masts arranged in rows and without suspending return cables and protective wires; separate earth electrode should be installed (in the section where there is signal track circuit available) or direct connection with rail via earthing wire should be made (in the section where there is no signal track circuit available) for the earthing of scattered separate masts.
- c) For steel mast, return cables and protective wires should be insulated; For steel reinforced concrete masts, whether return cables and protective wires need to be insulated or not may be determined by the thickness of concrete protective layer and the result of power supply calculations.
- d) The boosting wires connected with return cables or protective wires can directly be connected to the N-point of the choke transformer winding in the section where there is signal track circuit, or directly connected to the rail in the section where there is not signal track circuit.

## 2 Safe earthing

- a) For each metal structure (bridge railing, water crane, signal etc.), separate earth electrode shall be set within the range of 5m away from the live part of overhead contact line system in order to realize safe earthing.
- b) For the brackets of switchgear, arrester and booster transformer etc. , separate earth electrode shall be set so as to realize safe earthing.
- c) For steel masts of overhead contact line system, safe earthing can be realized by erecting aerial earth wire or setting earth electrode separately.
- d) At the termination of anchor section or in the middle of the anchor section with length more than 1000 m, separate earth electrode shall be installed to realize safe earthing.
- e) The earthing resistance of the earthing device for the equipment of overhead contact line system and its surrounding structures shall not be more than the values stipulated listed in Table below. Normally, the earthing part is welded by galvanized flat steel or angle steel. Round steel is generally adopted as earthing wire. The diameter of embedded earthing

wire shall be not less than 12 mm, while that of exposed earthing wire shall be not less than 10 mm.

Table 9: Values of Earthing Resistance of Earthing Device for Overhead Contact Line Equipment and its Surrounding Structures

Type	Value of Earthing Resistance
Switchgear, arrester, booster transformer	10
Aerial earth wire	
Scattered mast of overhead contact line system	30
Metal structures within the range of 5 m away from the live part of overhead contact line system	
Lightning protection wires	10

#### 4. System modeling

##### General trolley and simple catenary OCS model analysis steps

- 1 For the given geographical location of station, meteorological factors are analyzed to come up with the designating value of wind speed, minimum temperature and maximum temperature based on given data and standards
- 2 Calculate loads acting on the OCS, horizontal components, vertical components and resultant load during various extreme weather conditions/states such as  $S_{Tmin}$ ,  $S_{Tmax}$  and  $S_{wind}$
- 3 Set the maximum allowed tension on messenger wire (the load acting on this wire should not create tension on this wire which is greater than this allowed max load).
- 4 Calculate the nominal tension of the contact wire
- 5 Determine the maximum span length and anchor section
- 6 Place the OCS mast on the station plan by considering the maximum span length
- 7 Calculate the critical span length

- 8 Determine the value of tensile force of messenger wire by considering horizontal contact wire without sag
- 9 Determine the weather state that create the highest tension on the messenger wire and adjust the critical span length
- 10 Prepare installation table of the OCS based on the most extreme weather state for trolley and semi compensated OCS.
- 11 Determine the change of sag of contact and messenger wire for the most extreme weather condition for trolley and semi compensated OCS.

### **Application of OCS models**

**4.1** OCS are modeled in order to:

- Preparing installation graph and installation table to fix sag height and tensile force when installing new OCS and regulate conductor during temperature change
- Checking whether the designed OCS will meet horizontal and vertical clearance requirements, in accordance with the standard or pre-specified limit value, during operation for ever extreme meteorological state
- Determining the tensile force of conductors at various meteorological states. This helps to determine the load that will be transferred on various structures and mast of an OCS.

**4.2** The modeling of OCS will result two equations are used frequently. These are:

Equation of state of changes

$$t_i = \left( t_1 - \frac{q_i^2 l^2}{24 \alpha H^2} + \frac{H_1}{\alpha EA} \right) + \frac{q_1^2 l^2}{24 \alpha H_1^2} - \frac{H_i}{\alpha EA},$$

Equation for sag height

$$f_i = \frac{gl_i^2}{8H_i},$$

**4.3** Installation table is calculated by taking initial condition to be the most extreme weather condition.

**4.4** The extreme weather condition is determined by, comparing the design value of span

length  $l$  with  $l_{cr}$ .

