Transmission Line Design: Ahuachapán Geothermal Plant- Don Bosco University

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***Resumen*— Una línea de transmisión eléctrica es básicamente el medio físico mediante el cual se realiza la transmisión y distribución de la energía eléctrica, está constituida por conductores, estructuras de soporte, aisladores, accesorios de ajustes entre aisladores y estructuras de soporte, y cables de guarda (usados en líneas de alta tensión, para protegerlas de descargas atmosféricas como los rayos); por lo que resulta de suma importancia el estudio de las características de las mismas debido a que son utilizadas para transportar la energía eléctrica a grandes distancias, a niveles de voltajes muy elevados. El diseño de las líneas de transmisión debe incluir el cálculo de parámetros eléctricos, así como el estudio mecánico de la línea bajo ciertas condiciones climáticas, las cuales modifican las características del conductor de acuerdo a la zona de ubicación de la línea.**

***Abstract*—An electric transmission line is the physical medium through which the transmission and distribution of electrical energy is carried out. It consists of conductors, support structures, insulators, accessories for adjusting insulators and support structures, and guard cables (Uses in high voltage lines, to protect atmospheric discharges such as lightning); What is of great importance is the study of the characteristics of the same thanks to a system of electric power transport at great distances, at very high voltage levels. The design of the transmission lines must include the calculation of the parameters of use, as well as the mechanical study of the line under certain climatic conditions, the modifications of the characteristics of the conductor according to the zone of location of the line.**

***Índice de Términos*— Línea de transmisión, potencia de transporte, coordinación de aislamiento, cálculo eléctrico, cálculo mecánico, conductores, herrajes, sobrecargas.**

***Index Terms*— Transmission line, transport power, insulation coordination, electrical calculation, mechanical calculation, conductors, fittings, overloads.**

I. INTRODUCTION

For the study and design of transmission lines, it is necessary to conduct an analysis of voltages, currents, transport powers, as well as the electrical and mechanical characteristics in accordance with the various points of an electrical network. The results obtained are generally used to determine the feasibility of installing a line with certain predetermined characteristics in a specific area.

The main objective of the transmission line design is to establish a sequence of logical steps, enabling the calculation of electrical parameters, including fundamental and derived characteristics. This facilitates the subsequent analysis of other phenomena influencing the lines, such as power losses due to corona effects, overload analysis due to location-specific zones, wind force on conductors and hardware, as well as safety distances. These safety distances are of great utility in determining the types of structures to be used.

II. TRANSMISSION LINE DESIGN PROCESS

For the transmission line design, the following aspects were considered:

- Geometric mean distance
- Electrical calculation (fundamental and derived characteristics)
- Corona effect
- Mechanical calculation and state change equation for sag calculation
- Insulation coordination

Initially, the route was traced using Google Earth since it is necessary to determine the length of the line to be designed.

Illustration 1. Transmission line route to be designed

Four possible routes were identified; however, some of these routes pass through urban areas with many constructions. Therefore, the route with the least obstacles was selected. This route is 82.2 kilometers long, which also represents the length of the line to be designed.

A. Geometric Mean Distance and Geometric Mean Radius

In our country, it is common to observe structures with conductors in triangular, horizontal, and hexagonal configurations, with one or two conductors per phase. For the line design, structures with a horizontal configuration, two guard cables, and one conductor per phase will be used.

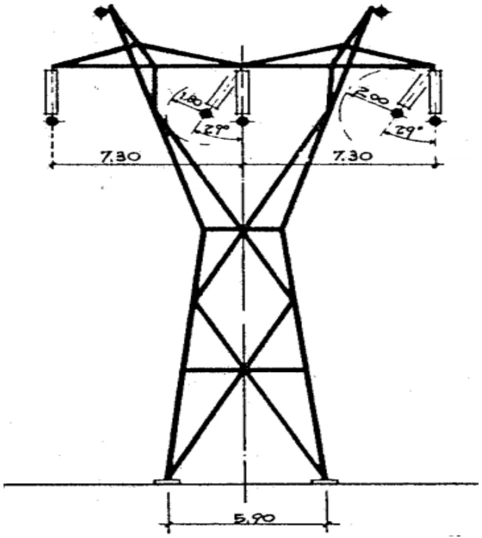

Illustration 2. Structure with horizontal configuration and one conductor per phase

The equivalent mean distance or geometric mean distance is the geometric mean of the distances of each wire of each phase with each of the wires of the other phases [1]. The geometric mean radius will be the distance between conductors of the same group. In this case, it will not be necessary to calculate it as there is one conductor per phase.

