INSULATION COORDINATION
IN THE TURKISH E.H.V. TRANSMISSION SYSTEM

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IN THE TURKISH E.H.V. TRANSMISSION SYSTEM

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ABSTRACT

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This thesis reviews the line insulation coordination practices of Turkish Electricity Transmission Company with special focus on E.H.V. transmission line towers' top geometry and ground clearances. In respect of this, the national regulation, "Elektrik Kuvvetli Akım Tesisleri Yönetmeliği", is critically evaluated.

The national regulation lags behind the modern world practice and the provisions of the regulation lead to uneconomical designs. The possible benefits of the modern practices are shown by application examples.

Keywords: Tower Top Geometry, Ground Clearances

ÖZ

TÜRKİYE ÇOK YÜKSEK GERİLİM İLETİM SİSTEMİNDE İZOLASYON KOORDİNASYONU

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Bu tez çok yüksek gerilim iletim hatları direklerinin tepe geometrisi ve düşey açıklıklar odaklı olarak Türkiye Elektrik İletim A.Ş.'nin hat izolasyon koordinasyonu pratiklerini gözden geçirmektedir. Bu bağlamda, "Elektrik Kuvvetli Akım Tesisleri Yönetmeliği" kritik olarak değerlendirilmektedir.

Yönetmelik modern dünya pratiğinin gerisinde kalmıştır ve yönetmelik hükümleri gayri ekonomik tasarımlara yol açmaktadır. Modern pratiklerin olası kazanımları uygulama örnekleriyle gösterilmektedir.

Anahtar Kelimeler: Direk Tepe Geometrisi, Düşey Açıklıklar

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CHAPTER 1

INTRODUCTION

1.1 General

IEC 60071-1 defines insulation coordination as “Selection of the dielectric strength of equipment in relation to the voltages which can appear on the system for which the equipment is intended and taking into account the service environment and the characteristics of the available protective devices”. The first task is to analyze the system and determine the electrical stress that the insulation should withstand. Then, the strength should be selected considering the strength characteristics of the insulation. For self restoring insulations, the selection can be made by using probabilistic techniques, which is becoming the preferred technique.

For line insulation coordination, the insulation strength depends on the geometry of the towers and properties of the insulator string. In determination of these, the influence of environmental conditions should also be taken into account.

Ideally, the selection should be based on a desired degree of reliability. However, in most countries, national regulations exists which impose directly the design requirements and restrict the choices offered to the designers.

1.2 Purpose and Scope of the Thesis

Along with the circuit configuration (horizontal, vertical, delta), tower height, clearances between the phase conductor and the grounded tower sides, phase spacing and shielding angle are the parameters defining the tower geometry. In respect of determination of these parameters; this thesis work reviews the literature, analyses present E.H.V. tower designs and critically evaluates the national regulation and the practices of Turkish Electricity Transmission Company.

In general, it is the switching surges that dictate the required strike distances at 380 kV. The strike distance can be determined with the probabilistic method on the basis of an acceptable failure rate. Chapter 2 deals with the determination of the strike distance for type designs.

Although lightning is not the dominant design criterion at 380 kV, the likelihood of direct lightning strikes to the phase conductors should be minimized. In chapter 3, the geometric model is presented and used to evaluate the shielding performance of the present designs.

Climatic actions, such as wind or ice, play important roles when defining the tower top geometries. Ice drop and galloping are important considerations for towers with vertical conductor arrangement. With the action of wind, internal clearances at the towers are reduced due to the deflection of the insulator sets, and in mid span, possible oscillation of adjacent conductors due to differential wind speed may result in flashovers. To prevent clashing of conductors in mid span and to ensure that the necessary internal clearances are achieved between live parts and earthed members of towers, there should be proper distance between the attachment points of conductors at the tower. In chapter 4, the method proposed in Cigre Technical Brochure 348 is compared with the empirical approach of the national regulation by means of an application example.

Mid span phase to ground clearances should be sufficient to prevent a flashover, even under quite unfavourable conditions. On the other hand, the requirements for the mid span phase to ground clearances have a considerable effect on the cost of the line and chapter 5 is devoted to a critical evaluation of the ground clearance requirements of the national regulation.

CHAPTER 2

INTERNAL CLEARANCES AT TOWER

2.1 Introduction

There should be enough clearance between live parts and earthed tower members to ensure that desired degree of reliability can be achieved. In the case of towers equipped with V strings, the conductor can be assumed stationary in the tower window. If towers are equipped with I strings, the wind action should also be taken into account.

2.2 Insulation Strength Characteristics of Towers

From experiments it is known that, strength of a self restoring insulation is a random variable and obeys Normal Law. Thus the probability density function of this random variable is:

$$f_X(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{1}{2}[\frac{x-\mu}{\sigma}]^2} \tag{2.1}$$

where σ is standard deviation and μ is the mean. The event of flashover is equivalent to the event of this random variable being lower than x, i.e. the applied voltage. Therefore the probability of flashover when x volts is applied to the insulation is:

$$F_X(x) = \frac{1}{\sqrt{2\pi\sigma^2}} \int_{-\infty}^{x} e^{-\frac{1}{2}[\frac{x-\mu}{\sigma}]^2} dx \tag{2.2}$$

Instead of evaluating this integral, Equation 2.3 can be used with the error function table.

$$F_X(x) = \frac{1}{2} + erf\left(\frac{x-\mu}{\sigma}\right) \tag{2.3}$$

In electrical engineering terminology μ is called Critical Flashover Voltage or CFO. The probability of flashover is 50% when this voltage is applied to the insulation. In IEC 60071-1[1], a flashover probability of 10% is used to define the statistical withstand voltage.

It can be observed that when the applied voltage is 3 σ below the CFO, the probability of flashover is 0.5 + erf(-3) =0.5 - erf(3)=0.00135 =0.135%, which can be practically considered as zero.

While it is true that since Gaussian distribution is unbounded one can always calculate a probabality of flashover - even when the voltage is zero- , within the practical range it can be used without any significant error.

Under nonstandard conditions, the strength of insulation differs from the strength under standard conditions. A correction is needed if the insulation will be tested under nonstandard conditions. Also, for line or station insulation coordination purposes, for desired insulation strength, the required withstand voltages for standard conditions should be known. As per IEC 60060-1 [2], the relation between the withstand voltage under standard conditions, V_S, and the withstand voltage under nonstandard conditions, V_A , is:

$$V_A = \delta^m H_c^w V_S \tag{2.4}$$

where δ: Relative air density;

H_c: Humidity correction factor;

m, w: Constants which are functions of G_0.

As described in Reference [3], G_0 is a factor which is related with the mode of the discharge.

$$G_0 = \frac{CFO_S}{500S} \tag{2.5}$$

where S is the strike distance in meters.

The humidity correction factor is:

$$H_c = 1 + 0.0096\,[\frac{H}{\delta} - 11] \tag{2.6}$$

where H is the absolute humidity in grams/m^3.

For wet conditions H_c =1.

Since lightning impulses have very small fronts, the leader mode of discharge is not present and thus the factor G_0 is about 1 to 1.2 . Therefore, for lightning impulse, the exponents m and w are unity.

For switching surges both corona streamers and the leader mode of discharge are present. Consequently, G_0 is less than 1. For this case,

$$m = 1.25\,G_0\,(G_0 - 0.2) \tag{2.7}$$

The relative air density is a function of pressure and temperature. Therefore the strength of insulation changes with altitude. As per IEC 60071-2, the relative air density is:

$$\delta = e^{-A/8.15} \tag{2.8}$$

where A is the altitude in kilometers.

In general, for E.H.V. transmission lines it is the switching surges that dictate the required strike distances.

Full scale tower tests [4] show that below conclusions can be made about switching impulse strength of towers:

-There is a critical wavefront depending on the strike distance which produces the minimum CFO. For positive polarity, it is approximately 50(S-1) where S is the strike distance in meters.

-Negative polarity strength of towers is significantly larger than that for positive polarity, so designs can be made considering only positive polarity surges.

-Wet conditions decrease the CFO.

-Under dry conditions, if the insulator length is equal to the strike distance, the CFO remains unchanged. However, under wet conditions, the insulator length should be 1.05-1.10 times of the strike distance to avoid a decrease in the CFO. Even in this case a reduction of 4% is recommended by the authors of the mentioned reference.

- Coefficient of variation, (σ /CFO) is about 5%.

-Since existence of grounded members modify the electric field distribution and reduce the CFO, outside phases have higher withstand. (In this case one side is not grounded, however for center phase both sides are grounded). For outside phases, CFO is 1.08 times that of the center phase.

To estimate the critical flashover voltage of a given gap at the critical wave front and under dry conditions, the following equation can be used [5] :

$$CFO = k_g \frac{3400}{1+8/S} \tag{2.9}$$

where k_g is gap factor and S is the strike distance in meters.

For center phase (conductor-window):

$$k_g = 1.25 + 0.005(\frac{h}{S} - 6) + 0.25(e^{-\frac{8W}{S}} - 0.2) \tag{2.10}$$

where h is conductor height and W is tower width [6]. For lattice type towers kg is about 1.2.

Since design is made for wet conditions, with a reduction of 4%, the CFO is:

$$CFO = 0.96k_g \frac{3400}{1+8/S} \qquad (2.11)$$

2.4 Determination of the Required Clearances

Ideally, determination of the strike distance should be based on the accepted switching surge flashover rate. Acceptable switching surge flashover rate can vary from point to point in a network depending on the consequences. According to IEC 60071-2[7], acceptable failure rates due to switching surges lie in the range 1/100 to 1/1000 per switching operation.

The switching surge flashover rate depends on the strength characteristics of the towers, the switching overvoltage distribution, the number of towers and the overvoltage profile along the line. Since a flashover at any of the towers of the line means a switching surge flashover, the switching surge flashover probability for a single switching operation is given by the following equation:

$$SSFOR = \frac{1}{2} \int_{E1}^{Em} (1 - \prod_{i=1}^{n} q_i) f_s(V) dV \qquad (2.12)$$

where

E_m: The maximum switching surge overvoltage, which can be conservatively assumed to be infinity;

E_1 : 1.0 per unit of system line to neutral voltage;

q_i : The probability of no flashover at tower i;

$f_s(V)$: The probability density function of the switching overvoltage distribution.

Since negative polarity strength of towers is significantly larger than that for positive polarity, the multiplication factor of ½ is included in the equation.

The tower designs of Turkish Electricity Transmission Company are type designs, which means that once a tower is designed it is used for a long time, sometimes 30 years or even more. For each voltage, circuit configuration and conductor combination, there is a type tower design used for all transmission lines with the corresponding configuration. Since, at the design stage, the parameters affecting the flashover rate can not be exactly known, some reasonable and conservative assumptions should be made.

E_2 , the overvoltage which has a 2% probability of being exceeded is called the statistical switching overvoltage. For energizing, if circuit breakers are not equipped with closing resistors, (which is the normal practice of Turkish Electricity Transmission Company) for an inductive feeding network and shunt compensation less than 50%, the estimates of E_2 given by Reference [8], in per unit of the maximum line neutral voltage, are as below:

-Minimum:1.66 pu

-Average: 2.31 pu

-Maximum:2.90 pu

- Standard deviation, σ : 0.17(E_2-1)

In Turkish E.H.V. grid, the typical transmission line length is about 200 km. With an average span length of 400 m, this length corresponds to 500 towers.

The necessary critical flashover voltages for the towers to achieve a switching surge flashover rate of 1/100 and 1/1000 are obtained from Eq. 2.12 as 2.738 pu and 2.966 pu respectively, with the following assumptions:

-The voltage profile is flat. This is a conservative assumption. In reality receiving end voltage is higher than the sending end voltage.

-The insulation strength of the towers and the overvoltage distribution is Gaussian.

-The number of towers is 500.

- E_2 =2.31 pu and σ : 0.17(E_2-1)=0.2227.

- Coefficient of variation, (σ /CFO) is 5%.for the towers.

For 380 kV system, the maximum line to ground voltage is 420 kVx(√2/√3)=343 kV. Then, 2.738 pu and 2.966 pu correspond to 940 kV and 1017 kV, respectively. The required strike distances in meters at the altitudes of 1000 and

1800 m are calculated from equations (2.4), (2.5), (2.7), (2.8) and (2.11) with a gap factor of 1.2 and given in Table 2.1.

As per the TEİAŞ specification, for 380 kV, the required strike distance is 3 meters.

Table 2.1: Required strike distances

	Switching Surge Flashover Rate	
	1/100	1/1000
1000 m	2.73	3.03
1800 m	2.9	3.2

In reality, a tower window is not a simple air gap due to the presence of insulators and grading rings. In addition, the switching surges do not necessarily result in flashovers across the shortest strike distance. Therefore, these values should be considered as crude estimates. Ideally, the strength characteristics should be deduced from full scale probability run tests.

2.5 Concluding Remarks

- All currently used E.H.V. towers in Turkey have V strings in all phases. Therefore, the conductor can be assumed to be stationary and an additional consideration of wind is not required while determining the strike distance.

-The required strike distance varies significantly with the altitude and accepted switching surge flashover rate. The altitudes of 1000 and 1800 m are representative for Central Anatolia and Eastern Anatolia. Therefore it appears that designing at least two different type projects for each conductor and circuit configuration combination is a better idea. Increasing the number of type designs would be beneficial in respect of the structural design too; climatic conditions differ considerably throughout the country.

- Turkish E.H.V. grid is interconnected, if a switching surge flashover rate of 1/100 is accepted, the necessary strike distances at 1000 and 1800 m can be taken as 2.75 and 2.9 m respectively.

- If three phase reclosing is not made, which is the normal practice of Turkish Electricity Transmission Company, the switching surges generated by reclosing operations have lower magnitudes than that generated by energizing. Therefore the calculations were based on the estimate of the statistical switching overvoltage for energizing with an average magnitude of 2.31 pu. However, it can be as high as 2.9 pu. For type design purposes, determining the required strike distance using the average value may be a better choice. In this case, after the project of a line is completed, switching surge studies can be made. Since then a realistic overvoltage distribution will be available and the properties of the line will be known (number of towers, altitude variation of the line), a probabilistic analysis can be employed and if the resultant switching surge flashover probability is deemed high, measures can be taken to reduce the stress placed on the insulation. An example of them is to place line end arresters which not only protects the station equipment but also somewhat reduces the switching surge flashover rate of the line. Another solution is to equip the circuit breakers with closing resistors.

- In the past, switching surge requirements and contamination could dictate different insulator lengths, because the requirement of a specified creepage distance was equivalent to a specified number of insulators. However, with the increasing use of silicon rubber (composite) insulators which have excellent contamination performance, future designs can be based on a desired switching surge flashover rate.

CHAPTER 3

SHIELDING ANGLE

3.1 Introduction

The main function of the shield wire is to minimize the likelihood of direct lightning strikes to the phase conductors. The shielding failure rate depends on the shielding angle, ground flash density, height of the tower and strength characteristics of the tower.

Full scale tower tests conducted at Fuat Külünk High Voltage Laboratory of İstanbul Technical University [9] have showed that, for the type tower 3PB, which is the type design of Turkish Electricity Transmission Company for 380 kV lines with Pheasant conductor, with composite insulators, the critical flashover voltages for negative polarity lightning impulses varied between 1800 and 1910 kV, depending on the corona ring design. The flashovers were across the shortest strike distance. In comparison, for the same tower, with glass insulators, even with 22 insulators, all flashovers were across the insulator string; indicating that glass insulators intervene with the flashover mechanism significantly and control the negative polarity withstand level.

Figure 3.1: Discharge along the insulator surface.

Since composite insulators are used for all new lines in Turkey, in this chapter, 1800 kV is assumed as the representative negative polarity lightning impulse withstand voltage for 380 kV lines.

As for switching surges, lightning surge withstand characteristics can be assumed to be normally distributed, however with a much smaller coefficient of variation. Therefore normal practice is to consider the withstand voltage as a single number and if a voltage greater than this value is applied to the insulation, the probability of breakdown is assumed to be 100%.

3.2 The Lightning Flash

There exist four types of lightning flash depending on the charge of the cloud and the direction of the leader. They are negative downward, negative upward, positive downward and positive upward. For open terrain, negative downward flash is the dominant type. However, in Turkey, many E.H.V. lines have portions that lie in mountainous regions. In these regions, towers located on top of hills are common and for these towers, a special treatment which takes negative upward and positive flashes into account may be necessary. To give an idea about the dependence of the type of lightning flash on the terrain, Berger's data [10] will be presented: 70 and 80 m masts located on top of 650 m Mt. San Salvatore were struck by 1196 flashes of which,

-75% were negative upward

-11% were negative downward

-14% were positive.

Therefore one should keep in mind that the analysis presented in this chapter is valid for open terrain.