- the critical span length is calculated as:

$$l_{cr} = H_{\max} \sqrt{\frac{24 \alpha (t_{wind} - t_{t \min})}{q_{wind}^2 - g^2}},$$

- If  $l < l_{cr}$  then the most extreme state is  $S_{tmin}$
- If  $l > l_{cr}$  then the most extreme state is  $S_{wind}$

### Maximum span length and anchor length

**4.5** The maximum design value of span length depends is chosen based on three criteria. These are:

1. For keeping conductor wind deflection within acceptable limit
2. For keeping acceptable OCS conductors vertical clearance limit
3. For reliable and smooth pantograph-OCS interaction, taken 65meter in Chinese standard

The design value of span length will be the minimum from the three span lengths.

**4.6** For keeping conductor wind deflection within acceptable limit, the maximum span length is calculated as:

$$l_{\max} = 2 \sqrt{\frac{K}{F'_w} \left( b_{k \lim} + \sqrt{b_{k \lim}^2 - a^2} \right)}$$

**4.7** For keeping acceptable OCS conductors vertical clearance limit,

- the maximum span length, for semi-compensated OCS is calculated with the help of computer program for the equation below:

$$0.25 \text{ m} = (l_{\max} - 2c)^2 \left( \frac{q_i + \frac{q_0 K (l_{\max} - 2c)^2}{T_0 l_{\max}^2}}{8(T_i - Y_i K)} - \frac{g_0}{8T_0} \right),$$

- the maximum span length, for fully-compensated OCS is calculated by the equation below:

$$l_{\max} = \sqrt{\frac{2(K + T)}{q_0 - q_i}}$$

**4.8** For reliable and smooth pantograph-OCS interaction, the maximum span length is taken as 65meter /Chinese standard/

**4.9** The maximum anchor section for fully-compensated OCS is calculated by considering weight aggregate displacement on anchoring mast.

$$L_{\text{anchor} - \max} = \frac{A_{\max}}{k\alpha(t_{\max} - t_{\min})},$$

### **Traction impedance**

**4.10** Resistance of OCS conductors per unit length is calculated for all elements of OCS as follows

- **Wires and conductors resistance**

The resistance per unit length of wires and conductors is calculated by:

$$R'_c = \frac{R}{l} = \frac{rl}{Al} = \frac{r}{A}$$

Where:

$R'_c$  = per unit resistance,  $r$  = specific resistivity of the conductor in  $\Omega m$ ,  $l$  = conductor length

$A$  = cross sectional area of the conductor

- **Running rails**

The resistance of steel running rails can be obtained from table below which shows the characteristic properties of commonly used running rails. Where rail joints are used, the resistance  $R'_c$  is increased according to the material and cross section. A commonly accepted value is 0,5% per joint.

Table 10: Resistances per unit length of conductors at 20 °C and 40 °C, values in mΩ/km

Conductor	A mm <sup>2</sup>	R <sub>c</sub> ' at 20 <sup>0</sup> C		R <sub>c</sub> ' at 40 <sup>0</sup> C	
		New	20 % worn	new	20 % worn
Cu AC-80	80	223	278	240	300
Cu AC-100	100	179	223	193	240
Cu AC 120	120	149	186	160	200
CA BzII	70	422	-	455	-
CA BzII	95	298	-	321	-
CA BzII	120	237	-	255	-

Table 11: Characteristic properties of commonly used running rail types

Rail type	m'	H	F <sub>w</sub>	A	U	r' <sub>eq</sub> A	R' mΩ/km	R' mΩ/km
	kg/m	Mm	Mm	mm <sup>2</sup>	mm	mm	wear 0 %	wear 15%
R50	50,50	152	132	6450	620	45.31	34.5	40.6
R65	65,10	180	150	8288	700	51.36	25.2	29.9

Note: m-mass per unit length, H-height of rail, F<sub>w</sub>-foot width, A-cross section,

r<sub>eq</sub> –cross section-area-equivalent radius:  $r_{eq} = \sqrt{A/\pi}$

R'-resistance at 20 °C

- **Earth return path**

The resistance per unit length of the earth return path  $R_E$  is a function of the frequency of the power supply.

