DEPARTMENT OF ELECTRICAL ENGINEERING

EEEN60372 – OHL DESIGN COURSEWORK

Design of 275kV Transmission Line Tower

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Contents

1 Introduction

This report contains a design for the proposed new transmission system between Manchester to Birmingham. It includes schematic diagrams and calculations.

1.1 System Design Data

The calculations are made for the components and attributes mentioned in the table below. Certain changes have been made in terms of the values given from the coursework to adapt it to SI units, or manipulate multiplication factors to make calculations easy. This **symbols and data** mentioned in this section is repeatedly used across all other sections and cross reference is provided appropriately.

Table 1: Design Data for transmission system

Rated Voltage, V_r	275kV
Number of Circuits, N_c	2
Span length, L_s	366m
Installed at Temperature, $T_{installed}$	5℃
Maximum Operating Temperature, T_{max}	75℃
Width of the Tower, W_t	2.7 m
Shielding angle(at no wind), θ_{shield}	30^o
Wind speed for clearances, V_w	18.8 m/s
Minimum heat loss due to convection, q_c	41.40 W/m
Minimum radiated heat loss, q_r	19.20 W/m
Maximum solar heat gain, q_s	14.30 W/m

Table 2: Design Data for Rubus single AAAC conductor

Diameter, D_{cond}	**Mass**, M_c	**Strength**, T_r	**Coeff. of expansion**, ε_t	**RAC at 20ºC**	**RAC at 75ºC**
0.0315 m	1.622 kg/m	173530 N	23 e^{-06} ℃$^{-1}$	0.0574 Ω/km	0.0688 Ω/km

1.2 Python Program

A Python program with all the calculations for tower design can be found at: $EEEN60372_{OHLCoursework.py}$

2 Power Rating Calculations

Thermal Rating of a conductor, also known as Power Rating, is calculated using its current carrying capacity at maximum operating temperature. “The ampacity of a conductor is that current which will meet the design, security and safety criteria of a particular line on which the conductor is used.” (Stephen, 1992) This is calculated using the law of conservation of thermal energy. The balance between Heat gain(caused by Ohmic losses and Solar heating) and Heat loss(due to atmospheric conditions and wind) is equated, and current value is obtained from the following equation:

$$I = \sqrt{\frac{q_c + q_r - q_s}{R_{TC}}} \tag{1}$$

where,
q_c = Convection heat loss, W/m
q_r = Radiated heat loss, W/m
q_s = Solar heat gain, W/m
I = Conductor current, Amperes
R_{TC} = AC conductor resistance at maximum operating temperature, Ω/m

The MVA Rating can be calculated from the following equation:

$$MVA_{Rated} = \sqrt{3} * V_r * I * N_c * 1e^{-06} \tag{2}$$

2.1 Results

Substituting values from Table 1 and Table 2 on the above equations, and rounding off to nearest whole number fetches the following results:

$$MVARating = 781.483 \approxeq 780MVA \tag{3}$$

3 Tower Diagram

This design schematic shown below is a hybrid model where the left hand side of the vertical purple axis shows the values for a conventional Pin-cap type glass insulator whereas the right hand side design shows the values for Polymer rod type insulator. The external clearances are same for both cases. All measurements labeled are physical dimensions validated against electrical clearances.