3.3 The Crest Current Distribution

In Cigre Technical Brochure 63[11], Berger's data along with some additional measurements is analyzed. The parameters of the suggested lognormal distribution for negative downward flashes in two current regions are given in Table 3.1:

Table 3.1: First Stroke Current Distribution Suggested by CIGRE

Parameter	I<20 kA	I>20 kA
M, median	61.1	33.3
B, log std. dev.	1.33	0.605

The probability density function is in the form:

$$f(x) = \frac{1}{\sqrt{2\pi}\beta x} e^{-\frac{1}{2}[\frac{\ln(x/M)}{\beta}]^2} \tag{3.1}$$

Using the parameters given in Table 3.1 and the probability distribution function, the probability of lightning current being less than 20 kA is 20%, 33 kA is 50% and 90 kA is 95%. In other words, only 1/20 of the lightning flashes have a current of greater than 90 kA.

As mentioned previously these parameters were mainly based on Berger's data. However, they are biased towards a higher median. The reason is that, as the height of the structure is increased, the median of the collected flash current also increases. Using Brown and Whitehead striking distances [12], ground level current distribution can be obtained:

Table 3.2: Ground Level Current Distribution

Parameter	I<20 kA	I>20 kA
M, median	28.55	25.3
B, log std. dev.	1.58	0.630

In this case, as expected, a lower median is obtained.

3.4 Ground Flash Density

The ground flash density, N_g, is the number of the flashes per square km – year. The best method to obtain this value is direct measurement. However, if such data is not present, number of thunderstorm days (keraunic level) can be used to estimate the ground flash density [13]:

$$N_g = 0.04 T_d^{1.25} \tag{3.2}$$

where T_d is the number of thunderstorm days per year.

3.5 Field Data

The field data compiled by Eriksson and analytical models show that the number of flashes collected by ground wire per 100 km-years is [13]:

$$N(G) = \frac{N_g (28h^{0.6} + S_g)}{10} \tag{3.3}$$

where

N_g : Ground flash density (Flashes per km^2-year)

h : Height of the structures. Normally the tower height minus 2/3 of the sag can be used. Another alternative is to use the height of the tower top which is conservative.

S_g : Separation between the ground wires.

The above formula applies for negative downward flashes. If tower heights exceed 100 m, the proportion of upward flashes increases. From transmission line point, on flat terrain, the average tower height for 380 kV lines, considering suspension towers with a span length of 400 m is: 14 m sag + 9.5 m ground clearance + 8 m conductor to ground wire peak $\approx$ 32 m. Therefore on level terrain, the formula presented above would give good results. However, in mountainous terrain, this may not be true. Eriksson also gives a formula for the proportion of the upward strokes to the total strokes:

$$N(G^{-}) = 1.26x10^{-4} h^{1,48} \tag{3.4}$$

In this case, with h=32m, equation (3.4) yields 2%.

3.6 Shielding Failures

To obtain the shielding failure flashover rate, the geometric model has been used widely, which is explained in [11].

The geometric model assumes that there are two different strike distances to the conductors (r_c) and to the ground (r_g). These are shown in the Figure 3.2. There are various proposals for these strike distances. For example, Brown-Whitehead formula is:

$$r_c = 7.1xI^{0.75} \tag{3.5}$$

$$r_g = 6.4xI^{0.75} \tag{3.6}$$

D_g and S_g shows the portions of the line that will collect the lightning flash by ground wire. Any flash which approaches from the portion D_c will be collected by the phase conductor (Shielding failure). Finally the other will strike to the ground.

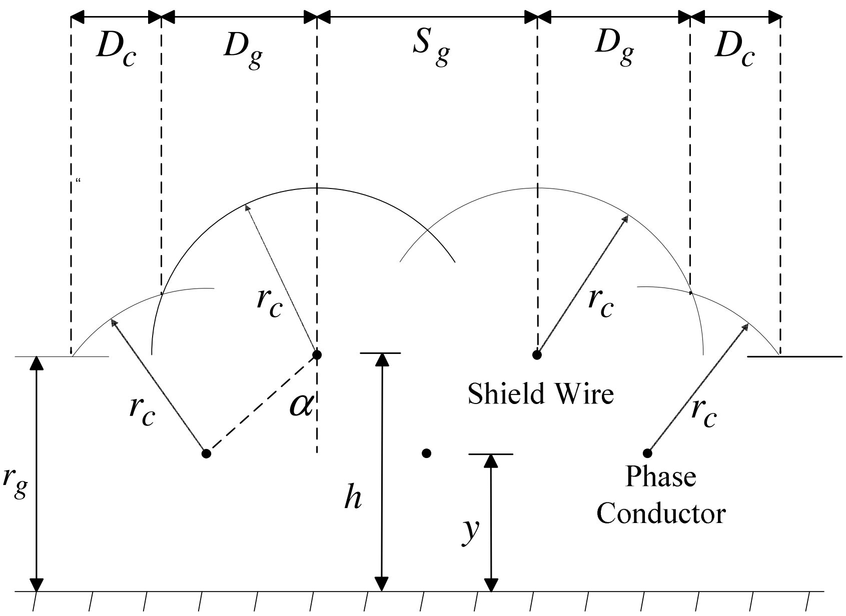

Figure 3.2: The Geometric Model, Distances.

Therefore for a specific current, the distances r_c and r_g are determined first, the circles are drawn, and the number of flashes that will be collected by the phase conductor is determined. As the current grows larger, the portion D_c gets smaller, and there exists a maximum current, I_m , that can penetrate through the shielding. Thus only small lightning currents can penetrate through the shield wires. However, in this case, the voltage is applied directly between the phase conductor and the ground. There is a critical value of current that will breakdown the gap between the live part and the earthed tower. If this current is denoted as I_c , the equation relating the CFO and I_c is given by:

$$CFO = \frac{ZxI_c}{2} \tag{3.7}$$

where Z is the surge impedance of the phase conductor. Although natural lightning impulse generally has a longer tail (median is 77 μS), it is generally treated as standard lightning impulse and the critical current can be calculated from 50% flashover voltage.

The shielding failure flashover rate is:

$$SFFOR = 2N_g L \int_{I_c}^{I_m} D_c(I) f(I) dI \tag{3.8}$$

where

N_g : Ground flash density (Flashes per km ^{2} -year);

L: Length of the line (in km);

$f(I)$: Probability density function of the lightning current.

Calculation of $D_c(I)$:

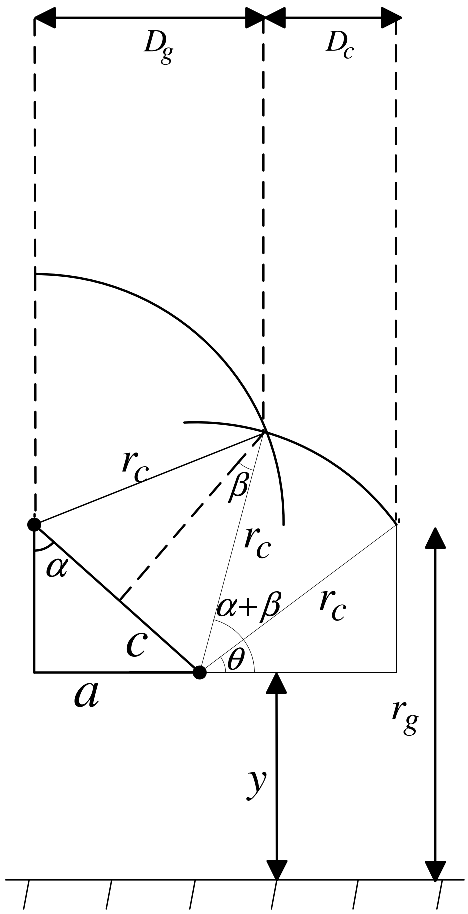

Figure 3.3: Calculation of $D_c(I)$.

$$\theta = \arcsin(\frac{r_g - y}{r_c}) \tag{3.9}$$

$$\beta = \arcsin(\frac{c}{2r_c}) \tag{3.10}$$

$$D_c = r_c[\cos\theta - \cos(\alpha+\beta)] \tag{3.11}$$

Calculation of the Maximum Shielding Failure Current:

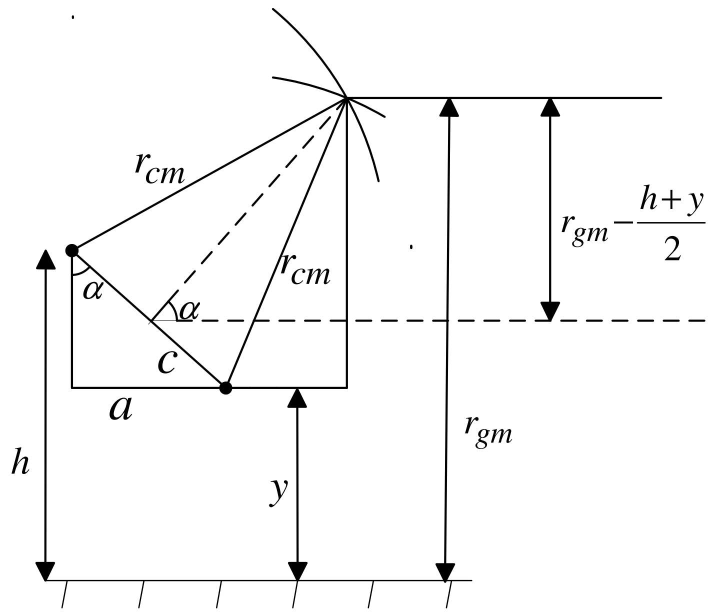

Figure 3.4: Finding the Maximum Shielding Failure Current.

From the geometry:

$$\sin\alpha = \frac{r_{gm} - \dfrac{h+y}{2}}{\sqrt{r_{cm}^{2} - \dfrac{c^{2}}{4}}} \tag{3.12}$$

If the shielding angle is adjusted so that I_m equals I_c, this is called perfect shielding.

3.7 Selection of Shielding Angle

3.7.1 The Keraunic Level

The numbers of thunderstorm days measured by meteorological stations in Turkey are given in Appendix A.

As seen from Table A.1, a keraunic level of 40 can be chosen conservatively. .In this case equation (3.2) yields 4. Expressed in other words, at least for a flat terrain, the flash density can be taken as 4 per km square- year in Turkey.

3.7.2 Average Conductor Height

In Turkey, assuming a flat terrain, 550 m represents the maximum span length for 380 kV lines. In this case, the approximate heights of the phase conductors and shield wires are given in Table 3.3.

Table 3.3: Typical Conductor Heights (550 m)

	Attachment Height (m)	Average Height (m)
Phase Conductors	34	19.5
Shield Wires	41.75	30.75

The attachment height for the phase conductors is calculated by adding the basic ground clearance, 9.5 m to the maximum phase conductor sag. Since the conductor geometry can be approximated by a parabola, the average heights of the conductors are taken as tower height minus 2/3 of the sag at 15^{o}C .

The sag of the shield wire is less than that of the phase conductor and thus, the shielding angle gets smaller towards the mid span.

3.7.3 Present Designs

This example will be given for the suspension tower type 3PB which is the type suspension tower for 380 kV lines with Pheasant conductor. The horizontal distance between the outermost wire of the bundle and the shield wire, a, is approximately 2.25 m. With considering the sag of the conductor and the shield wire, the average shielding angle is approximately 11.3^{o}. In comparison, the shielding angle at the tower is 16.2^{o}. The top geometry of this tower is shown in Figure 3.5.

As per the national regulation [14], the required shielding angle for suspension towers is 20^{o}.

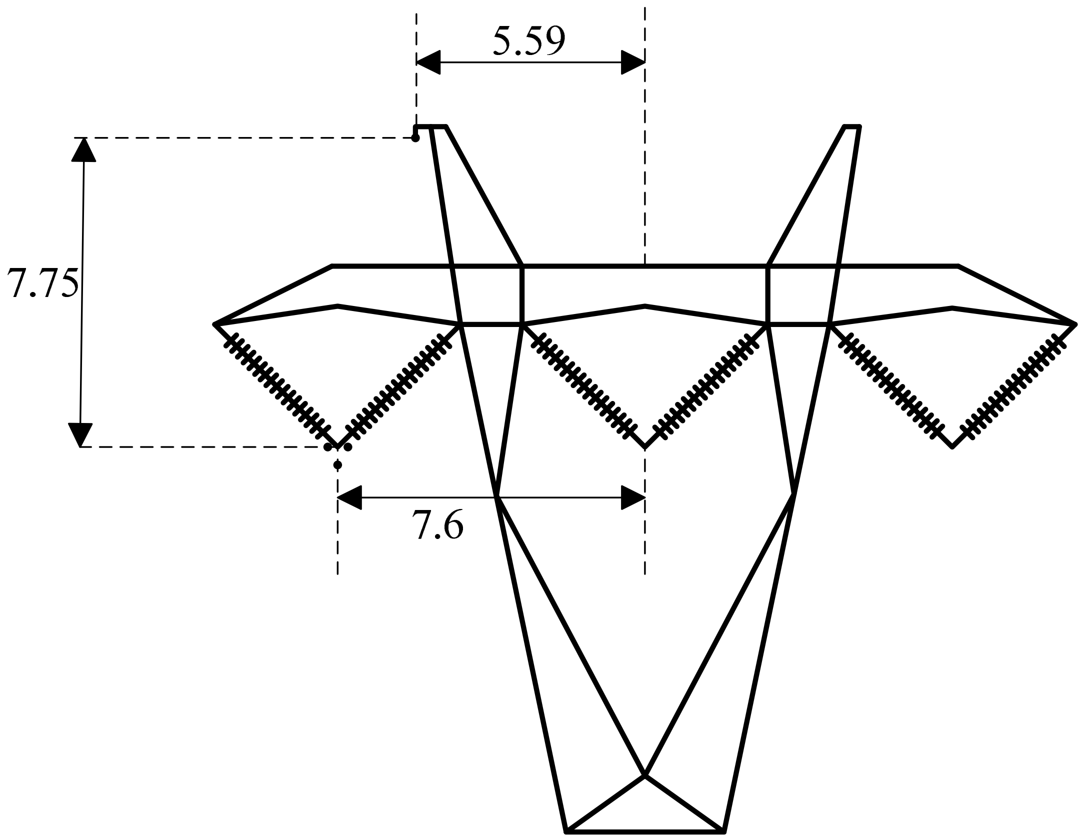

Figure 3.5: Top Geometry of Type 3PB tower. (Distances are in m).

3.7.4 The Critical Current and the Maximum Current

Assuming a surge impedance of 400 ohms, which is a quite conservative value for bundled conductors, and a CFO of 1800 kV, I_c is 9 kA from equation (3.7).

With average phase conductor and ground wire heights, from equations (3.5), (3.6) and (3.7) I_m is obtained as 8.56 kA. For this case, the maximum current that can penetrate through the shield wires is less than the critical current and the probability of shielding failure flashover is zero.

With the same phase conductor and shield wire heights, for a ground flash density of 4, the necessary average shielding angle to achieve a shielding failure flashover rate of 0.05 per 100 km-year is obtained as 20.3^{o} from equation (3.8), using the ground level current distribution. The horizontal distance between the phase conductor and the shield wire corresponding to this average shielding angle is 4.16

m. As seen from Figure 3.5, the vertical distance between the shield wire and the phase conductor is 7.75m and thus the necessary shielding angle at the tower is 28.2^o.

3.8 Concluding Remarks

The calculations in the previous part show that there can be no shielding failure flashover for moderate heights with this typical present tower design and even with maximum span lengths, a shielding angle of 28.2 ^{o} would be sufficient to achieve a shielding failure flashover rate of 0.05 per 100 km-year, for a flat terrain. On the other hand, the towers located on hill tops are more vulnerable to shielding failures and for towers located on hillsides, an approximate value for the effective perfect shielding angle can be calculated as the perfect shielding angle minus hillside angle [11]. Another factor that should be kept in mind is that, the above calculations are valid for negative downward strokes. In mountainous regions, negative upward or positive lightning flashes may be dominant.

The shielding angles of present designs are unnecessarily small for flat terrain and increasing the number of type projects for each conductor and circuit configuration combination would be useful in this respect too.

CHAPTER 4

PHASE SPACING

4.1 Introduction

To prevent clashing and flashover between conductors at mid span, (where the sag is largest) there should be proper distance between the attachment points of conductors at the tower. The possible reasons of clashing of conductors at mid span are ice drop, galloping and differential wind speed. If the tower is equipped with I strings, with the consideration of wind, the required strike distance at the tower can also dictate larger phase spacing then that required to maintain the necessary mid span clearance.

4.2 Ice Drop

Ice drop is an important consideration for towers with vertical conductor arrangement. With a sudden ice drop, the conductors jump above its un-iced position, which may cause a flashover between the jumping conductor and the iced conductor above it.