$$R_E = \left( \frac{\pi}{4} \right) \cdot \mu_0 \cdot f$$

**4.11** Assuming that, the total current on the combined overhead lines flows to the combined rails,  $I_O = I_r = I_{traction}$ , then, the total equivalent impedance i.e. the traction impedance

of a single track catenary OCS, per kilometer, is calculated as shown in the table below:

Table 12: Summary of OCS traction impedance modeling and calculation ( $\Omega/km$ )

<b>Conductor self impedance</b>	$Z_c = R' + j0.5\omega \cdot 10^{-3}$
	$Z_m = R' + j0.5\omega \cdot 10^{-3}$
	$Z_{r_1} = R' + \left(\frac{\pi}{4}\right) \cdot \mu_0 \cdot f \cdot 10^{-3} + j0.5\omega \cdot 10^{-4}$
	$Z_{r_2} = R' + \left(\frac{\pi}{4}\right) \cdot \mu_0 \cdot f \cdot 10^{-3} + j0.5\omega \cdot 10^{-4}$
<b>Mutual impedance</b>	$x_{cr_1}^m = 2\omega \cdot 10^{-4} \ln \frac{d_{mr_1}}{d_{mc}}$
	$x_{r_1c}^{r_2} = 2\omega \cdot 10^{-4} \ln \frac{d_{r_2c}}{d_{mr_1}}$
<b>Loop impedance</b>	$Z_{cr_1} = Z_c + j2\omega \cdot 10^{-4} \ln \frac{d_{cr_1}}{R_c}$
	$Z_{r_1c} = Z_{r_1} + j2 \cdot 10^{-4} \ln \frac{d_{cr_1}}{R_{r_1}}$
	$Z_{cm} = Z_c + j2\omega \cdot 10^{-4} \ln \frac{d_{cm}}{R_c}$
	$Z_{mc} = Z_m + j2\omega \cdot 10^{-4} \ln \frac{d_{cm}}{R_c}$
	$Z_o = \frac{Z_{cr_1} Z_{mc} + jx_{cr_1}^m Z_{cm}}{Z_{mc} + Z_{cm}},$

Combined impedance	$Z_r = 0.5 (Z_{r1c} + jx_{r1c}^{r2})$
Equivalent or traction impedance	$Z_{eq} = Z_o + Z_r$ ,

## 5. System arrangements and layout

### Overlaps arrangement

5.1 The subdivision of the overhead line into different feeder zones, with feeders having the same electrical phase, is required at the boundaries of stations and non-station section

5.2 The arrangement of overlap in station is as shown in the figure below.

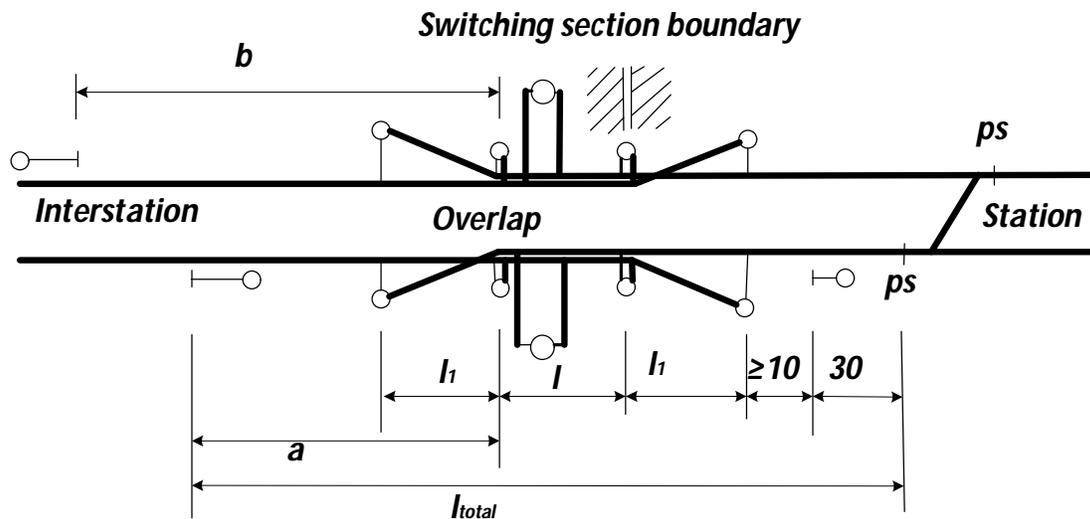


Figure: Arrangement of insulated overlapping sections relative to signaling and track points