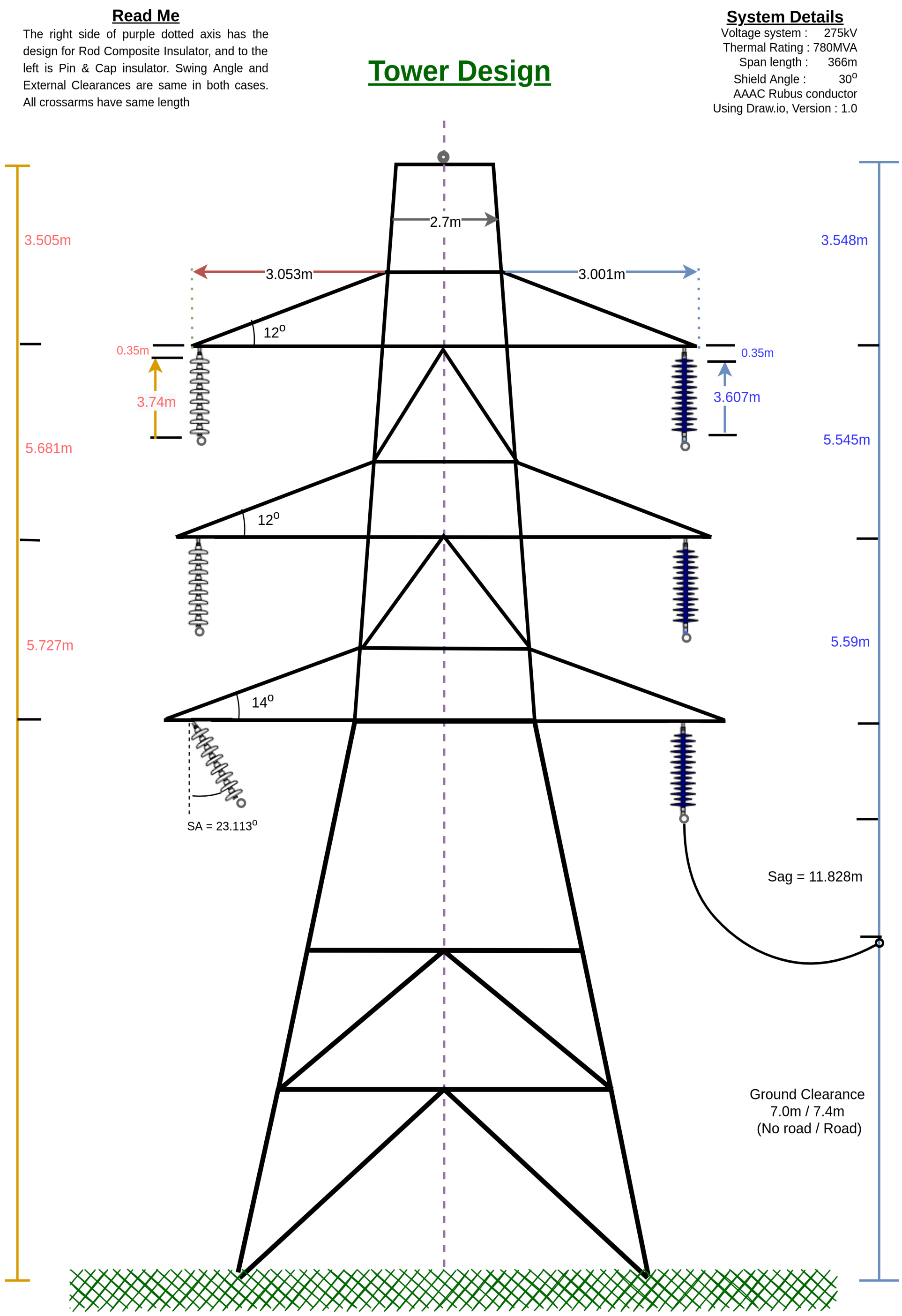

Figure 1: Tower Design

4 Internal Clearance Calculations - Top Tower Geometry

The internal clearance calculations for Top tower design is done here.

4.1 Insulator Length - U160BLP

The primary insulator design uses a Pin-Cap type glass insulator U160BLP. An alternate design using a polymer rod type insulator. The calculations, results and comparison is provided in a section below.