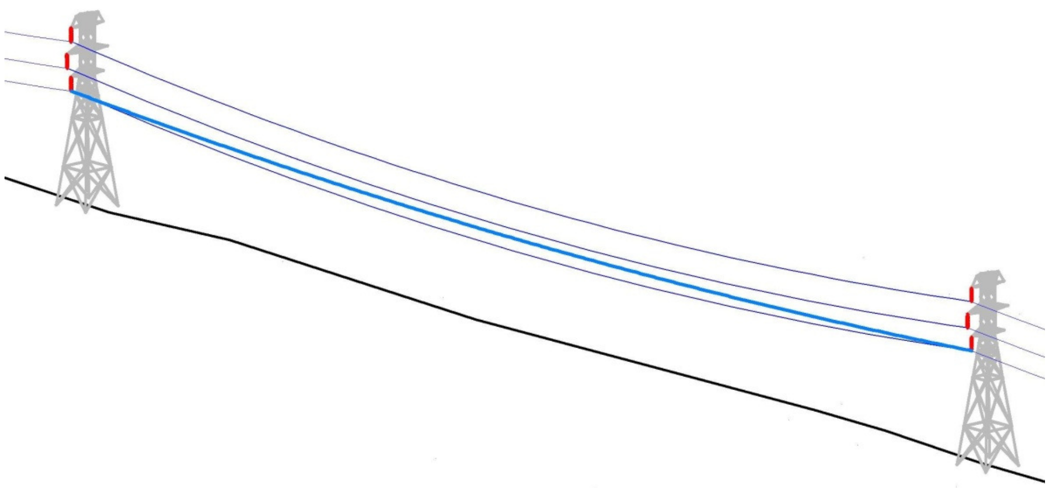

Figure 4.1 Ice Drop.

The thick line represents the upper position of the wire after jumping.

A possible measure against ice drop is to design the middle crossarm longer than the bottom and top crossarms to provide a horizontal offset in such a situation.

4.2 Galloping

“Galloping is a low frequency, high amplitude wind induced vibration of both single and bundle conductors, with a single or few loops of standing waves per span. Frequencies can range from 0.1 to 1 Hz and amplitudes from 0.1 to 1 times the sag of the span. Galloping is generally caused by moderately strong, steady crosswind acting upon an asymmetrically iced conductor surface”. [15]

Galloping can cause both mechanical and electrical failures. When galloping amplitudes are large enough, flashover can occur between adjacent phases.

In galloping, the conductor at mid span traces an elliptical orbit and the motion is a dominantly vertical motion, thus this consideration is important for towers with vertical or delta conductor configuration.

The proposed ellipse for clearance design against galloping for power lines by Cigre Publication 322 is shown in Figure 4.2 with the following parameters:

For single (unbundled) conductors:

$$MAJOR = 80xdx\ln\frac{8xf}{50xd} \tag{4.1}$$

For bundled conductors:

$$MAJOR = 170xdx\ln\frac{8xf}{500xd} \tag{4.2}$$

$$MINOR = 0.4xMAJOR \tag{4.3}$$

$$B = 0.3xMAJOR \tag{4. 4}$$

where d is the conductor diameter and f is the sag .This proposal is based on 166 observations complemented with simulations and represents the maximum galloping amplitudes that should be expected.

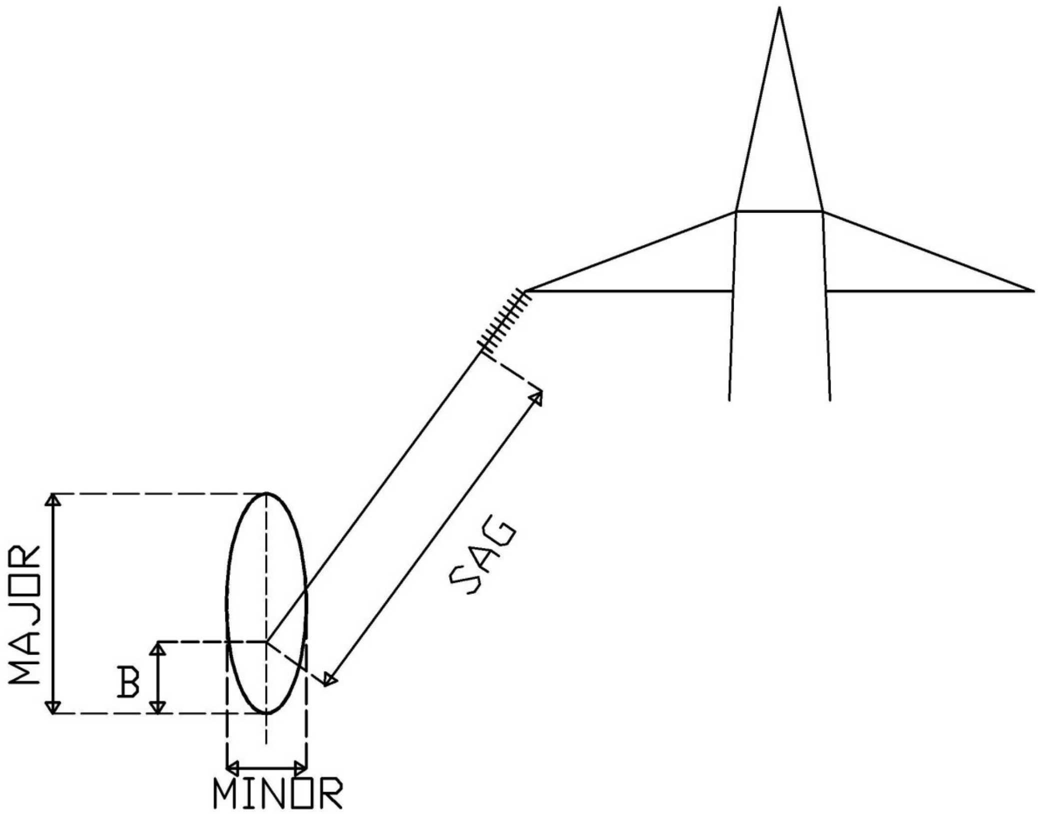

Figure 4.2 Galloping ellipse.

In general, galloping has not been a serious problem in Turkey. Among the existing transmission lines, the most frequently galloping line is 154 kV Hopa-Muratlı double circuit transmission line with Pheasant (1272 MCM) ACSR conductor. An example will be given for tower type 2FA which is the type design of Turkish Electricity Transmission Company for 154 kV double circuit lines with Pheasant conductor. The conductor diameter is 35.10 mm. With a span length of 400 m, which is the typical span length for this tower, with a sag of 10.88 m and a wind velocity of 15 m/s, the galloping ellipses of this tower are shown in Figure 4.3:

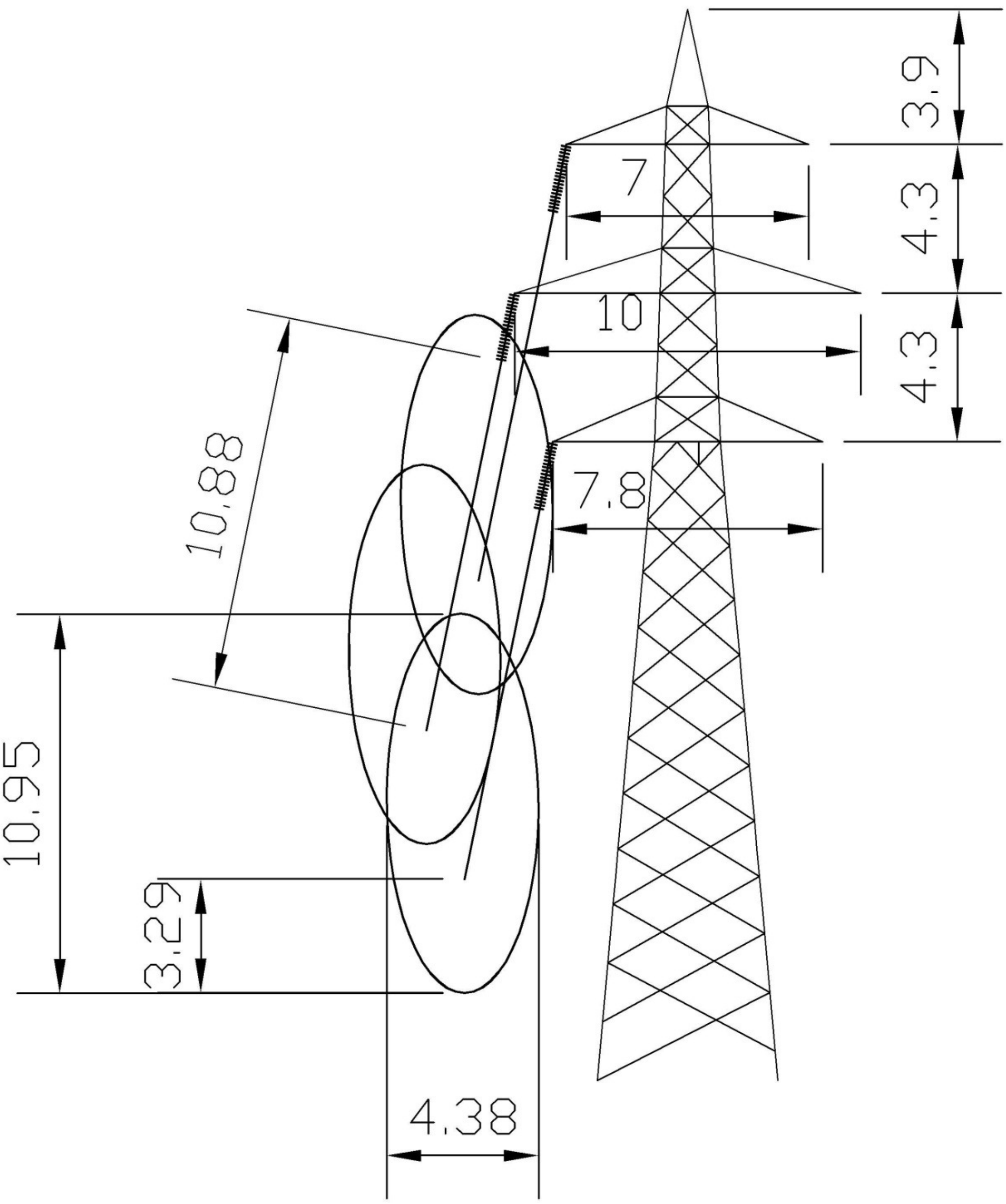

Figure 4.3 Galloping ellipses, 2FA. (Distances are in m).

This example shows that this tower doesn't meet the galloping clearances with even its basic span. For a longer span, the overlap would be larger.

4.3 Effect of Wind

Wind action plays an important role when defining tower top geometries. With the action of wind, clearances at the tower are reduced due to the deflection of the insulator sets. At mid span, possible oscillation of adjacent conductors due to differential wind speed may result in flashovers. One of the most recent publications dealing with these issues is Cigre Technical Brochure 348, “Tower Top Geometry and Mid Span Clearances” [16]. In this part, the approach proposed in this publication will be compared with the empirical approach of the national regulation.

4.3.1 Cigre Method

4.3.1.1 General Considerations

- Under still air conditions which may include a small wind speed as well; the gap should be able to withstand the anticipated lightning and switching impulses. Still air conditions apply to conductor positions occurring during at least 99% of the operation period.
- Under extreme wind conditions the clearance should be sufficient to withstand the power frequency voltages.

In the past, deterministic designs were dominant for structural design. The effects of climatic actions were combined with factors of safety and the structural designs were performed with these calculated loadings. For structural design, new methods based on reliability based design considerations have emerged. There, a wind velocity having a given return period is selected as the basis for structural design representing an ultimate load which may stress the structure to its ultimate strength capacity. For the design of the tower top geometry, the same meteorological data should be used to determine the positions of conductors and insulator strings.

4.3.1.2 Calculation of Swing Angles of Conductors and Insulator Sets

Wind velocity varies with time and space. It is not constant along the span length, also the wind speed increases with height above ground.

Hornisgrinde tests [17] show that, calculated swings are significantly lower than the measured ones if in the calculation the gust (winds with a short duration, such as 2-3 seconds) speeds are taken into account. The gust speeds do not act on the whole span length, therefore a span factor which takes care of spatial distribution of the wind should also be taken into account.

Wind load on conductors can be calculated as:

$$F_{wc} = n.q_z.C_{xc}.G_c.G_L.d.L_w \tag{4.5}$$

where

n : Number of subconductors;

q_z : Wind pressure corresponding to the mean wind velocity at height z;

C_{xc} : Drag coefficient of the conductor. Generally taken as 1;

G_c : Gust factor of the conductor which depends on the terrain category and the height above ground;

G_L : Span factor;

d : Conductor diameter;

L_w : Wind span: Arithmetic mean of the two adjacent span lengths of the tower. Wind span is a measure of the transverse force transferred by the conductors to the attachment points.

Recommendations for G_L and G_c are given in IEC 60826 [18].

The mean wind pressure is given by:

$$q_z = (p/2).V_z^2 \tag{4.6}$$

where p is the air density and V_z is the mean wind velocity at height z. The air density at a temperature of 15°C at sea level equals 1.225 kg/m^3.The result is in N/m^2 with wind velocity in m/s.

According to IEC 60826, the mean wind velocity at height z can be obtained from:

$$V_z = V_R(z/z_R)^{\alpha} \tag{4.7}$$

where

V_R =Reference mean wind velocity for the reference height;

α = Roughness exponent depending on the terrain category.

With increasing terrain roughness, turbulence intensity increases and the wind speed decreases near ground level. The roughness factor KR, given in Table 4.1 represents a multiplier of the reference wind speed for conversion from one terrain category to another.

Table 4.1: Terrain Categories as per IEC 60826

Terrain Category	Characteristics	α	KR
A	Open sea, lakes with at least 5m fetch upwind and smooth flat country without obstacles	0.10 to 0.12	1.08
B	Farm land with boundary hedges, occasional small farm structures, houses or trees	0.16	1
C	Suburban or industrial areas and permanent forests	0.22	0.85
D	Urban areas in which at least %15 of the surface is covered with buildings with mean height greater than 15 m	0.28	0.67

The equation relating the mean swing angle of an insulator string to the mean wind speed is [19] :

$$\phi = \tan^{-1}[q_z \frac{C_{xc}.G_c.G_L.d.n.L_w + C_{xins}.A_{ins}/2}{m_c.g.n.L_c + M_{ins}.g/2}] \qquad (4.8)$$

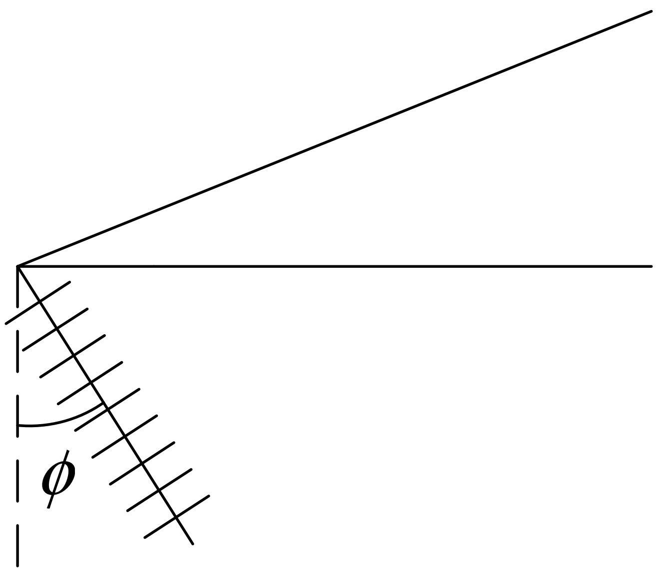

Figure 4.4 Insulator Swing Angle.

First term of the numerator is the wind force on the conductor, and second term is the wind force on the insulator (C_{xins} is the drag coefficient of the insulator taken as 1.2 and A_{ins} is the insulator wind area) divided by 2. First term of the denominator is the vertical force of the conductor (L_c is the weight span, m_c is the linear mass of the conductor) and second term is the weight of the insulator divided by 2.

With the action of wind, the whole span swings. The mean swing angle of a conductor (span), i.e. the angle between the vertical plane and the plane in which a conductor lies under the action of wind, is given by:

$$\phi = \tan^{-1}[q_z \frac{C_{xc}.G_c.G_L.d}{m_c.g}] \tag{4.9}$$

The swing angles actually vary around the mean swing angle. The distribution of the swing angle for a given wind speed is normal and its standard deviation in degrees is given by [20]:

$$\sigma_\phi = 2.25[1-\exp(-V^2/230)] \tag{4.10}$$

Based on the measurements, the mentioned publication concludes that the swing angles of insulators and conductors can be reliably calculated based on equations (4.8) and (4.9) using a mean wind speed averaged over 5 to 10 minutes. With these averaging periods, G_c can be taken as 1.