- Suburban rapid transit systems  $v_{max} < 200$  km/h  $a > 100$  m;
- High-speed lines with  $v_{max} > 200$  km/h  $a > 100$ ;
- In Suburban rapid transit systems  $v_{max} < 200$  km/h  $b > 200$  m;
- High-speed lines with  $v_{max} > 200$  km/h  $b > 500$  m;
- $l = 0.75l_{max}$
- $l = l_{max}$

**5.3** For standard lines operated at speeds up to 200 km/h, the distance  $l_{total}$  between the signal and point start should, therefore, be at least 275 m for a three-span overlap.

### **Neutral section arrangement**

**5.4** Phase separation sections must ensure that trains can move from one section to an adjacent one without bridging the adjacent phases.

**5.5** Adequate means need to be provided to allow a train that is stopped within the phase separation section to be restarted.

**5.6** The neutral section arrangement should consider that, all the pantographs of the longest trains can be accommodated within the neutral section.

**5.7** The length of the neutral section has to be at least 142 m in this case.

**5.8** The maximum spacing between the outer pantographs is 140 m. reserve of 2 m leads to a spacing of 142 m.

**5.9** Neutral section of overhead contact line system shall be located in traction substation, sectioning post, and at the boundary between railway bureaus.

**5.10** The location of the neutral section of overhead contact line system shall fulfill the requirements of the operation mode of electric locomotive, convenience for shunting operation, reasonable arrangement of power supply line, as well as the requirements of the position and display of home signal etc.

**5.11** The location of the neutral section of overhead contact line system shall be more than 300m away from home signal or the first turnout of the station

### **Mast layout in station**

#### **5.12 OCS mast location determination near track turnouts**

- For simple turnout, the most preferable position of OCS mast near this turnout is at a distance “C” from the track intersection point, **PC**.

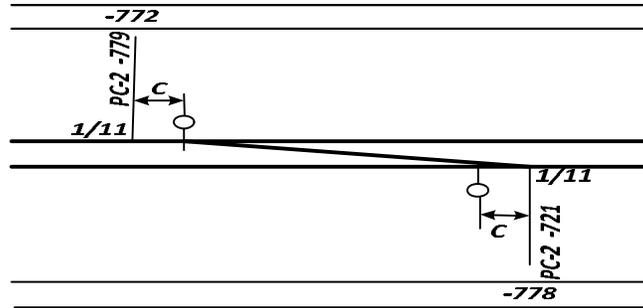


Table 13: Mast distance from turnout point

Type of turnout	1/22	1/8	1/11	1/9
Optimal distance of the mast from the track intersection point	12.5	11	6	5

Note:

- The above length might be taken smaller considering the actual scenarios, however the distance between the point center to the mast must not be less than that 4-6 meter.
- The above distance might be increased considering site conditions but not more than 1 meter.
- For the diamond crossing; OCS mast are placed at the center point of the crossing and if necessary the mast can be displaced 1 or 2 meter to either sides of the center point of the diamond crossings.
- For a curve after the crossing turnout found at the far end of station tracks; the mast location should be chosen to be at the center of the curve.

### 5.13 Placing pole at turnout and side track curve area

- Near the center of turnouts of main tracks; mast with supporting structure should be placed.
- To avoid short span length, a mast above track points could have a pull of structure rather than a supporting structure, if only if the OCS wire did not change direction at this point and the turnout or track point is at side tracks rather than main track.
- For simple turnout, the most preferable position of OCS mast near this turnout is at a distance “C” from the track intersection point, **PC**.