Table 3: Design Data for insulator

Required Creepage distance, D_{cr}	11.6m
Length of fittings, L_{fit}	0.35m
U160BLP Creepage distance, D_{u160}	0.525m
U160BLP Spacing, P_{u160}	0.17m

The number of discs required for insulator is calculated by

$$N_{discs} = ceil(\frac{D_{cr}}{D_{u160}}) \tag{4}$$

The length of insulator is given by:

$$D_{insulator} = N_{discs} * P_{u160} \tag{5}$$

$$D_{insulator} = 3.74m \tag{6}$$

4.2 Gap Factor, K

The gap factor K in the equations is used to describe the shape of the electrodes across the gap, d, (in meters). Ref:3. "The air gaps, filled or not with insulators, are of the self-restoring type. The geome- trical configuration of the gap influences its withstand capability." (CIGRE Green Books). "Ground level electric and magnetic field effects of overhead power lines have become of increasing concern as transmission voltages are increased. The electric fields are especially important because their effects on human beings and animals have been a concern in the last decades. Serious views still exist that prolonged exposure to electric and magnetic fields could be associated with adverse health effects or with increased risks. However, it is not appropriate to consider unlikely conditions when setting and applying electric field safety criteria because of pos- sible consequences; thus statistical considerations are necessary",(CIGRE Green Books).

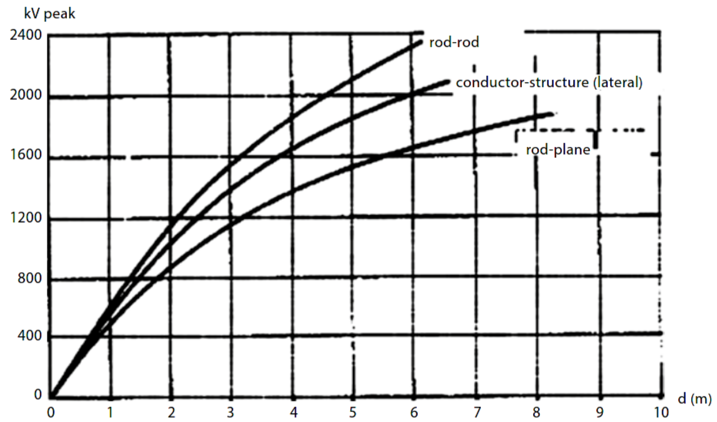

Figure 2: Gap Factor , Image Courtesy : CIGRE Green Books

In this design, two Gap factors are considered,

1. For Phase-Ground calculations, K = 1.45, without insulator
   - This corresponds to Conductor-Body of the tower and Conductor-Crossarms
   - Flashover possibility due to pollution on insulators is assumed to have less impact
2. For Phase-Phase calculations, K = 1.4, without insulator
   - This accounts for rod-rod electrodes separated by air dielctric

4.3 Clearances

The three major electrical clearances are as follows:

1. AC voltage clearance is associated with the peak voltage through the conductor
2. Switching impulse is caused by faults and switchgear operation
3. Lightning impulse calculations are done for a direct lightning hit on the conductor or electrode.

IEC 60071-1 standards suggest standard RMS voltage of 300kV for Electrical clearance calculation.

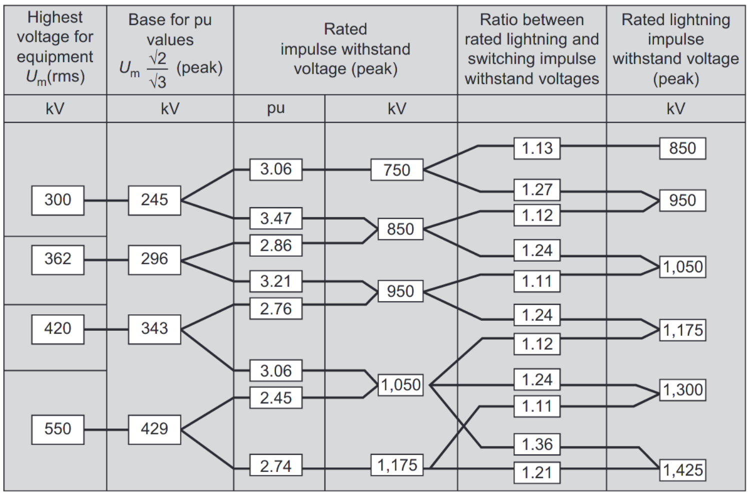

Figure 3: Standard Insulation [2]