4.3.1.2 Time Distribution of Wind Velocities

According to IEC 60826, the probability of yearly extreme values of wind velocity may be described by the Gumbel distribution:

$$P(V_{obs} > V) = 1-\exp[-\exp(-\pi(V - V_{mean} + 0.45\sigma_v)/(\sqrt{6}\sigma_v))] \tag{4.11}$$

where V_{mean} is the mean of the yearly maximums and σ_v is the standard deviation. From this formula, a wind velocity with a return period T, or yearly probability of 1/T can be determined as:

$$V_T = V_{mean} - \sigma_v [0.45 + (\ln(-\ln(1-1/T)).\sqrt{6})/\pi] \tag{4.12}$$

The yearly time distribution of the wind velocities follows the Weibull distribution [21].

$$P(V_{obs} < V) = 1 - \exp[-(V/V\eta)^{\beta}] \tag{4.13}$$

If time distribution of wind speeds is not known but if extreme value statistics are available (yearly maximums), Technical Brochure 348 gives a formula to calculate the parameter $V\eta$:

$$V\eta = V_2 / 2.825 \tag{4.14}$$

where V_2 is the wind velocity having a 2 year return period which can be calculated from Eq. (4.12). In this case β should be taken as 2.

Even if wind statistics are available, they rarely give information about the wind direction. Therefore, this technical brochure recommends that the probability of the swing angle should be assumed as half of that of the corresponding wind velocity for swing angles of more than 2^o.

4.3.1.3 Coordination of Conductor and Insulator Set Positions and Electrical Stresses

According to TB 348, two conditions should be considered when designing the tower top:

-Under the action of design wind velocities, the clearances between live conductors and earthed tower members and the clearances between adjacent conductors at mid span should be sufficient to withstand the power frequency voltages.

-Under “still air” conditions, which correspond to a time probability of 99%, the clearances between live conductors and earthed tower members and the clearances between adjacent conductors at mid span should be sufficient to withstand the anticipated lightning and switching impulses.

Under the action of wind, the swing angles vary around the mean swing angle. Two standard deviations can be added to the mean swing angle of the insulator set to determine an unfavourable insulator position. To determine an unfavourable conductor position at mid span, two standard deviations can be added to the mean swing angle for the first conductor and two standard deviations can be subtracted from the mean for the adjacent conductor.

4.3.2 Turkish Practice

As per the national regulation, the design wind pressures on towers, insulators and conductors are given in Table 4.2.

Table 4.2: Design Wind Pressures According To the National Regulation

Height Above Ground (m)	Wind Pressure (kgf/m^2)	
	Towers and Insulators	Conductors
0-15	55	44
15-40	70	53
40-100	90	68
100-150	115	86
150-200	125	95

The swing angles are calculated with 70% of the design wind pressures. The required clearance between live parts and earthed tower members is U/150+0.05 m where U is the nominal system voltage. The span factor is given by the equation:

$$G_L = 80 / L_w + 0.6 \quad (4.15)$$

4.3.3 Application Example

The approach proposed in CIGRE Technical Brochure 348 for the design of the tower top geometry represents an improvement on the existing empirical methods. In this part, the possible benefits of this approach will be demonstrated by means of an application example. All currently used E.H.V. towers in Turkey have V strings in all phases; therefore this example will be given for a 154 kV type design, 2FA.

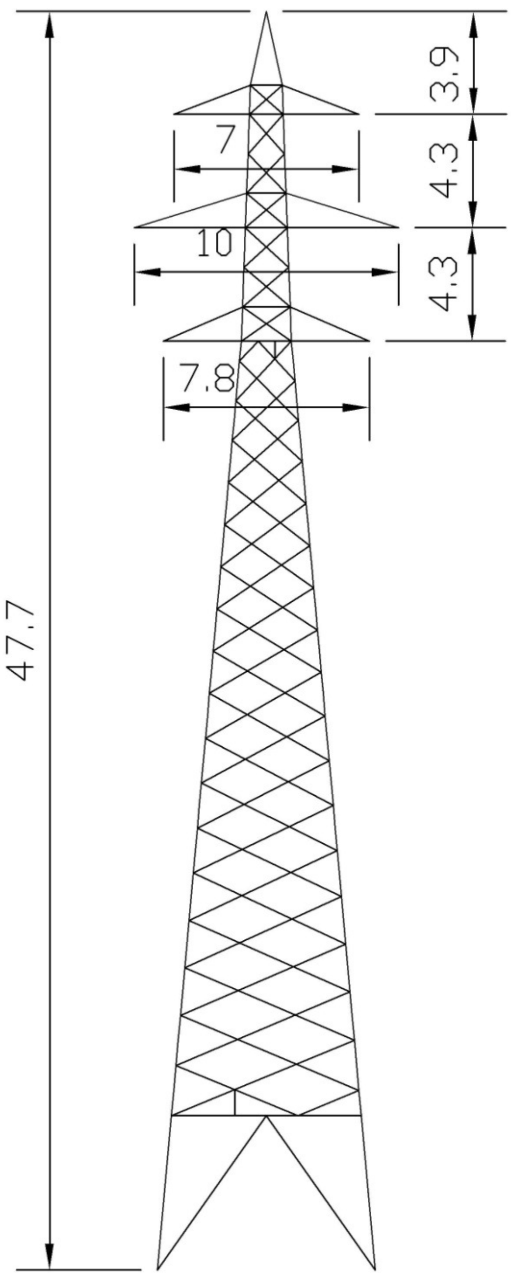

Figure 4.5 Outline of 2FA type tower. (Distances are in m).

4.3.3.1 Basic Data

Maximum wind span: 400 m;

Maximum weight span: 1000 m;

Minimum weight span at 400 m wind span: 163 m;

Phase conductor: Pheasant ACSR (1272 MCM);

Unit weight of the conductor: 2.435 kgf/m;

Diameter of the conductor: 35.10 mm;

Wind exposed area of insulator set: 0.5 m^2;

Weight of the insulator set: 75 kgf;

Length of the insulator set: 2.19 m.

Free swinging length of the insulator set: 2.05 m.

4.3.3.2 Calculation with the emprical approach

Figure 4.6 shows how the crossarm length and the phase spacing were determined for this tower.

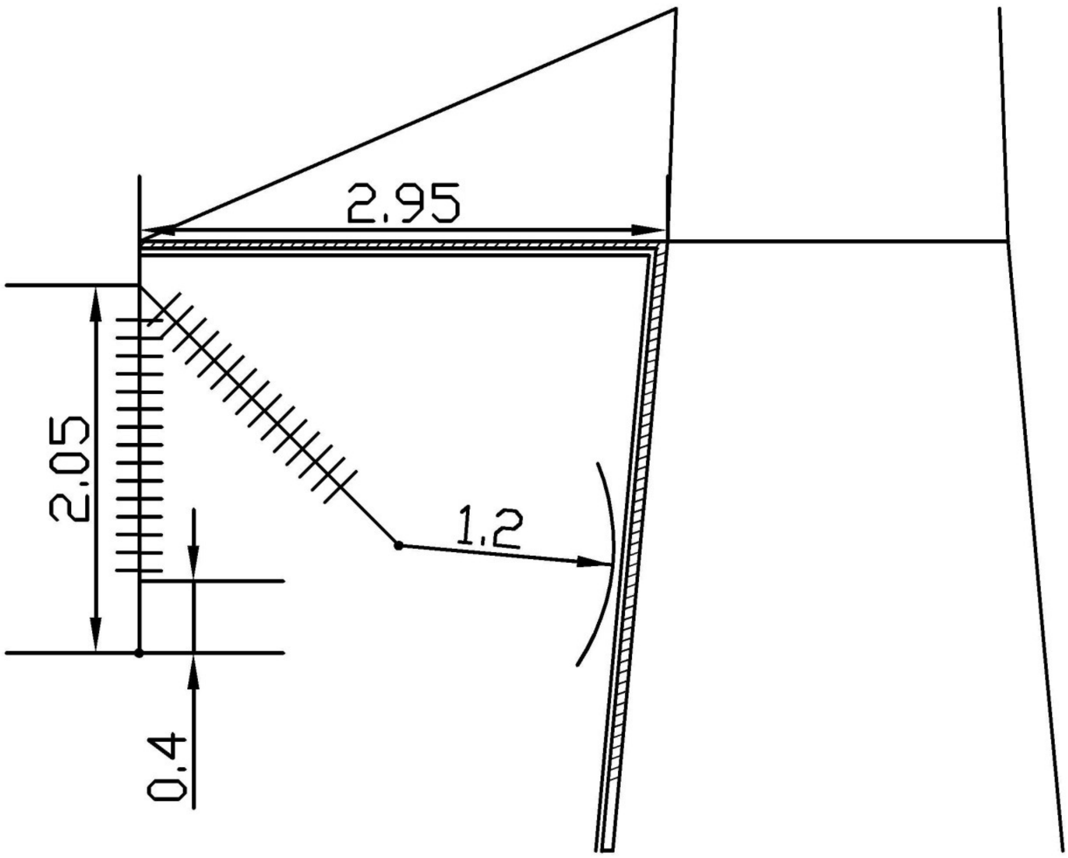

Figure 4.6 Determination of the geometry with empirical approach. (Distances are in m).

In general, the average conductor heights for 154 kV lines are less than 40 m. Therefore, to determine the swing angle, wind pressures of 70%x53 kgf/m^2 and 70%x70 kgf/m^2 were considered for the conductors and the insulators, respectively. The span factor is 0.8 from equation (4.15) for a 400 m span. With a wind span of 400 m and weight span of 163 m, a swing angle of 45^o was calculated and was combined with a clearance of 1.2 m, which is slightly higher than the value required by the regulation.

4.3.3.3 Calculation according to TB 348

As mentioned previously, in respect of structural design of transmission line towers, the modern practice is to select a wind velocity having a given return period as the basis for structural design. The approach presented in TB 348 recommends using the same meteorological data to determine the positions of conductors and insulator sets. One of the most widely adopted reliability based design standard is IEC 60826. In this standard, it is shown that if the strength being exceeded with 90% probability is set equal to the climatic load having a return period of T, the yearly failure probability is around 1/2T. Here, the strength refers to the strength of the highest strained member of the tower, such as the buckling strength of the leg. In general, the following condition should be checked for the design of the components when towers are used at their maximum allowable spans:

$$Load < \varphi x R_c \tag{4.16}$$

where φ is the strength factor and R_c is the guaranteed strength. The strength factor depends on the number of components exposed to the limit load (φ_n), the coordination of strengths between components (φ_s), the difference in the quality of the component during protype testing and actual installation (φ_q) and the difference between the actual exclusion limit of R_c and the supposed exclusion limit, 10%(φ_c). According to IEC 60826, on flat terrain, the maximum number of towers exposed to maximum gust wind is 5 and φ_n is 0.92 assuming a coefficient of varition 10% for the strength. For the weakest designed components (suspension supports), φ_S is 1. With these assumptions, in the case of wind action the design equation becomes:

$$Load < 0.92 x R_c \quad (4.17)$$

In Appendix B, the statical calculation of type tower 2FA is given with wind loads calculated according to IEC 60826. For a wind velocity of 30 m/s (at 10 m height, 10 minute average) the compression of the leg of attains a value of 41613 kgf which is approximately 92% of the compression capacity of this member, which is 45250 kgf. In other words, for a wind velocity of 30 m/s blowing perpendicular to the line, the probability of the failure due to buckling of the leg (rightmost member of Figure 4.7) is 10% and for a given geographical location the yearly probability of mechanical failure is 1/2T where T is the return period for the wind velocity of 30 m/s for this location.

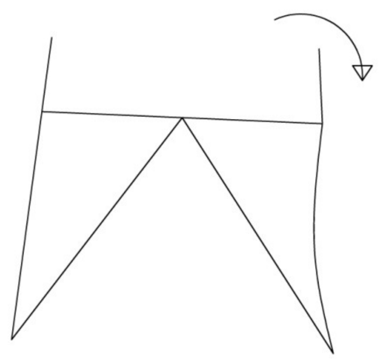

Figure 4.7 Buckling of the leg.

The position of the insulator set is shown in Figure 4.8 for a wind span of 400m, weight span of 163 m and wind velocity of 30 m/s. The average conductor height is taken as 23.9 m. The wind velocity at this height is calculated from equation (4.7) and equals 34.5 m/s, assuming terrain type B. The wind pressure corresponding to this wind velocity is obtained from equation (4.6) as 74.3 kgf/m^2. The span factor is taken from Figure 4 of IEC 60826 to be 0.945 for 400 m. With these values, a mean swing angle of 66.7^o results from equation (4.8). Equation (4.10) yields a standard deviation of 2.24^o. To determine an unfavourable position, an extreme swing angle of $\phi + 2\ \sigma_\phi$ is assumed, which is equal to 71.2^o.

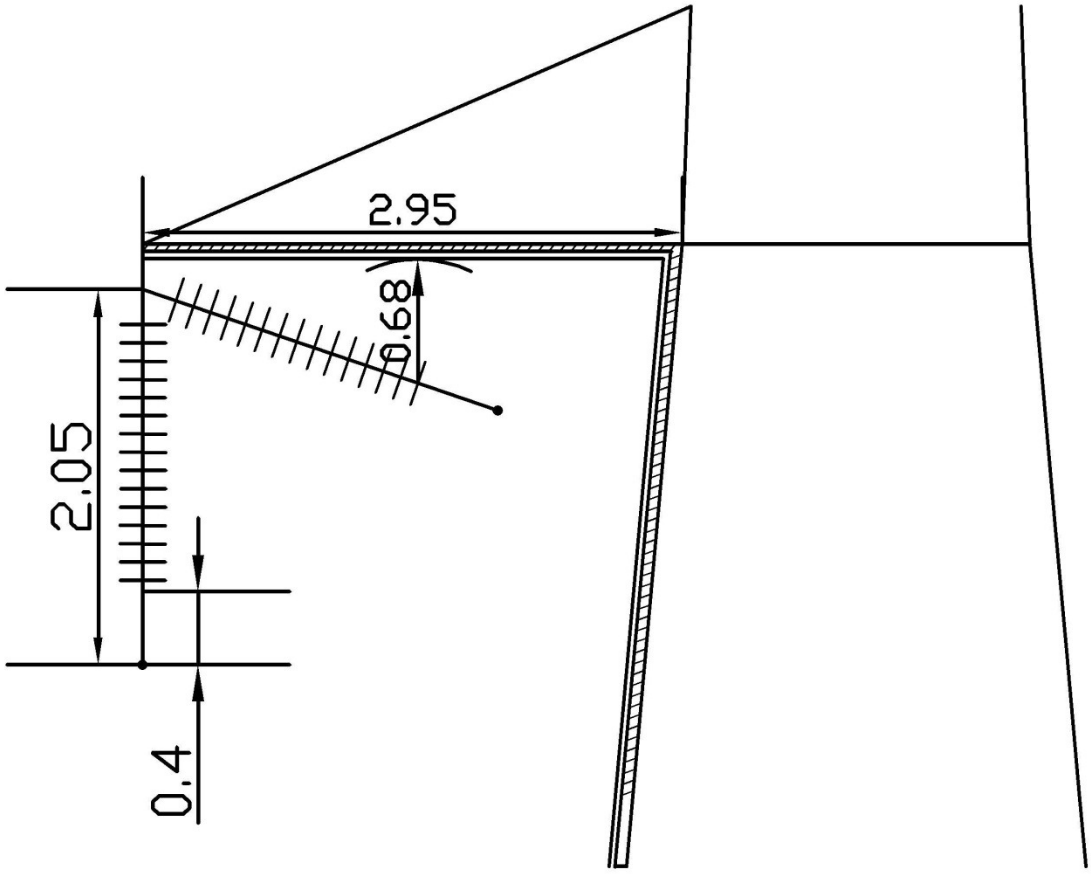

Figure 4.8 Swing of the insulator set for extreme wind. (Distances are in m).

In this case, the shortest distance between the live part of the insulator set and the earthed tower body is 0.68 m. For gap lengths about to 1 m, the dielectric strength of the air gap under power frequency voltage is not influenced by the gap configuration and 50% breakdown gradient is approximately 400 kV/m [6]. For a distance of 0.68 m, this corresponds to a breakdown voltage of 270 kV, which is much higher than the maximum phase to ground voltage of a 154 kV line. Therefore, even under a wind load that stresses this tower close to its failure limit, a flashover due to the power frequency voltage can not occur.

IEC 60826 suggests selecting a reliability level characterized by return periods of 50 years for lines with a nominal voltage of less than 230 kV. 30 m/s is a very high wind velocity, and this wind velocity probably corresponds to a return period of more than 50 years for most of the transmission line routes in Turkey. According to IEC 60826, the typical values of the standard deviation of yearly maximum wind velocities, σ_v, lies in the range 0.12 to 0.20 and 0.12 was found in several countries in Europe. In this example, it is assumed that 30 m/s is the wind velocity with a return period of 50 years and the coefficient of the variation 0.12. Then, the wind velocity which has a time probability of 98% is obtained as 15.7 m/s. from equations (4.12), (4.13) and (4.14). In accordance with the recommendation of TB 348, it is assumed that the time probability of the corresponding swing angle is 99%. To determine an unfavourable position, a swing angle of $\phi + 2\ \sigma_\phi$ is assumed, which is equal to 35.9 ^{o}. Figure 4.8 shows the position of the insulator set for this swing angle.