- Masts supporting portal structure are used to support OCS wire across three to eight tracks
- At the departure and entrance end of station, where the number of track not greater than two; a metallic or concrete mast with one or two cantilever structures are used
- Near station area with more than 8 tracks; head-span structures are used which is supported by metallic or concrete mast.
- In any case, the span length, or distance between two masts with supporting structure, should be lower than the calculated maximum allowable span length.
- In multiple track section of stations, with parallel main track and side tracks, where head-span or portal are used; the span length between two consecutive head-span or portal, should be selected as the minimum of allowable span length calculated for main track and side track.
- The maximum of span length should be 65 meter and the minimum should be 30 meter.
- The difference between two adjacent span length should be lower than 25%.
- Independent masts in opposite tracks should be place facing each other.
- Considering site conditions and layout conditions, the mast location could be shifted within 1-or 2 meter from the first selected position at point center of the turnout.

#### **5.14 Placing masts in between station departure and entrance area**

- Placing OCS supporting structures opposite to public entrances, exits area, station building doors, platform or passenger overpass bridge staircases, gang ways and signaling & interlocking equipments shall be avoided. In general, OCS supporting structures shall be placed not in a way that hinders people's movement as well as freight loading and unloading.
- OCS supporting structures can be placed on station platform. However, the setting of masts, i.e. the distance between the mast and the rail track center line, on platforms shall not be less than 4.75 m. As far as possible, masts shall be located in line with other masts or obstructions on platform and shall be of minimum possible dimensions and fit in with the architectural pattern prevailing in the vicinity.
- For separate group of tracks or track groups other than tracks grouped together with main

tracks; a separate OCS supporting structures or portal shall support the OCS wires.

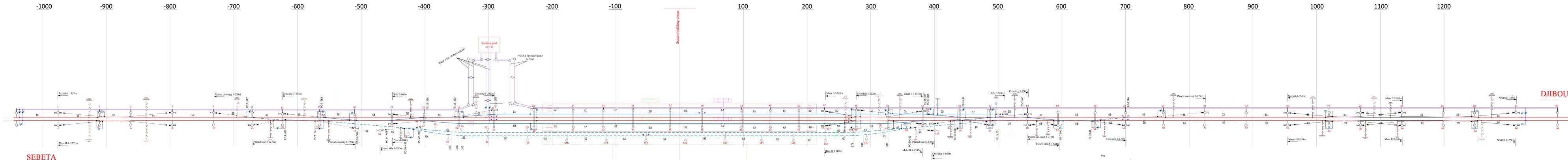
- To pass OCS under the passenger overpass bridge; there shall be OCS supporting structures placed at the left and right side of the bridge with equal distance separation to keep the bridge at the center of the span.
- Mostly, the middle of the anchor section of fully compensated or half compensated OCS systems falls at the middle station area. Hence, the span length of two spans, in the middle of the anchor section of fully compensated OCS, shall be lower by 10% of the maximum span length calculated in order to accommodate the middle anchoring. For semi-compensated OCS only one span, found in the middle of anchor section, should be lower by 10% of the maximum span length calculated.
- If there exist turnout at the middle of station, OCS above track points or point center shall be fixed by portal supporting structures. If this is not possible, other mast which will fix OCS above track point shall be provided.
- There shall not be anchoring and tensioning device near the station platform area to avoid the risk of breakage on passengers/people on the platforms.
- Head-span or portal OCS supporting structures permit the termination of overhead contact lines. It can however be expedient to provide separate termination anchor poles in order to limit the overhead contact line length or to avoid sharp bends and intersections.
- The standard length of portal type mast is 44 meters (for 8 tracks), and if the number of track is greater than 8, there shall be another portal supporting mast in between tracks. In this case, the *setting of masts* shall be at least 3.1. In difficult conditions, the *setting of masts* shall be placed at 2.5 meter from but not less than this.
- No live conductor should be run over platforms.