4.3.1 Phase – Ground (P-G) Clearances

As per figure 2, following values are used for clearance calculations:

$$\text{Highest Voltage for equipment, (RMS value)}, U_{50-AC} = 300kV \tag{7}$$

$$\text{Switching impulse withstand voltage, Phase-to-earth kV (peak)}, U_{50-SI} = 750kV \tag{8}$$

$$\text{Lightning impulse withstand voltage kV (peak)}, U_{50-LI} = 850kV \tag{9}$$

The AC peak value is calculated by:

$$U_{50} = \sqrt{3} * U_{50-AC} kV \tag{10}$$

The AC, Lightning and Switching Voltage clearances in meters are calculated as follows:

$$D_{ac} = \frac{8 * U_{50-AC}}{3740 * K - U_{50-AC}} \quad (11)$$

$$D_{li} = \frac{U_{50-LI}}{380 + (150 * K)} \quad (12)$$

$$D_{si} = \frac{8 * U_{50-SI}}{3400 * K - U_{50-SI}} \quad (13)$$

$$D_{el} = max(D_{ac}, D_{li}, Dsi) \quad (14)$$

4.3.2 Phase – Phase (P-P) Clearances

As per figure 2, following values are used for clearance calculations:

$$\text{Highest Voltage for equipment, (RMS value),} U_{50-AC} = 300kV \quad (15)$$

$$\text{Switching impulse withstand voltage, Phase-to-earth kV (peak),} U_{50-SI} = 1.5 * 750kV \approxeq 1125kV \quad (16)$$

$$\text{Lightning impulse withstand voltage kV (peak),} U_{50-LI} = 1.5 * 850kV \approxeq 1270kV \quad (17)$$

4.3.3 Results

1. Phase - Ground By using a Gap Factor K = 1.45,
   Following are the values for clearances

Parameter	Value, m
D_{ac}	0.679
D_{li}	1.423
D_{si}	1.435
D_{el}	1.435

$$D_{el} = 1.435m \quad (18)$$

2. Phase to Phase Using the (11), (12), (13), (14) and a Gap Factor K = 1.4 The phase to phase clearance values are calculated as:

Parameter	Value, m
$D_{ac\text{-}PP}$	0.679
$D_{li\text{-}PP}$	2.153
$D_{si\text{-}PP}$	2.476
$D_{el\text{-}PP}$	2.476

$$D_{el-PP} = 2.476m \quad (19)$$

4.4 Swing Angle

Swing Angle is required to calculate the minimum distance required for Phase to ground electrical clearance. The primary factor in Swing angle is the horizontal force acted on the conductor system due to wind. In the calculation below, the weight of insulators is neglected and a simplified diagram is shown in the figure above. Following are the calculations for swing angle:

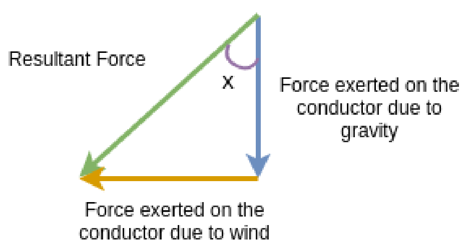

Figure 4: Swing Angle

Force due to wind on conductors, F_w, is given by:

$$F_w = \frac{1}{2} * V^2 * D_{cond} * L_s * N_{cb} \tag{20}$$

where, N_{cb} = Number of conductors in the bundle

Force due to gravity on the conductors, F_g, is given by:

$$F_g = M_c * 9.81 m/s \tag{21}$$

Swing Angle, ϕ_s is then calculated using:

$$\phi_s = tan^{-1}(\frac{Fw}{Fg}) \tag{22}$$

4.4.1 Results

Substituting values from Table 1 and Table 2 on the above equations,

$$\theta_{swing} = 23.113^o \tag{23}$$

4.5 Cross arm

4.5.1 Length of crossarms

The length of crossarms has a critical role in maintaining the minimum Phase-Ground clearance between swinging conductors and the body of the tower. Shown in Figure 5 , the length of cross arm is calculated using:

$$L_{crossarm} = L_{displacement} + D_{el} \tag{24}$$
$$L_{displacement} = \sin \phi_s * L_{hanging} \tag{25}$$
$$L_{hanging} = D_{insulator} + L_{fitting} + D_{cond} \tag{26}$$