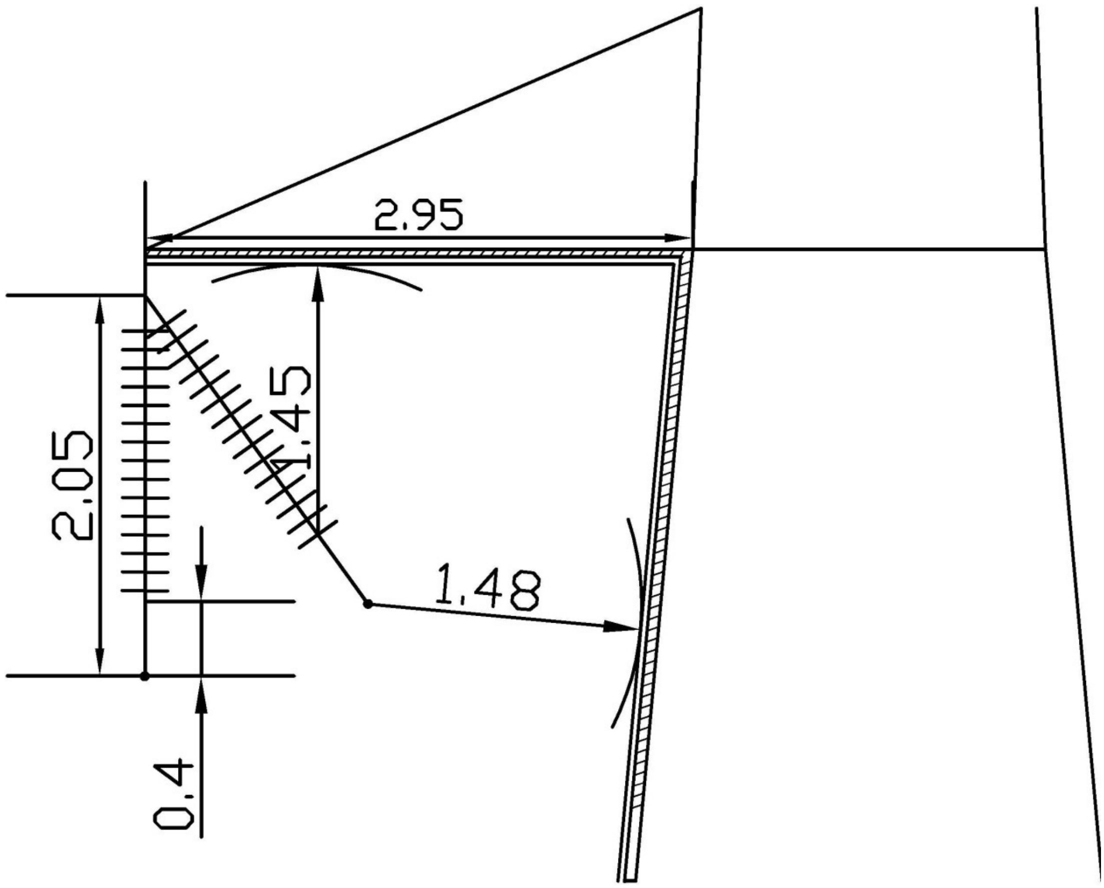

Figure 4.9 Swing of the insulator set for reduced wind. (Distances are in m).

The insulator set is equipped with arcing horns and the length of the air gap between the the arcing horns is 1.18 m. The shortest distance between the live part of the insulator set and the earthed tower body is 1.45 m for this case, which is 23% greater than the length of the gap between the arcing horns. The breakdown characteristics of the gap between the arcing horns differ from that of the rod-rod gaps with the same length due to the influence of the insulators and earthed tower members. Smilarly, with the deflection of the insulator set, the gap between the live part and the upper truss differs from the normal conductor to crossarm case. Therefore, without test data, comparing the breakdown characteristics of these two alternative flashover paths is difficult. As a general guide, Belgium practice will be presented: Under still air conditions, the required clearance between the live parts and the earthed tower members is 1.25 times the length of the gap between the arcing horns. Under reduced wind condition which corresponds to the 25% of the design pressure, the required clearance is 1.1 times of the length of the gap between the arcing horns. Therefore, for this case it is reasonable to assume that the deflection of the insulator set does not control the insulation level.

Even with quite conservative assumptions of this example, the approach does not yield a larger distance between the tower body and the attachment point of the conductor. Thus it can be concluded that, the empirical approach of the national regulation results in overconservative designs.

4.4 Concluding Remarks

While flashovers due to ice drop can be avoided easily, it is not economical to design all towers to fully meet the galloping clearances. It may be more practical to accept the risk and apply corrective measures when needed.

The probabilistic approach proposed in CIGRE Technical Brochure 348 for the design of the tower top geometry represents an improvement on the existing empirical methods. However, this approach requires statistical wind data, at least yearly maximums.

CHAPTER 5

GROUND CLERANCES

5.1 Introduction

The energized conductors of overhead lines must remain at safe distances from objects, people or vehicles passing beneath the line at all times. The required clearances are specified by code regulations or company standards. In this chapter, the mid span ground clearance requirements of the national regulation are reviewed and the possible reasons of clearance violations are listed with the proposed measures to prevent them. Finally, the necessary ground clearances are calculated for 380 kV lines in respect of the ICNIRP guidelines.

5.2 Required clearances

The required vertical clearances as per the national regulation are given in Appendix C. The basic clearance requirement for 380 kV, 9.5 m is high when compared to that of other national standards. As an example, for the same terrain category, as per the National Electric Safety Code the necessary mid span clearance for a line with a phase to ground voltage of 22 kV is 5.6 m and this clearance must be increased by 1 cm per kV in excess of 22 kV. Considering a maximum phase the ground voltage of 420/√3, the required clearance is 8 meters.

In general, the required mid span clearances are determined by assuming an object beneath the line, such as a person, vehicle, tree etc., and the electrical clearance is added to the height of this object. For 380 kV lines, the main consideration is the switching overvoltages and the necessary electrical clearance can be calculated by using the Gallet equation [5]:

$$CFO = k_g \frac{3400}{1 + 8/S} \tag{5.1}$$

The conductor to plane gap factor is 1.15 for the Gallet equation. In the case of an object beneath the phase conductors, the actual gap factor is greater than the conductor to plane gap factor and thus, the calculated clearance with this gap factor is on the conservative side. Assuming a coefficient of variation, (σ /CFO) of 5% and equating a statistical switching surge of 3 pu to the CFO-3σ results in a strike distance of 3.6 m at sea level. At an altitude of 1800 m, the required strike distance increases to 4.05 m. With the basic ground clearance of the National Regulation, 9.5 m, this corresponds to a reference height of 9.5-4.05=5.45 m, which is clearly too much.

The mid span clearances must be maintained at the maximum sag condition. There are two possible conditions under which the sag of the conductor is maximum: The maximum temperature and existence of an external load on the conductor, such as wind or ice load. Except for heavy icing areas, the clearance is controlled by the maximum temperature condition. As per the regulation, the maximum temperature is assumed to be 50^{o}C for ice load Zone I, 45^{o}C for Zone II and 40^{o}C for Zone III and IV. Some countries check the required clearances at 80^{o}C, for ACSR type conductors. The reasoning behind this is that the maximum allowed temperature of ACSR type conductors is 80^{o}C. If the conductor is forced to carry more current, irrecoverable loss of mechanical strength occurs. The current ratings of ACSR type conductors are calculated with this maximum temperature as well. However, since the current carried by the line rarely attains the rated value of the line, the Turkish regulation requires the designer to check the clearance at ambient temperatures. Also, one should keep in mind that, the required clearances as per Turkish regulations are higher when compared to requirements of other national standards. A more logical procedure would be the following, which is incorporated in some other national regulations: A required clearance for the ambient temperature and a lower required clearance for the maximum conductor temperature. This is more realistic because for the same clearance at ambient temperature, a longer span will have less clearance at the maximum conductor temperature than that of a shorter span.

Another type of check, which is again incorporated in some other national standards, is the consideration of partial icing condition. For a tension section which is composed of two dead ends and suspension towers between them, partial icing, i.e.

icing on a few of spans may result in large sags. Under this condition, the sag of the iced span may be even larger than that would occur under the condition at which all of the spans of the tension section are coated with ice. This kind of check is nonexistent in the Turkish national regulation.

If the clearance specifications of the current regulation are to be revised, since the specified clearances include safety factors, clearance violations of the existing lines should be compiled and used to assist to determine the required clearances.

5.3 Possible Reasons of Clearance Violations

The possible reasons for clearance violations are given by the following considerations:

Incorrect Terrain Data: This appears to be the primary reason when past clearance violations are examined. When towers are erected and conductor is sagged, the clearance violation is detected but it is too late at this stage. The towers have to be deassembled and with the proper towers, the conductors have to be strung again.

Incorrect Tower Application: If the tower is erected in a different position from the coordinates where it should be erected, a clearance violation may occur. In this case the span length may be larger than the value assumed at the spotting stage, which results in larger sag when the cables are strung with the design tension. This is also a common cause of clearance violations.

Use of Templates: Prior to the tower spotting, the ruling span is not known. Therefore sag templates are prepared with the most likely ruling span value, which is 400 m for 380 kV lines. If, after the spotting is completed, the ruling span doesn't match the assumed ruling span, the sag template will not represent the conductor geometry accurately. If the assumed ruling span and the actual ruling span differ by more than 5%, a new template should be used. However, for manual operation, using many templates is not practical. Turkish Electricity Transmission Company has purchased a line design program, for optimum tower spotting. With this program, the above problem will not be present.

Incorrect Sagging: If the person stringing the conductors can not properly sag the conductors or if the offsett clipping is not done properly, a clearance violation is likely.

Modelling Errors: Different sag tension calculations methods use different mathematical models to calculate the sag and tension of the conductor. However, they all give very close results for majority of cases. Turkish Electricity Transmission Company uses a method developed by Aluminum Company of America. This method is based on the stress strain properties of the conductors obtained by testing.

A newly produced conductor has a nonlinear stress strain relationship. This nonlinearity is due to settling and creep of the conductor and results in permanent elongation when the conductor is subjected to load. Also, creep continues throughout the whole life of the line with an ever decreasing rate. The designer should be able to calculate the amount of permanent elongation and check the required clearances at this final stage. Therefore, the above mentioned program calculates both initial and final sag and tensions. Initial tensions are used for sagging, and final tensions are used for checking the required clearances.

One of the inputs to the program is the ruling span. Exact sag tension calculation for a series of suspension spans between two dead end towers is a difficult task. Therefore the series of suspension spans is replaced with a single imaginary span, the ruling span, for sag tension calculations. This concept is based on the assumption that under all loading conditions, the suspension insulators' movements will equalize the horizontal tensions of all spans. This concept is widely used throughout the world due to its simplicity and accuracy. However there are some cases for which this assumption will not produce good results. One of such cases is slack spans, where the tension is low, the span is very short (~50 m) and the heavy strain insulators are present at the two ends. An example of this is the span between the terminal tower and substation. A simple spreadsheet program is developed using the formulation in Appendix D and this program is used by Turkish Electricity Transmission Company to calculate terminal tower heights.

5.4 Restrictions Due To Electric and Magnetic Fields Produced By Line

As discussed in the previous part, the primary objective while determining the minimum permissible ground clearances is to prevent flashover, even under quite unfavorable conditions. However, recently, a new type of constraint has emerged and has been incorporated to many of the national standards in Europe: The electric and magnetic field intensity must be below the reference levels.

In 1992, the International Commission on Non-Ionizing Radiation Protection (ICNIRP), an independent scientific organization, was established. This Commission aims to investigate the biological effects reported from exposure to electric and magnetic fields and to establish guidelines for limiting EMF exposure that will provide protection against known adverse health effects. In 1998, "Guidelines For Limiting Exposure To Time-Varying Electric, Magnetic, and Electromagnetic Fields" [22] was published. This publication provides a general review of relevant literature on the biological and health effects of electric and magnetic fields and establishes exposure limits based on this data. In summary,

- When induced current density exceeds 100 to several hundred mA/ m^2 for frequencies between about 10 Hz and 1 kHz, thresholds for neuronal and neuromuscular stimulation are exceeded.
- Occupational exposure should be limited to fields that induce current densities less than 10 mA/m^2 (A safety factor of 10)
- For the general public exposure should be limited to fields that induce current densities less than 2 mA/m^2 (an additional safety factor of 5)
- Reference levels are obtained from the above basic restrictions, and compliance with the reference level will ensure compliance with the relevant basic restriction.
- The reference level for electric field intensity at 50 Hz is 5 kV/m and 10 kV/m for public exposure and occupational exposure respectively.
- The reference level for magnetic field intensity at 50 Hz is 100 µT and and 500 µT for public exposure and occupational exposure respectively.
- These restrictions are based on short-term, immediate health effects such as stimulation of peripheral nerves and muscles. The current densities induced by transient or very short term peak fields should be regarded as instantaneous values which should not be time averaged.

- Induction of cancer from long- term EMF exposure was not considered to be established and it was concluded that available data are insufficient to provide a basis for setting exposure restrictions, although epidemiological research has provided suggestive, but unconvincing, evidence of association between possible carcinogenic effects and exposure at levels of 50/60 Hz magnetic flux densities substantially lower than those recommended in these guidelines.

5.4.1 Current Practice in Turkey

Currently there is no explicit rule in “Elektrik Kuvvetli Akım Tesisleri Yönetmeliği” regarding exposure to electric and magnetic fields. As for 380 kV lines, provided that required vertical (8.7 m) and horizontal (5 m) clearances are maintained, one can construct a building even directly below the line. There are now plans to change the national regulation and incorporate additional rules to limit the exposure to electric and magnetic fields although at this stage it is unclear what they will be.

5.4.2 Ground Clearances in Residential Areas

Currently, there are many lines that have routes passing through residential areas. As explained above, at this stage, the restrictions on electric and magnetic field intensities that will be incorporated to the national regulation is unknown, so it would be logical to assume that recommendations of ICNIRP (5 kV/m, 100 μT for general public) will be accepted directly. If this happens, the minimum ground clearances should be higher in residential areas.

5.4.3 Electric and Magnetic Field Profile of a Line

Since the electric field intensity around the line depends on the voltage of the line, it is relatively constant. In contrast magnetic field intensity of the line depends on the load current. To analyze the exposure to electric and magnetic fields, measurement is preferable. However, at the design stage calculations are necessary. An exact calculation for the electric and magnetic fields is a difficult task, and some reasonable assumptions and simplifications should be made. The methodology recommended in Cigre TB 21 [23] for a simplified analysis assumes the following:

-The wires are infinitely long and straight.

-Bundles are modeled with their equivalent diameter.

-The effects of earth return currents are ignored.

-The ground is flat and all points have the same elevation as that of centerline.

-The earth is a perfect conductor.

-Shielding effects from structures at ground potential are ignored.

In addition to these, it is the author's idea that following assumptions are reasonable:

-Since the electric field depends on the geometry of the conductors, maximum sag condition described in the national regulation is used to calculate the electric and magnetic fields. Turkish regulation requires the designer to check the required clearances at 45^{o}C, 40^{o}C, and 40^{o}C for ice zones II, III and IV respectively. Although the current ratings of the lines are calculated considering a continuous operating temperature of 80^{o}C, a line attaining its rated current is a rare event and it may be over conservative to use the rated current to calculate the electric and magnetic field intensities.

-As a conservative assumption, the height of the wires is taken to be the height at the lowest point of the sag curve.

-The nominal voltage of the line (380 kV) is taken into account instead of the maximum voltage (420 kV).

-The line is assumed to be balanced.

It is easy to meet the requirement for the magnetic field, i.e., 100 μT. It is the electric field intensity which requires higher clearances. Therefore the calculation will be given only for the electric field.

The calculation method is as the following:

$$[V] = [P][Q] \tag{5.2}$$

where

-[V] is the column vector of potentials

-[P] is Maxwell potential coefficients matrix

-[Q] is the column vector of linear charge

Using the above relation, the linear charge vector can be obtained:

$$[Q] = [P]^{-1}[V] \tag{5.3}$$

$$P_{ii} = \frac{1}{2\pi\varepsilon}\ln(\frac{2y_i}{r_{eq}}) \tag{5.3}$$

$$P_{ij} = \frac{1}{2\pi\varepsilon}\ln[\frac{(x_i - x_j)^2 + (y_i + y_j)^2}{(x_i - x_j)^2 + (y_i - y_j)^2}]^{1/2} \tag{5.4}$$

The electric field produced by a single charge and its image is:

$$E_x = \frac{q}{2\pi\varepsilon}[\frac{(x - x_i)}{(x - x_i)^2 + (y - y_i)^2} - \frac{(x - x_i)}{(x - x_i)^2 + (y + y_i)^2}] \tag{5.5}$$

$$E_y = \frac{q}{2\pi\varepsilon}[\frac{(y - y_i)}{(x - x_i)^2 + (y - y_i)^2} - \frac{(y + y_i)}{(x - x_i)^2 + (y + y_i)^2}] \tag{5.6}$$

The resultant field at each point in space is a rotating elliptical field, except for ground level, where the electric field direction is perpendicular to the ground.