# Appendix B

## Term Definition

1. **Cantilever:** Support consisting of one or more transverse members projecting from a mast
2. **Catenary (Messenger) wire:** Longitudinal wire supporting the grooved contact wire or wires either directly or indirectly by means of droppers
3. **Compensating System:** A system which compensates the change of tensile force on OCS wire due to temperature change and other factors
4. **Contact wire:** Electric conductor of an overhead contact line with which the current collectors make contact
5. **Contact wire height:** Distance from the top of the rail to the lower face of the contact wire, measured perpendicular to the track
6. **Dropper (Hunger):** Component used to suspend a contact wire the on catenary
7. **Mast (pole):** Mainly vertical structure to provide for support, tensioning and registration of the overhead contact line
8. **Overhead Contact System (OCS):** A system of conductors / equipments carrying traction power from traction substation to electric locomotive.
9. **Pantograph (Current Collector):** Apparatus for collecting current from one or more contact wires, formed of a hinged device designed to allow vertical movement of the pantograph head
10. **Span length:** The distance between the centre lines of the adjacent supporting masts for overhead equipment/lines.
11. **Stagger:** Stagger of the contact wire is the horizontal distance of the contact wire from the vertical plane through the centre of track.
12. **Section Insulator:** A device installed in the contact wire for insulating two elementary electrical sections from each other while providing a continuous path for the pantograph without break of current.
13. **System height:** Refers to the vertical distance between contact wire and the catenary (messenger) wire at the mast.
14. **Tension (Anchoring) length:** Length of overhead contact line between two anchoring points

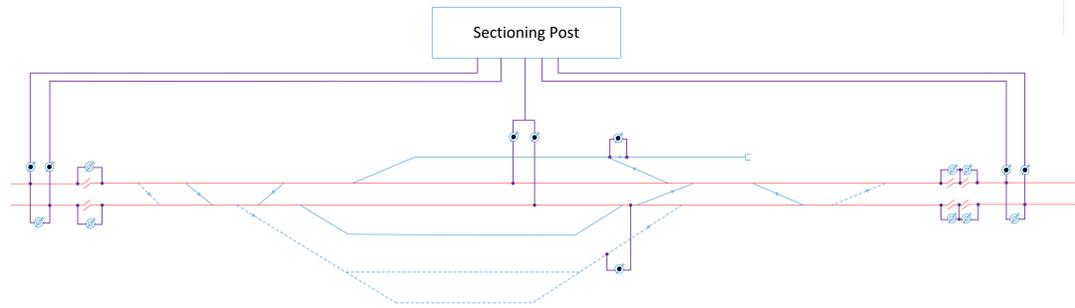
Mast location from the reference	976	911	882	797	731	671	624	566	510	452	401	347	292	229	167	120	73	-15	35	97	142	187	227	277	327	381	397	440	488	510	546	594	652	710	759	824	889	954	1019	1067	1134	1199	1248	1313	1378
Mast number	1,2	3,4	5,6	7,8	9,10	11,12	13,14	15,16	18,19	20,21	22,23	24,25	26,27	28,29	30,31	32,33	34,35	36,37	38,39	40,41	42,43	44,45	46,47	48,49	50,51	52,53	54	55,56	57,58	59	60,61	62,63	64,65	66,67	68,69	70,71	72,73	74,75	76,77	78,79	80,81	82,83	84,85	86,87	88,89



Mast number for planned root	51	52	53	54	55	56,57	58,59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100			
Mast location from the reference point	470	426	384	364	343	301	239	177	115	53	9	71	128	178	229	289	293	315	357	400																															

- Key
- Current carrying conductor
  - Non-current carrying conductor
  - Crossing and side conductor
  - - - Future extension line
  - Feeder line
  - 
  - 
  - 
  - 
  - 
  - 
  - 
  - 
  - 
  - 
  - 
  -

- Note:
- Poles must be placed at every 100m interval from station buildings to refer location
  - Mast number and span length must be included
  - PC point with their number and location must be specified
  - In the anchor length termination type of track and anchor length must included
  - It is possible to include all necessary information in the mast number and location table such as mast type, registration arm type and specification, etc.



Sectioning and feeder schema

By Beyene Ayabeta	Railway Overhead Contact System plan for Indoor station	Scale	1:1000
	Plan done and submitted for case study of Master thesis work in Electrical Engineering(Railway)	Date	August 2014