4.5.2 Distance between crossarms

The distance between crossarms is calculated in sync with minimum electrical phase to ground and phase to phase clearances. Distance between Cross arms is calculated using:

$$D_{ca-top-mid} = \frac{D_{hanging} + D_{el}}{\sin \theta_{12}} \tag{27}$$
$$D_{ca-mid-bottom} = \frac{D_{hanging} + D_{el}}{\sin \theta_{23}} \tag{28}$$

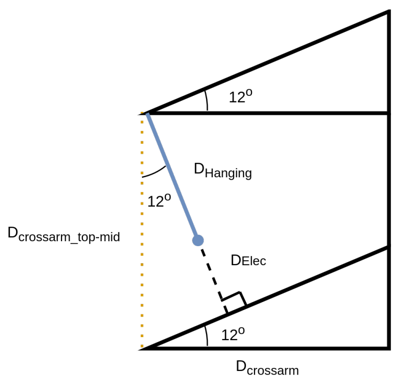

Figure 5: Crossarm distances

4.5.3 Results

Substituting values from Table 1, Table 2 and Table 3 on the above equations,

$L_{crossarm}$	3.053m
$D_{ca\text{-}top\text{-}mid}$	5.681m
$D_{ca\text{-}mid\text{-}bottom}$	5.727m

4.6 Shield wire

The distance to shield wire mount at an angle of 30° from top cross arm is calculated by:

$$D_{ca-shield} = \frac{L_{crossarm} + \frac{W_t}{2}}{\tan(\theta_{shield}) - L_{hanging}} \tag{29}$$

4.6.1 Results

$$D_{ca-shield} = 3.505m \tag{30}$$

4.7 Alternate Insulator Design

Considering the required Creepage for the tower is 11.6m, S248142V7 polymer type insulator is used. The technical details for this insulator is given below:

Table 4: Design Data for polymer insulator

	Failing load	Section length L	Dry Arc length P	Creepage distance
S248142V7	210 kN	3607mm	3272mm	12969mm

$$D_{el} = 3.272m D_{insulator} = 3.607m \tag{31}$$

4.7.1 Results

Using the (24), (27), Substituting values from Table 1, Table 2 and Table 4 on the above equations,

L_{crossarm}	3.053m
$D_{\text{ca-top-mid}}$	5.681m
$D_{\text{ca-mid-bottom}}$	5.727m

4.7.2 Implications of using Polymer rod insulator

The following table shows the primary differences between Glass and Polymer rod insulator, (Philips)

Glass insulator (U160BLP)	**Polymer rod insulator(S248142V7)**
Heavy	Light weight
Incoherent design(stacks of discs)	Single rod
Prone to easy Wear and Tear and vandalism, Avian causes	Relatively resistant to wear and tear
Easily affected by pollution	Better protection against pollution
Relatively costly	Relatively cheap
Can withstand failure of one disc	Hydrophobic failure/cracks, causes dry band arc

The changes with respect to tower dimensions are shown in TowerDiagram . A brief comparison of distinct changes are recorded in Discussion section

5 External Clearance Calculations – Tower Legs Geometry

5.1 Sag Calculation

The property of metallic malleable adds to conductor elasticity which results in a sag within a span of two towers. Elasticity coupled with atmospheric temperature increases the sag towards earth at the middle. Sag could be calculated using the following formula:

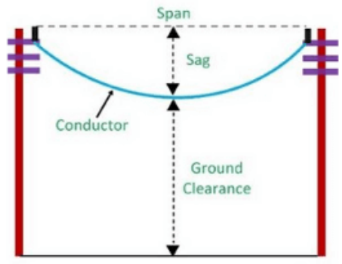

Figure 6: Sag. [5]