Assuming that, E_x and E_y are obtained in phasor form E_x= a +jb, E_y=c+jd, then in time domain:

$$E^2 = E_x^2 + E_y^2 = (a^2 + c^2)\cos^2 wt + (b^2 + d^2)\sin^2 wt - 2(ab + cd)\cos wt \sin wt \tag{5.7}$$

The maximum field intensity occurs when $\frac{dE^2}{dwt} = 0$

It can be shown that

$$E_{\max,\min} = \sqrt{[(a^2 + c^2)\frac{1}{1+p^2} + (b^2 + d^2)\frac{p^2}{1+p^2} - 2(ab+cd)\frac{p}{1+p^2}]} \tag{5.8}$$

where

$$k = \frac{((b^2 + d^2) - (a^2 + c^2))}{(ab + cd)} \tag{5.9}$$

$$p_{12} = \frac{-k + -\sqrt{k^2 + 4}}{2} \tag{5.10}$$

<u>An example:</u>

The majority of the lines in Turkey at 380 kV are single circuit with Pheasant conductors and single circuit with Cardinal conductors. The spacing between the subconductors for Pheasant lines is 50 cm, whereas it is 457 mm for Cardinal lines. This means that for the same operating voltage, Pheasant lines will have stronger electric fields due to larger capacitance. Therefore this example will be given for two tower types used in lines with Pheasant conductor: Type 3PD tension and type 3PA suspension towers. The geometric mean radius of the phase conductor is 13.67 cm and the radius of the shieldwire is 0.635 cm.

Two Successive 3PD type towers-Tower heights are adjusted to meet the required basic ground clearance of 9.5 m:

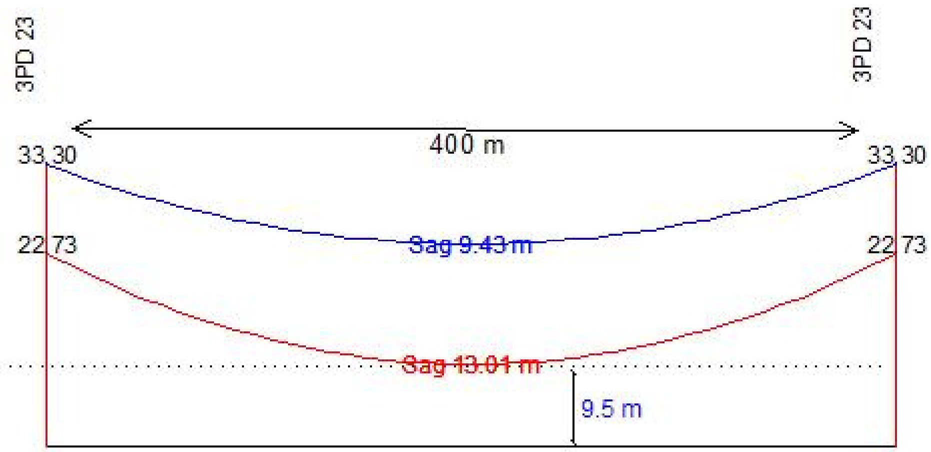

Figure 5.1: Two successive 3PD(23) type towers with a span length of 400 m.

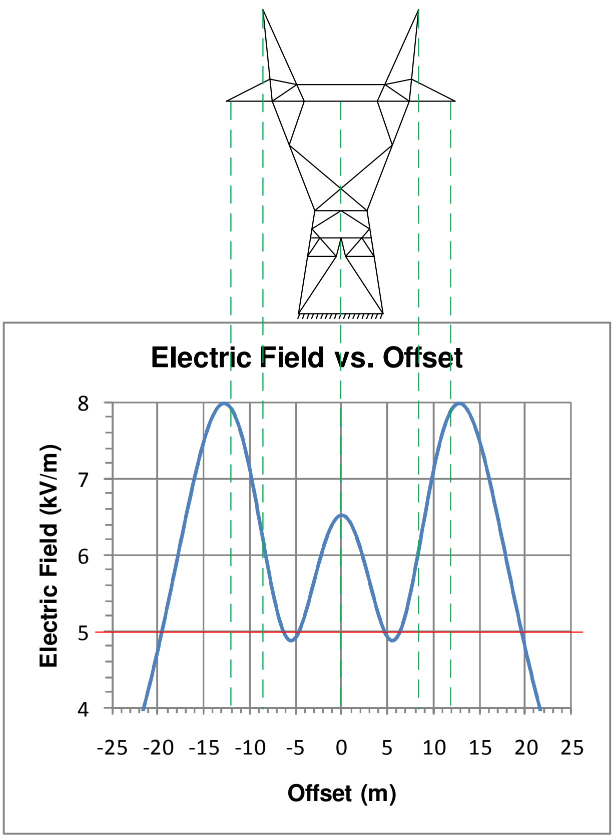

Figure 5.2: E field pattern of two successive 3PD (23) type towers, 1m above ground at mid span.

Two Successive 3PA type towers-Tower heights are adjusted to meet the required basic ground clearance of 9.5 m:

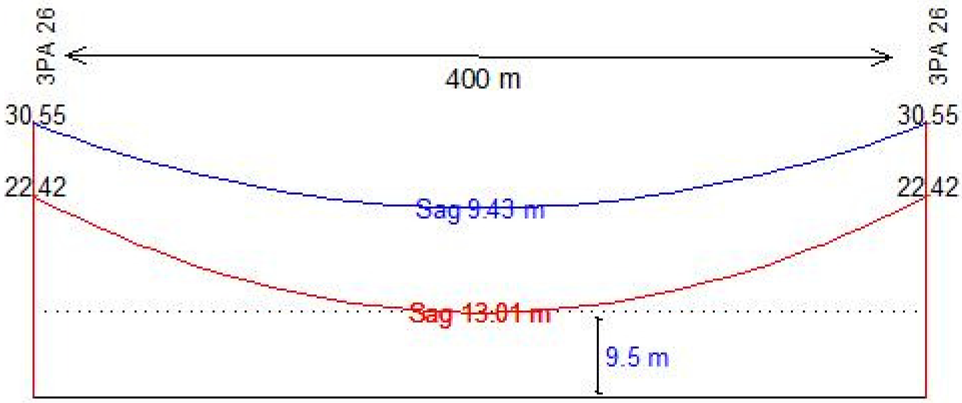

Figure 5.3: Two successive 3PA (26) type towers with a span length of 400 m.

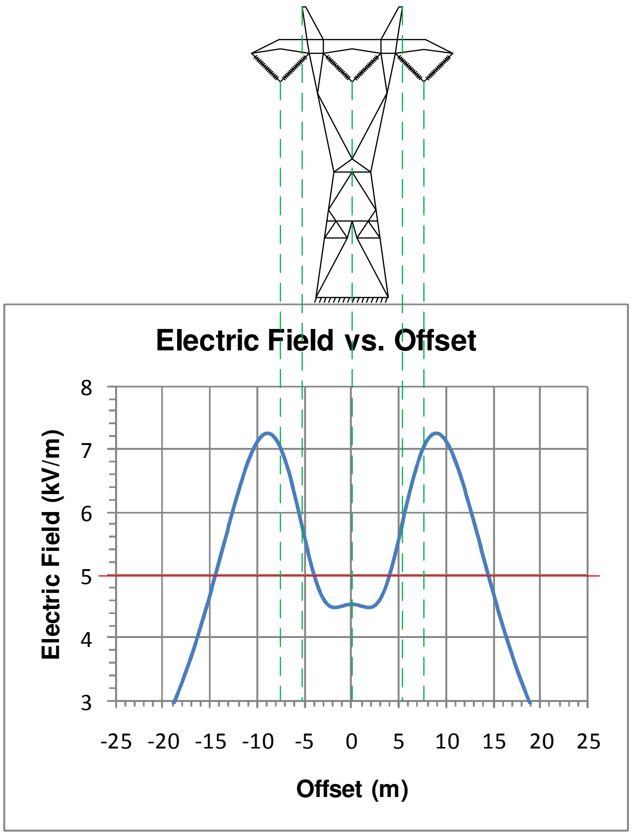

Figure 5.4: E field pattern of two successive 3PA (26) type towers, 1m above ground at mid span.

Two Successive 3PD type towers-Tower heights are adjusted to meet the requirement for electric field (5 kV/m):

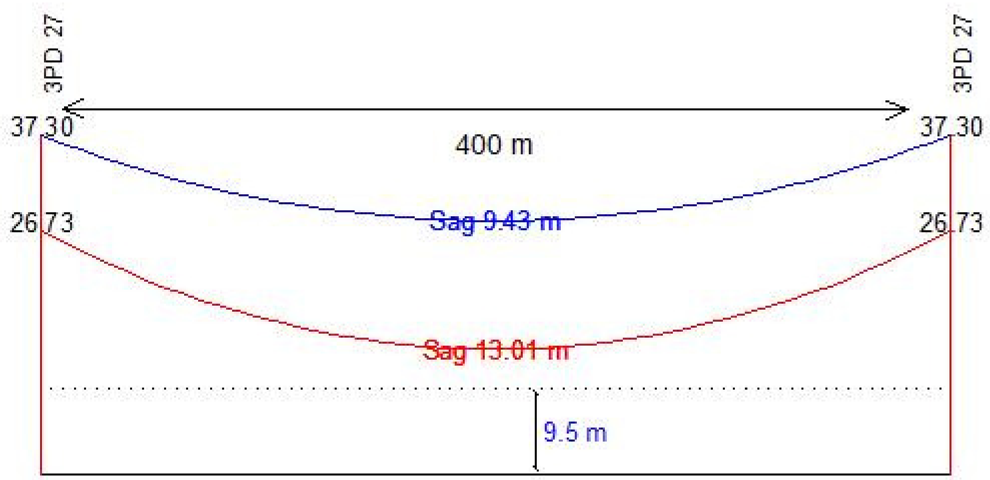

Figure 5.5: Two successive 3PD (27) type towers with a span length of 400 m.

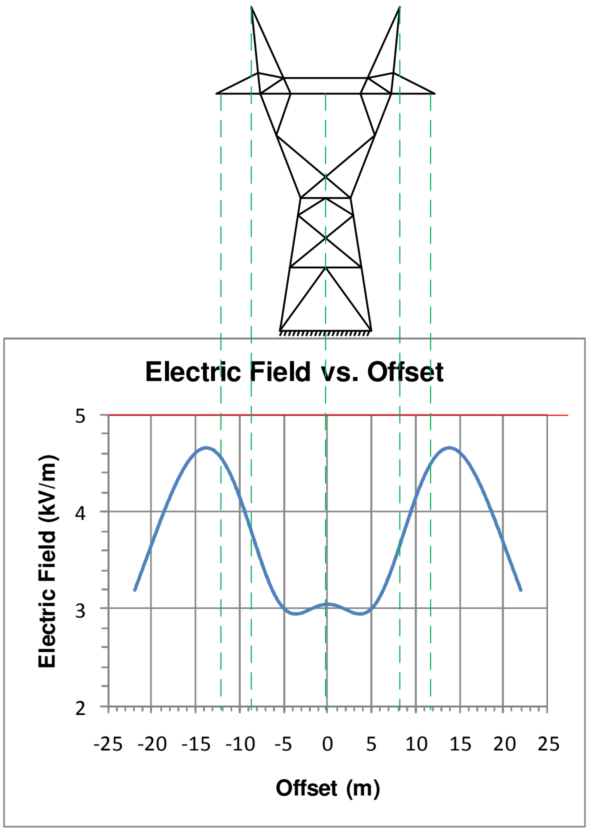

Figure 5.6:E field pattern of two successive 3PD (27) type towers, 1m above ground at mid span.

Two Successive 3PA type towers-Tower heights are adjusted to meet the requirement for electric field (5 kV/m):

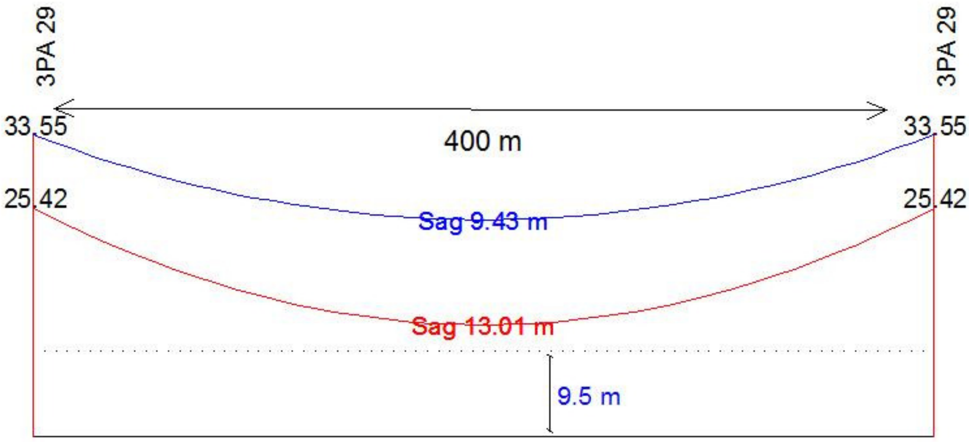

Figure 5.7: Two successive 3PA (29) type towers with a span length of 400 m.

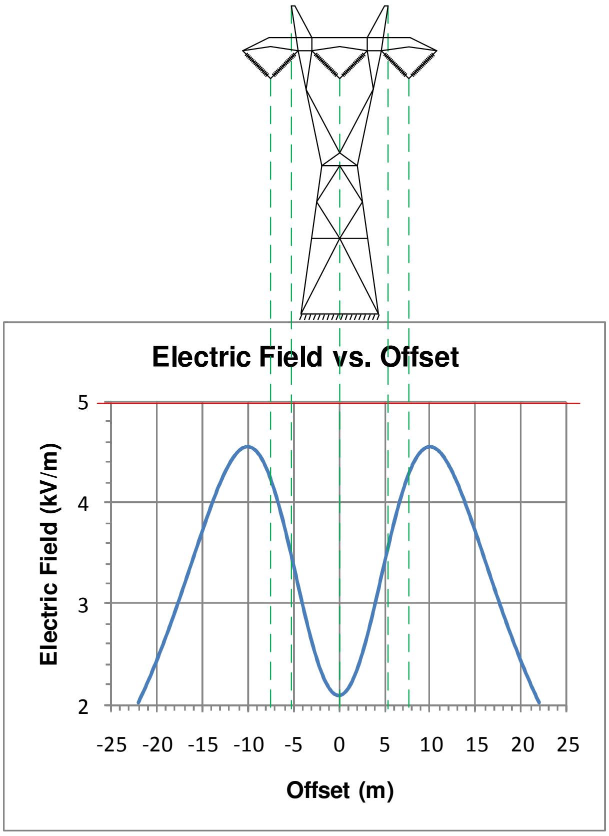

Figure 5.8:E field pattern of two successive 3PA (29) type towers, 1m above ground at mid span.

The following conclusions can be drawn from the above graphs:

-For the same ground clearance, 3PD type tension tower produces higher fields when compared to 3PA type suspension tower. This is expected as the phase spacing is greater for 3PD (12 m) and there is less cancellation from adjacent phases.

-Basic ground clearance is not sufficient to limit the electric field intensity to 5 kV/m. Depending on the tower type, an extra clearance of 3-4 m is needed. However this may not be always true because the presence of grounded object may significantly alter the electric field distribution and the clearance requirement may be higher or lower. As already mentioned, these calculations are based on a simplified model and can only provide rough estimates. For detailed analyses, precise models, or better, measurements are needed.

5.5 Concluding Remarks

The basic clearance requirement for 380 kV, 9.5 m is high when compared to that of other national standards. The cost of one meter extra clearance is approximately 1000 USD/km for 380 kV lines. As discussed before, majority of the past clearance violations were due to incorrect survey data. Perhaps, it was one of the reasons to select such a high clearance requirement. If modern survey techniques are adopted, this requirement can be reduced and considering the cost of one meter extra clearance, 1000 USD/km, it is well worth the effort.

On the other hand, it seems impossible to meet the requirement for electric field intensity with the basic ground clearance, 9.5 m. Therefore, if the recommendations of ICNRP are incorporated to the national regulation, the ground clearance should be around 13-14 m in residential areas.

CHAPTER 6

CONCLUSIONS

For line insulation coordination, the insulation strength depends on the geometry of the towers and properties of the insulator string. The selection of the parameters defining the tower geometry such as tower height, strike distance, phase spacing and shielding angle, should be based on the desired degree of reliability, considering the overvoltages which can appear on the system and the climatic data.

In general, for E.H.V. transmission lines it is the switching surges that dictate the required strike distances. The altitude varies considerably throughout the country and the required strike distance varies significantly with the altitude and the accepted switching surge flashover rate.

Although the shielding angles of present E.H.V. transmission line towers' are adequate for flat terrain, in mountainous areas they may not guarantee a satisfactory performance.

Climatic loads such as wind or ice play an important role when defining tower top geometries. In respect of the determination of the geometry, icing is an important consideration for towers with vertical conductor arrangement. Currently there is almost no statistical data on ice loads in Turkey.

For structural design, new methods based on reliability based design considerations have emerged. There, a wind velocity having a given return period is selected as the basis for structural design representing an ultimate load which may stress the structure to its ultimate strength capacity. For the design of the tower top geometry, the modern practice is to use the same meteorological data to determine the positions of conductors and insulator sets. With this approach, the mechanical and electrical reliability of the line becomes consistent.

For the climatic loads, to obtain statistically meaningful results, a minimum measurement period of 10 years is required. Therefore, Turkish Electricity Transmission Company should undertake meteorological observation programs with the collaboration of the national weather bureau and collect field data by means of instrumented lines without delay.

The basic clearance requirement for 380 kV, 9.5 m, is high when compared to that of other national standards. However, if the recommendations of ICNRP are incorporated to the national regulation, the ground clearances should be around 13-14 m in residential areas.

In general, Turkish Electricity Transmission Company should have at least two different type projects for each conductor and circuit configuration combination. Increasing the number of type designs would be beneficial in respect of the structural design too.

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APPENDIX A

KERAUNIC LEVELS IN TURKEY

Table A.1: Annual frequency of thunderstorm days in Turkey

STATION	T_d	STATION	T_d	STATION	T_d
KOZAN	45	DENİZLİ	27	SEFERİHİSAR	23
ALANYA	44	İNEBOLU	27	TOKAT	22
ANTALYA	40	GÜMÜŞHANE	26	SENİRKENT	22
KARS	38	ÇANAKKALE	26	PAZAR (RİZE)	22
MUĞLA	36	ANKARA	26	ALATA-ERDEMLİ	22
İSKENDERUN	36	SARIKAMIŞ	26	GÖKSUN	22
İSPİR	35	ACIPAYAM	26	BOLVADİN	22
GAZİPAŞA	34	SİİRT	26	KİREÇBURNU	22
ESENBOĞA	33	SAMSUN	26	KOCAELİ	22
ARPAÇAY	33	ERZİNCAN	25	GİRESUN	22
SİLİFKE	33	SAMANDAĞ	25	MAZGİRT	22
GÖKÇEADA	33	KASTAMONU	25	BODRUM	22
KÖYCEĞİZ	33	EMİRDAĞ	25	KAYSERİ	22
MANAVGAT	32	TOMARZA	25	DİNAR	21
YATAĞAN	32	ÇERKEŞ	25	ELAZIĞ	21
ZONGULDAK	32	HORASAN	25	ETİMESGUT	21
ADANA	32	DÖRTYOL	25	SİVAS	21
YUMURTALIK	31	MERZİFON	24	AKŞEHİR	21
KARAİSALI	31	DEVREKANI	24	TURHAL	21
EDİRNE	31	MİLAS	24	AĞRI	21
ÇORUM	31	EĞİRDİR	24	MUŞ	21
MERSİN	31	DİKİLİ	24	YUNAK	21
FİNİKE	31	ADIYAMAN	24	TORTUM	21
ISPARTA	30	KIRKLARELİ	24	ÇANKIRI	21
IĞDIR	30	POZANTI	24	KIRIKKALE	21
ERZURUM	29	ÖZALP	24	MANİSA	21
SEYDİŞEHİR	29	OSMANCIK	23	BEYPAZARI	21
ELMALI	29	DİVRİĞİ	23	TOSYA	21
DALAMAN	29	BOLU	23	AĞIN	21
ANAMUR	29	İZMİR	23	POLATLI	20
ARDAHAN	29	MARMARİS	23	AFYON	20
LÜLEBURGAZ	28	TEFENNİ	23	BURHANİYE	20
FETHİYE	27	AYDIN	23	OLTU	20
TEKİRDAĞ	27	KULU	23	CİDE	20
ANTAKYA	27	HOZAT	23	CEYHAN	20
KORKUTELİ	27	TUNCELİ	23	AKHİSAR	20

Table A.1 (cont'd): Annual frequency of thunderstorm days in Turkey

STATION	T_d	STATION	T_d	STATION	T_d
DURSUNBEY	20	ORDU	18	SİNOP	15
NAZİLLİ	20	KARABÜK	17	BİRECİK	15
PALU	20	GÖNEN	17	BOZKURT	15
ESKİSEHİR BÖLG.	20	AVANOS	17	DÜZCE	15
EDREMİT	20	KUMKOY	17	SARIZ	15
KIRŞEHİR	20	AMASYA	17	KESKİN	15
ARTVİN	20	SELÇUK	17	KIZILCAHAMAM	15
KAHRAMANMARAŞ	20	NİĞDE	17	KAMAN	15
SULTANHİSAR	20	BAYBURT	17	BASKİL	15
ESKİŞEHİR ANAD.	20	DEMİRCİ MANİSA	17	BAŞKALE	15
SİVRİHİSAR	20	SALİHLİ	17	KAHTA	14
BİLECİK	20	BURSA	17	AKSARAY	14
KARATAŞ	20	HADIM	17	KEBAN	14
UZUNKÖPRÜ	20	BOĞAZLIYAN	17	YOZGAT	14
BURDUR	20	ŞANLIURFA	17	AMASRA	14
DATÇA	20	KONYA	17	EREĞLİ KONYA	14
AKÇAKOCA	19	ÜRGÜP	17	KELES	14
DOGUBEYAZIT	19	CİZRE	17	YENİŞEHİR	14
BERGAMA	19	SAKARYA	17	MUT	14
GEDİZ	19	TAVŞANLI	17	ÇERMİK	14
KÜTAHYA	19	ILGIN	16	SORGUN	14
ULUBORLU	19	ÜNYE	16	ERZURUMBÖLGE	14
AFŞİN	19	BORNOVA	16	ULUDAĞ ZİRVE	14
DİYARBAKIR	19	BOZÜYÜK	16	YÜKSEKOVA	14
ILGAZ	19	KALE-DEMRE	16	KARAPINAR	14
BALABAN	19	BALIKESİR	16	YALVAÇ	13
ÇORLU	19	ZARA	16	İPSALA	13
BANDIRMA	18	SUŞEHRİ	16	NALLIHAN	13
KUŞADASI	18	BAFRA	16	TERCAN	13
KAŞ	18	GÖZTEPE/İSTANB.	16	SAMSAT	13
KİĞI	18	ÖDEMİŞ	16	KARAMAN	13
MADEN ELAZIĞ	18	BİTLİS	16	TATVAN	13
VAN	18	GÖLBAŞI	16	RİZE	13
CİÇEKDAĞI	18	BATMAN	16	GAZİANTEP	13
UŞAK	18	GEMEREK	16	KANGAL	13
BİNGÖL	18	ARAPKİR	16	MALATYA	13
SİMAV	18	NEVŞEHİR	16	DEVELİ	13
TRABZON	18	SİVEREK	15	HOPA	13
AYVALIK	18	KARAKOÇAN	15	ERGANİ	13

Table A.1 (cont'd): Annual frequency of thunderstorm days in Turkey

STATION	T_d	STATION	T_d	STATION	T_d
AKÇAABAT	13	GEYVE	11	GENÇ	9
BEYŞEHİR	13	SİVRİCE	11	VARTO	8
ÇEŞME	13	CEYLANPINAR	11	AKÇAKALE	8
PINARBAŞI KAYS.	13	ŞEBİNKARAHİSAR	11	MURADİYE VAN	8
BAHÇEKÖY	13	GÜNEY	11	AHLAT	8
BOZCAADA	13	MARDİN	11	NUSAYBİN	8
MALAZGİRT	12	SOLHAN	11	GEVAŞ	7
CEMİŞGEZEK	12	ERCİŞ	11	ÇAY	7
HAKKARİ	12	ISLAHİYE	10	KARTAL	7
HİLVAN	12	DOĞANŞEHİR	10	HINIS	7
FLORYA	12	ŞİLE	10	ÇINARCIK	7
ZİLE	12	ÇUMRA	10	DİDİM	6
ULUKIŞLA	12	BOZOVA URFA	10	MALKARA	6
OSMANİYE	11	CİHANBEYLİ	10	MENEMEN ZR.FAK	5
YALOVA	11	ELBİSTAN	10		
BARTIN	11	KİLİS	9		

APPENDIX B

STRUCTURAL ANALYSIS OF THE TYPE TOWER 2FA

B.1 Analysis Data

Wind span: 400 m;

Weight span: 200 m;

Phase conductor: Pheasant ACSR (1272 MCM);

Unit weight of the conductor: 2.435 kgf/m;

Diameter of the conductor: 35.10 mm;

Shield wire: 7/16" E.H.S. Steel;

Unit weight of the shield wire: 0.58 kgf/m;

Diameter of the shield wire: 11.05 mm;

Wind exposed area of insulator set: 0.5 m^2;

Weight of the insulator set: 75 kgf;

Length of insulator set: 2.19 m;

Wind velocity (at 10 m height, 10 minute average):30 m/s;

Terrain category: B.

B.2 Loads

As per IEC 60826, for a wind blowing in perpendicular direction to the line, the wind load transferred by the conductors and insulators to the support is given by the following expressions:

<u>Wind Loads on Conductors:</u>

$$A_c = q_0.C_{xc}.G_c.G_L.d.L \tag{B.1}$$

where

q_0 : Dynamic reference wind pressure (at a height of 10 meters);

C_{xc} : Drag coefficient of the conductor, taken equal to 1;

G_c : Combined wind factor for the conductors which depends on the terrain category and height above ground;

G_L : Span factor;

d : Diameter of the conductor;

L : Wind span.

$$q_0 = \frac{1}{2} pV^2 \tag{B.2}$$

where p is the air density and equal to 1.225 kg/m^3 at sea level and V is the wind velocity in m/s. With these units the result is in N/m^2 .

$$G_c = 0.3733 \ln(h) + 0.9762 \tag{B.3}$$

where height is in meters and applicable for terrain type B.

$$G_L = 4x10^{-10} xL^3 - 5x10^{-7} xL^2 - 10^{-4} L + 1.0403 \tag{B.4}$$

<u>Wind Loads on Insulator Strings:</u>

$$A_i = q_0 . C_{xi} . G_t . S_i \tag{B.5}$$

where

q_0 : Dynamic reference wind pressure;

C_{xi} :Drag coefficient of the insulator, considered equal to 1.2;

G_t :Combined wind factor for supports and insulators which depends on the terrain category and height above ground;

S_i : Wind exposed area of insulator string.

$$G_t = -0.0002xh^2 + 0.0274xh + 1.6820 \tag{B.6}$$

where height is in meters and for terrain type B.

The conductor and insulator heights appearing in the above equations are given in Table B.1.

Table B.1: Effective heights for the conductors and insulators

	Insulator String(m)	**Conductor(m)**
Bottom Phases	34.1	23.9
Middle Phases	38.4	28.2
Top Phases	42.6	32.5
Shield wire	-	36.4

For a 400 m span, the sag of the conductor is approximately 13.7 m. The effective insulator heights are calculated by subtracting half of the insulator length from the attachment heights. The effective heights for conductors are calculated by subtracting two thirds of the sag and insulator length from the attachment heights.

The resultant loads, i.e. the vertical and transverse loads (in kgf) transferred by the insulators and the conductors to the supports are shown in Figure B.1.

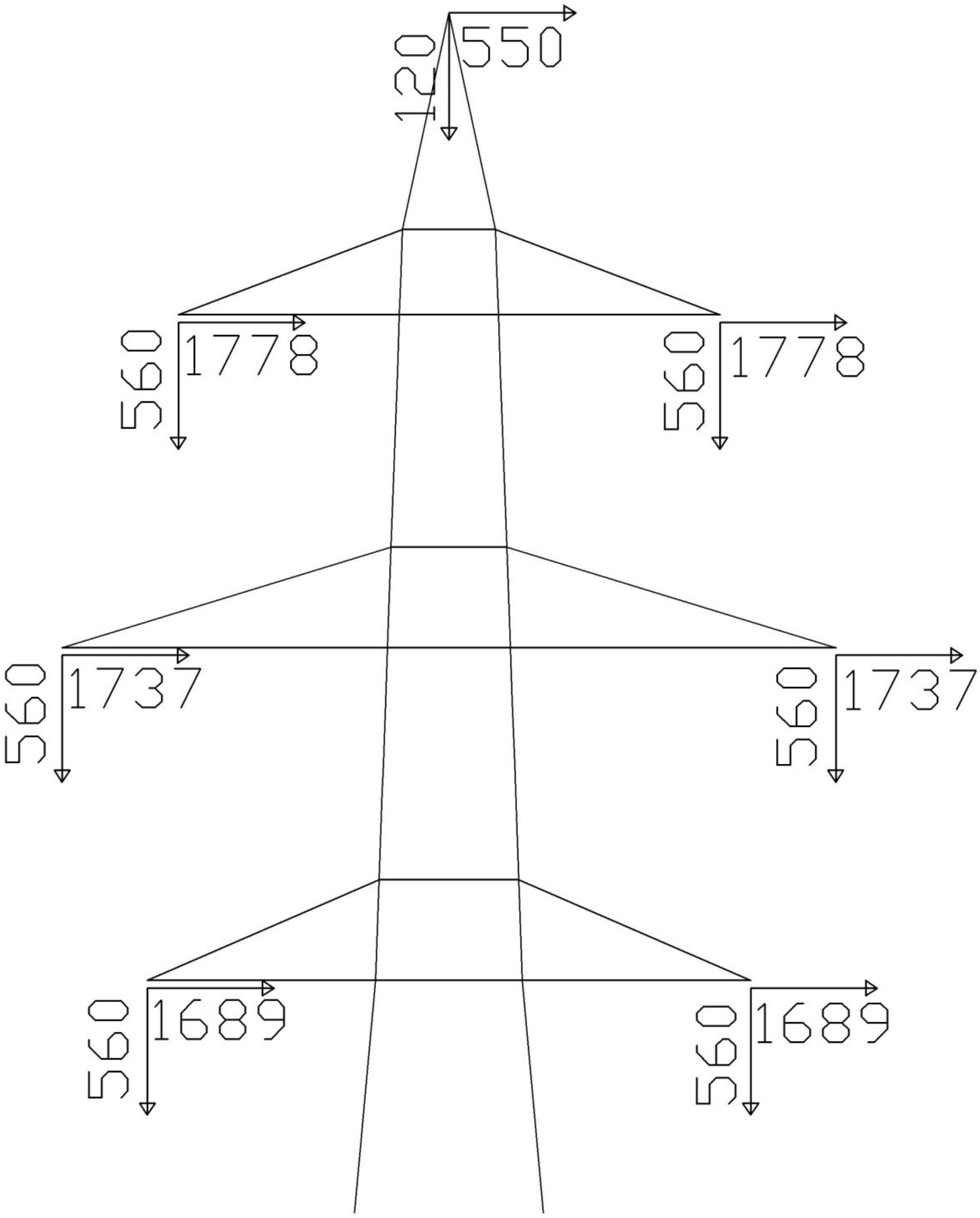

Figure B.1: The resultant loads transferred by the conductors and the insulators, in kgf.

Wind Loads on the Tower:

To calculate the wind load on the tower, the lattice tower is divided into different panels as shown in Figure B.2.

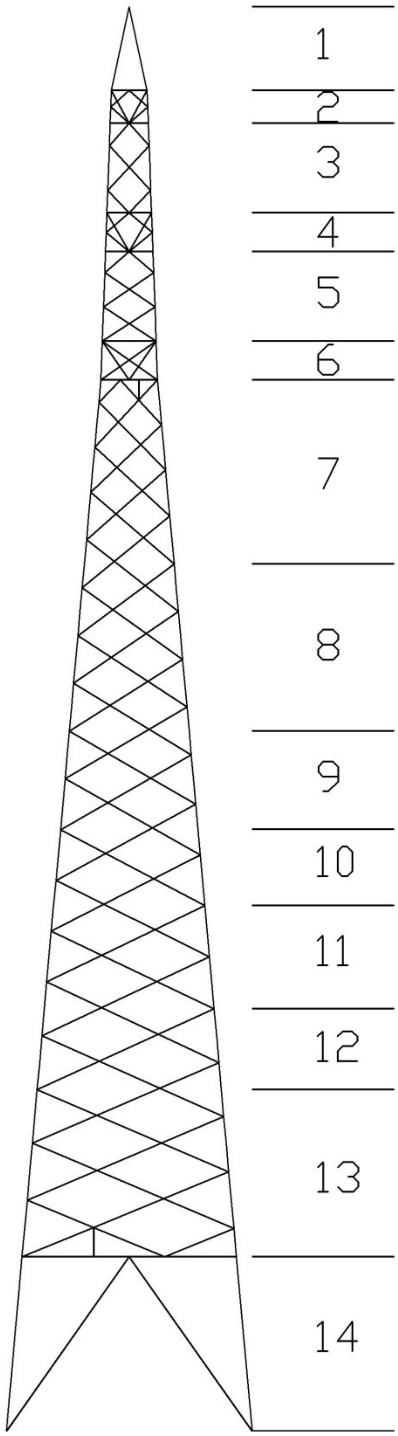

Figure B.2: Right view, panels for transverse wind.