5.1.1 Length of Conductor across span

The length of the conductor with elasticity is given by:

$$L_c = L_s + \frac{W^2 * L_s^3}{24T^2} m \tag{32}$$

$$W = M_c * 9.81 N/m \tag{33}$$

$$T = 0.2 * T_r N \tag{34}$$

where,
L_c = conductor length within a span, m
W = conductor weight N/m
T = Tensile Strength at installed capacity(20%), N

5.1.2 Thermal Elongation

The maximum length of conductor including thermal elongation is calculated by:

$$L_{thermalElongation} = \varepsilon_t * (T_{max} - T_{installed}) * L_c m \tag{35}$$

5.1.3 Maximum Sag

The maximum sag is then calculated by:

$$Sag_{max} = \sqrt{\frac{3L_sL_c - 3L_s^2}{8}} \tag{36}$$

5.1.4 Results

Substituting values from Table 1 and Table 2 in the above equations:

L_c	366.429m
$L_{thermalElongation}$	367.0193m
Sag_{max}	11.828m
$D_{ca\text{-}shield}$	3.48m

5.2 Ground Clearance

The ground clearance from the point of maximum conductor sag is applied from standards in United Kingdom. Ref:3

$$GroundClearance(NoRoad) = 7.0m \tag{37}$$

$$GroundClearance(Road) = 7.4m \tag{38}$$

6 Discussion and Conclusion

The design of any Overhead Transmission tower must consider a primary factor of Geography. In the northern part of England, in United Kingdom(UK), the terrain, weather, population, urban/rural planning has to be considered. UK has a set certain Standards and Laws and Regulations for laying out a transmission tower from one point to another. These are to be followed at planning stage. The atmospheric Condition; wind speed, temperature, humidity, wetness, and pollution plays and important role in the Electro-mechanical design of the tower and its components and accessories. Safety is of paramount importance. Critical Infrastructure, Housing in the path of the tower is to be considered. Presence of natural elements like river, forest, etc. will add to safety parameters.

Technically, the MVA/Thermal Rating determines how much power can be evacuated through the line. This depends of Generation, Load distribution and contingency analysis. Once this is identified then critical factors of normal and abnormal operating conditions are characterized in the design. Flashover voltage withstand capacity among dielectrics(air/insulator) are to be considered. Gap Factor between electrodes play a significant role in determining the electrical clearances. Gap factor choice is usually set conservative as safety is the utmost priority. Risk of failure of dielectrics to withstand abnormal conditions affect the calculation of clearances. Environmental factors affect the choice of gap factor. Corona losses (CL), radio interference (RI) and audible noise (AN) are usually considered with respect the design of transmission system, but are ignored in this design.

Insulators, two types are used in this design. A conventional Pin & Cap type glass insulator and a modern polymer rod insulator. The tower design improved with the use of Polymer insulator in terms of Insulator length, Cross arm length and distance between cross arms. This would mean less materials are required for construction and the cost would significantly come down. "It has been noted that the results of failure of polymer insulators can be more significant than that of hardened glass insulators. But the recent failure rates and life expectancy of later generation polymer insulators, while not at the same level of hardened glass insulators, more than make up for the difference in cost.", (Philips)

7 References

[1] Stephen, R.: The thermal behaviour of overhead conductors. Sections 1 and 2. Cigré SC:22 Overhead lines. Electra 144, 107–125 (1992)

[2] Ryan, H. M., & Ryan, H. (Eds.). (2013). High-voltage engineering and testing. Institution of Engineering & Technology.

[3] DR K. Kopsidas, Power System Plant, Asset Management and Condition Monitoring – BOOK 2 – Overhead lines and Switchgear handbook, University of Manchester

[4] CIGRE Green Books, OverheadLines, International Council on Large Electric Systems (CIGRE)Study Committee B2: Overhead Lines, Editor Konstantin O. Papailiou

[5] https://www.electrical4u.com/sag-in-overhead-conductor/

[6] D. L. Phillips, "Selection Considerations: Hardened Glass vs. Polymer Insulators," 2018 IEEE/PES Transmission and Distribution Conference and Exposition (T&D), 2018, pp. 1-5, doi: 10.1109/TDC.2018.8440399.