As per IEC 60826, the wind load acting on the tower panels is given by the following equation:

$$A_t = q_0 . C_{xt} . S_t . G_t \tag{B.7}$$

where

C_{xt} : Drag coefficient for the panel, depending on its solidity ratio;

S_t : Total surface area of the panel;

G_t : Combined wind factor for supports and insulators which depends on the terrain category and height above ground.

$$C_{xt} = 4.1727\chi^2 - 6.1681\chi + 4.0088 \tag{B.8}$$

where χ is the ratio between the total area of the members belonging to the panel and the area enclosed by the panel. It is a measure of the sheltering by windward members. The wind loads acting on the panels are given in Table B.2.

Table B.2: The wind loads acting on the panels

Panel	Height of Panel Center(m)	Gt	Solidity	Cxt	Area(m^2)	Force(kgf)
1	46.30	2.52	0.300	2.53	0.43	156
2	44.35	2.50	1.000	2.01	1.36	385
3	42.30	2.48	0.245	2.75	0.88	338
4	40.15	2.46	1.000	2.01	2.00	557
5	38.00	2.43	0.253	2.72	1.12	416
6	35.85	2.41	1.000	2.01	2.41	655
7	32.12	2.36	0.173	3.07	2.62	1064
8	26.25	2.26	0.132	3.27	2.61	1085
9	21.80	2.18	0.116	3.35	1.66	683
10	18.88	2.13	0.117	3.34	1.44	576
11	15.87	2.07	0.114	3.36	2.13	831
12	12.80	2.00	0.107	3.40	1.73	659
13	8.20	1.89	0.108	3.39	4.07	1469
14	2.92	1.76	0.084	3.52	3.80	1324

Dead Load:

The self weight of the tower is taken from its project and distributed among the stable joints.

B.3 Results

The tower is analyzed with structural analysis program SAP2000. The highest strained member of the tower (rightmost member of the Figure B.3) has a compression force of 41613 kgf. For this loading the uplift load at the foundations is 37427 kgf.

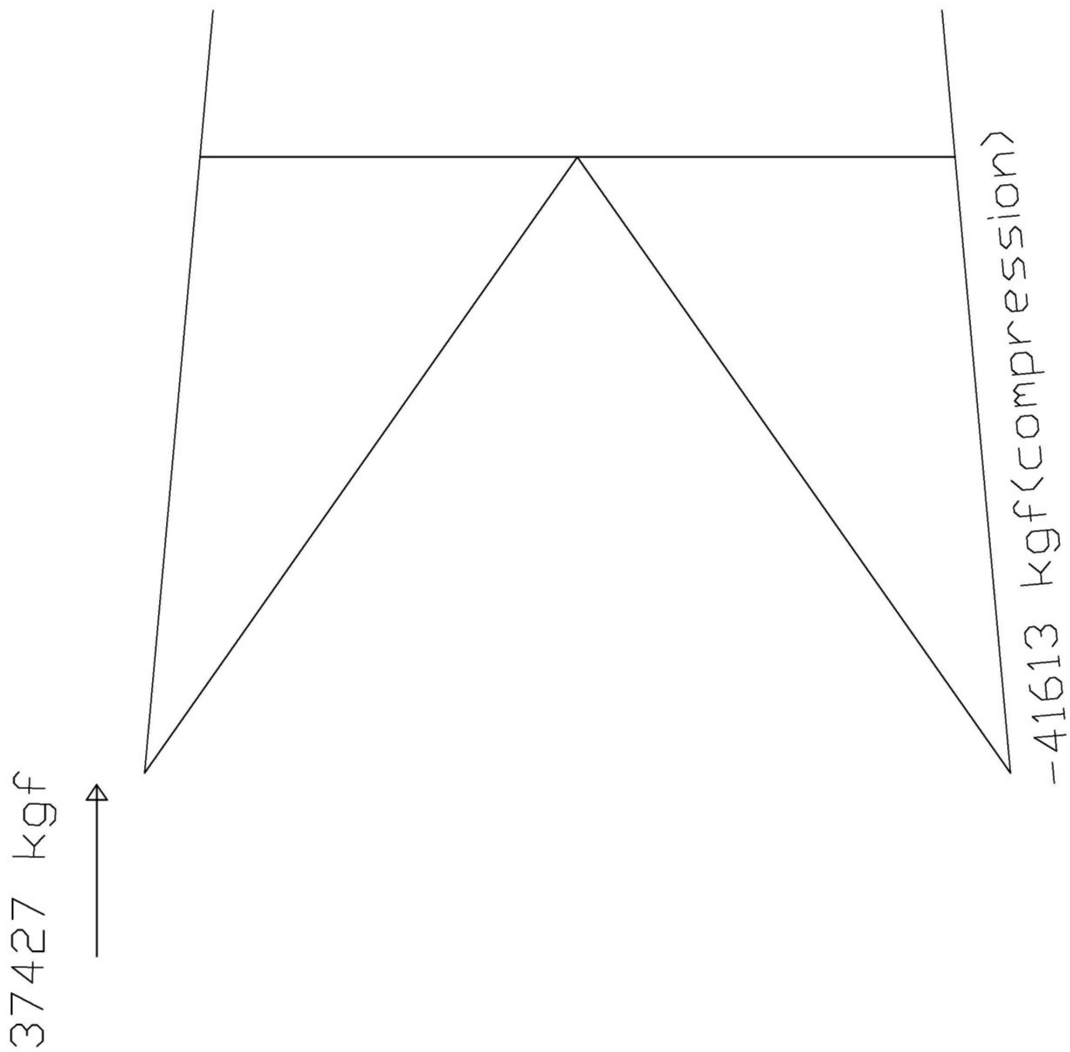

Figure B.3: The foundation reaction and the compression force of the leg.

APPENDIX C

REQUIRED MID SPAN GROUND CLEARANCES

Table C.1: Required Vertical Clearances as Per the National Regulation

	Vertical Clearances (m)					
Maximum System Voltage (kV)	0-1	1-17.5	36	72.5	170	420
Waterways without navigation on them	4.5	5	5	5	6	8.5
Meadow, field, pasture and smilar places suitable for passage of vehicles	5	6	6	6	7	9.5
Village and city roads available to the passage of vehicles	5.5	7	7	7	8	12
Intercity Highways	7	7	7	7	9	12
Trees	1.5	2.5	2.5	3	3	5
Open flat-roofed structures	2.5	3.5	3.5	4	5	8.7
Restricted slope-roofed structures	2	3	3	3.5	5	8.7
Electric lines	2	2	2	2	2.5	4.5
Oil and natural gas pipelines	9	9	9	9	9	9
Channels and waters with traffic	4.5	4.5	5	5	6	9
Telecomunication lines	1	2.5	2.5	2.5	3.5	4.5
Railways	7	7	7	7	8	10.5
Highways	14	14	14	14	14	14

APPENDIX D

A SAG TENSION CALCULATION METHOD TAKING THE STRAIN INSULATORS INTO ACCOUNT

Since the length of the strain insulators is much less than the length of the span, classical sag tension calculations do not take the presence of strain insulators into account. However, for slack spans, the length and the weight of the strain insulators becomes important and should be incorporated in the formulation of the model. The calculation technique outlined in this appendix is from [24].

The most primitive type of sag tension calculations is the change of state equation. It is based on the following assumptions:

-The cable has a linear stress strain relationship.

-The average tension can be approximated by the horizontal component of the tension.

With these assumptions, the following equation can be obtained:

$$l_2 - l_1 = \frac{H_2 - H_1}{SxE} x l_1 + (t_2 - t_1) x e_t x l_1 \tag{D.1}$$

where

l_2, l_1 : Length of the conductor in the second and first states;

H_2, H_1 : Horizontal tension of the conductor in the second and first states;

t_2, t_1 : Temperature of the conductor in the second and first states;

S : Cross section of the conductor;

E : Elasticity modulus of the conductor;

e_t : Thermal expansion coefficient of the conductor.

The first term on the right hand side of the equation is the mechanical strain and the second term is the thermal strain. The sum of them must be equal to the length difference of the cable. If the length of the cable on the right hand side is replaced by the span length, and if the length difference of the cable on the left hand side is approximated by the third order Taylor expansion of the sinh function, the classical change of state equation can be obtained :

$$a^2\left(\frac{g_2^2}{24H_2^2}-\frac{g_1^2}{24H_1^2}\right)=\frac{H_2-H_1}{SE}+(t_2-t_1)e_t \tag{D.2}$$

where g_2 and g_1 are the unit weights of the conductor in state 2 and state 1 and a is the span length.

However, as explained previously, this equation can not be used to calculate the tension of the slack spans.

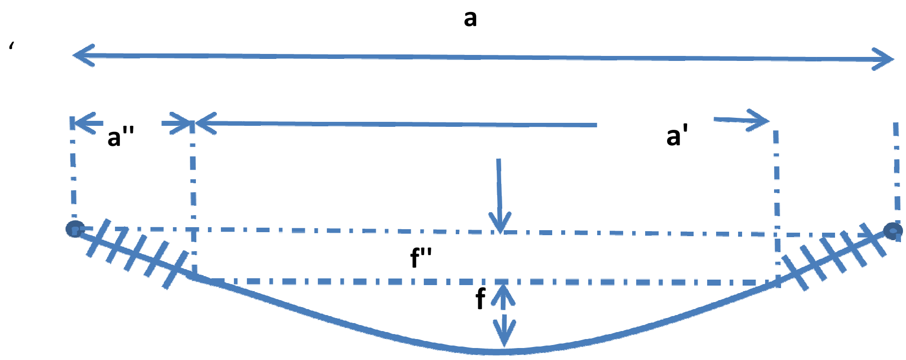

Figure D.1: Slack Span.

It can be shown that the length of the cable between two support points is:

$$l=2\frac{H}{g}\sinh\left(\frac{ag}{2H}\right) \tag{D.3}$$

where a is the span length, H is the horizontal tension of the conductor and g is the unit weight of the cable. If the sinh function is expanded about zero, an approximate equation can be obtained:

$$l = a + \frac{g^2 a^3}{24H^2} \tag{D.4}$$

Then, examining Figure D.1 and considering the mechanical and thermal stress strain properties of the cable, the unstressed length of the cable at zero degree Celsius, i.e. the length of the cable if it was laid on the ground at zero degree Celsius is:

$$l_u = a'_2 + \frac{g_2^2 a'^3_2}{24H_2^2} - e_t t_2 a'_2 - \frac{H_2}{SE} a'_2 \tag{D.5}$$

where

g_2 : Unit weight of the conductor in state 2;

H_2 : Horizontal tension of the conductor at state 2;

e_t : Thermal expansion coefficient of the cable;

t_2 : Temperature at state 2;

S : Cross section of the cable;

E : Elasticity modulus of the cable.

The first two terms are the length of the cable at state 2. When third and fourth terms are subtracted, the unstressed length of the cable at reference temperature is found. Writing down the same equation for state 1 yields:

$$l_u = a'_1 + \frac{g_1^2 a'^3_1}{24H_1^2} - e_t t_1 a'_1 - \frac{H_1}{SE} a'_1 \tag{D.6}$$

With l_i denoting the length of the insulator, since $a'_2 = a - 2a''_2 \approx a - 2l_i$, $a'_1 = a - 2a''_1 \approx a - 2l_i$ and the expressions of the unstressed length of the cable derived from both states must be equal, the following equation can be obtained:

$$\frac{g_2^2(a-2l_i)^3}{24H_2^2}-\frac{g_1^2(a-2l_i)^3}{24H_1^2}=2(a''_2-a''_1)+\frac{H_2-H_1}{SE}(a-2l_i)+e_t(t_2-t_1)(a-2l_i)$$

(D.7)

This is the change of state equation with a span with strain insulators. The unknown a'' should be replaced with a expression in terms of the known variables.

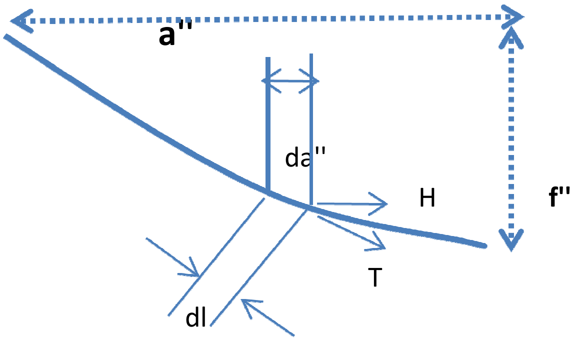

Figure D.2: Cable Element.

From the Figure D.2, the following equation can be obtained:

$$\frac{H}{T}=\frac{H}{\sqrt{H^2+(\frac{l_{ui}}{l_i}G_i+\frac{ag}{2})^2}}=\frac{1}{\sqrt{1+\frac{1}{H^2}(\frac{l_{ui}}{l_i}G_i+\frac{ag}{2})^2}}\approx 1-\frac{1}{2H^2}(\frac{l_{ui}}{l_i}G_i+\frac{ag}{2})^2$$

(D.8)

where

l_i : Total unstressed length of the insulator at the reference temperature;

l_{ui}: Unstressed length of the insulator up to a point on the insulator;

G_i : Weight of the insulator;

g : Unit weight of the conductor;

a : Span length.

Here T is a function of l_{ui} and attains its largest value at the attachment point where l_{ui} is equal to l_i.

$$dl = dl_{ui}(1+e_t t)(1+\frac{T}{SE}) \quad \text{(D.9)}$$

$$da'' = (1+e_t t)(1+\frac{T}{SE})(\frac{H}{T}) = (1+e_t t)(\frac{H}{T}+\frac{H}{SE}) \quad \text{(D.10)}$$

Now if $\frac{H}{T}$ is replaced with the above formula and both sides of the equation are integrated:

$$\int_0^{a''} da'' = (1+e_t t)\int_0^{l_i} dl_{ui} - \frac{G_i^2}{2H^2 l_i^2} l_{ui}^2 dl_{ui} - \frac{G_i a}{2H^2 l_i} l_{ui} dl_{ui} - \frac{g^2 a^2}{8H^2} dl_{ui} + \frac{H}{SE} dl_{ui} \quad \text{(D.11)}$$

$$a'' = (1+e_t t)[l_i - \frac{g^2 a^2}{8H^2} l_i - \frac{G_i a g}{4H^2} l_i - \frac{G_i^2 l_i}{6H^2} + \frac{H}{SE} l_i] \quad \text{(D.12)}$$

Since both $e_t t$ and $(-\frac{g^2 a^2}{8H^2} l_i - \frac{G_i a g}{4H^2} l_i - \frac{G_i^2 l_i}{6H^2} + \frac{H}{SE} l_i)$ are small, a'' can be approximated by:

$$a'' = l_i - \frac{g^2 a^2}{8H^2} l_i - \frac{G_i a g}{4H^2} l_i - \frac{G_i^2 l_i}{6H^2} + \frac{H}{SE} l_i + e_t t l_i \quad \text{(D.13)}$$

In this case, the change of state equation is:

$$\frac{a^3 g_2^2}{24H_2^2} + (\frac{a l_i g_2^2}{2H_2^2} - \frac{g_2^2 l_i^3}{3H_2^2}) - \frac{a^3 g_1^2}{24H_1^2} - (\frac{a l_i g_1^2}{2H_1^2} - \frac{g_1^2 l_i^3}{3H_1^2}) = -\frac{g_2 a l_i G_{i2}}{2H_2^2} + \frac{g_1 a l_i G_{i1}}{2H_1^2}$$

$$-\frac{l_i G_{i2}^2}{3H_2^2}+\frac{l_i G_{i1}^2}{3H_1^2}+\frac{H_2-H_1}{SE}a+e_t(t_2-t_1)a \tag{D.14}$$

The term in the parenthesis can be neglected, and the final form of the equation is:

$$\frac{a^3 g_2^2}{24H_2^2}-\frac{a^3 g_1^2}{24H_1^2}=-\frac{g_2 a l_i G_{i2}}{2H_2^2}+\frac{g_1 a l_i G_{i1}}{2H_1^2}-\frac{l_i G_{i2}^2}{3H_2^2}+\frac{l_i G_{i1}^2}{3H_1^2}+\frac{H_2-H_1}{SE}a+e_t(t_2-t_1)a \tag{D.15}$$

The total sag (the sag of the conductor and the sag of the insulator) is:

$$f=f^{'}+f^{''}=\frac{(a-2a'')^2 g}{8H}+\frac{l_i}{2H}(G_i+ag) \tag{D.16}$$