For the calculation of the geometric mean distance according to the established configuration, the following equation is used:

$$DMG = d\sqrt[3]{2} \qquad (1)$$

Where:
d: Distance between phases

Calculating:

$$DMG = 7.30\sqrt[3]{2}$$
$$DMG = 9.1974\ m$$

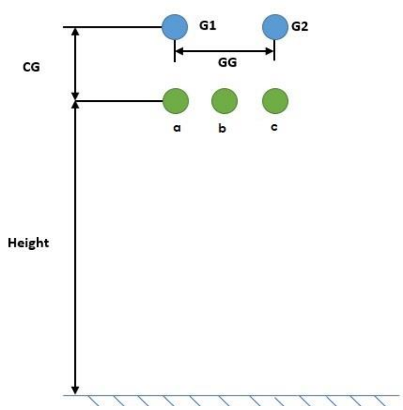

Illustration 3. Horizontal Configuration

B. Electrical Calculation

For this calculation, it is necessary to determine the type of conductor to be used, as the electrical resistance per kilometer of line and the radius will be required. In this case, Gull conductor [2] will be used, which is a commonly employed heavy ACSR conductor.

$$r_{conductor} = 12.7\ mm$$

The fundamental characteristic constants of an electrical line, per kilometer of its length, are four [3]:

Electrical resistance (according to the selected conductor)

$$R_{Gull} = 0.0882\ {}^{\Omega}/_{Km}$$

- Self-induction coefficient or inductance

$$Q_k = \left(0.5 + 4.6\ lg\frac{DMG}{r}\right)10^{-4} \qquad [{}^{H}/_{Km}] \qquad (2)$$

- Capacitance

$$C_k = \frac{24.2}{lg\frac{DMG}{r}}\ 10^{-9} \qquad [{}^{F}/_{Km}] \qquad (3)$$

- Conductance or loss

$$G = \frac{P}{V^2} \qquad [{}^{S}/_{Km}] \qquad (4)$$

For the designed line, a transport power of 100 MW and a nominal voltage of 230 kV will be considered. These values are initially set, and throughout the line design process, it will be analyzed whether it is convenient to maintain or modify them.

The calculated parameters are shown below:

$$Q_k = \left[0.5 + 4.6\ lg\frac{9.1974}{0.0127}\right]10^{-4} = 1.3655x10^{-3}\ {}^{H}/_{Km}$$

$$C_k = \frac{24.2}{log\left(\frac{9.1974}{0.0127}\right)}\ 10^{-9} = 8.4619x10^{-9}\ {}^{F}/_{Km}$$

$$G = \frac{100x10^6}{(230x10^3)^2} = 0.001890\ {}^{S}/_{Km}$$

From the four fundamental characteristics per kilometer of line considered above, four others are deduced, which are known as derived characteristics [4]:

Self-induction reactance:

$$X_k = Q_k\omega\ [\Omega/Km] \qquad (5)$$

Susceptance:

$$B_k = C_k\omega\ [S/Km] \qquad (6)$$

Impedance (complex vector magnitude)

$$\overline{Z_k} = R_k + jX_k \quad [\Omega/Km] \qquad (7)$$

Admittance (complex vector magnitude)

$$\overline{Y_k} = G_k + jB_k \; [S/Km] \quad (8)$$

Where the angular frequency is used (ω) which is obtained from the equation:

$$\omega = 2\pi f \quad (8.1)$$

Where:

f: Is the frequency

In the case of El Salvador, the frequency value is 60 Hz, therefore $\omega = 376.99 \approx 377 \; {}^{rad}/_{s}$

By using the formulas to calculate the derived characteristics, we have:

$$X_k = (1.3655x10^{-3})(377) = 0.5148 \; {}^{\Omega}/_{Km}$$

$$B_k = (8.4619x10^{-9})(377) = 3.1901x10^{-6} \; {}^{S}/_{Km}$$

$$\overline{Z_k} = 0.0882 + j0.5148 \; {}^{\Omega}/_{Km}$$

$$\overline{Y_k} = 0.001890 + j3.1901x10^{-6} \; {}^{S}/_{Km}$$

C. Corona discharge

When a conductor of a Transmission Line is subjected to an increasing voltage, the potential gradient (electric field) on the surface of the conductor grows and there comes a time when it is greater than the breakdown gradient of the air. It is in this situation that ionization of the air surrounding the conductor occurs, which is manifested by a crackle and a bluish luminosity that can be perceived in the dark (cross-section luminous halo). This phenomenon is called corona effect [5].

The corona effect has the following consequences:

- Losses that manifest themselves in the form of heat.
- High frequency electromagnetic oscillations (radio frequency).
- Audible radio.

In aerial conductors, the phenomenon is visible in the dark, and you can see how they are surrounded by a luminous, bluish halo with a circular cross section.

The corona losses per conductor are calculated as follows:

$$P = \frac{241}{\delta}(f+25)\sqrt{\frac{r}{DMG}}\left(\frac{U_{máx}}{\sqrt{3}} - \frac{U_c}{\sqrt{3}}\right)^2 * 10^{-5} \left[\frac{kW}{Km}\right] \quad (9)$$

Where:

δ: Correction factor for air density as a function of height above sea level

$U_{máx}$: Maximum voltage [6]

U_c: Disruptive critical voltage

The calculation of the air correction coefficient is generally done with the formula:

$$\delta = \frac{3.921h}{273+\theta} \quad (10)$$

Where:

h: Barometric pressure in centimeters of mercury column

θ: Temperature in degrees Celsius depending on the point considered.

To determine the value of the barometric pressure, it will be necessary to determine the average elevation of the route in Google Earth, with the elevation profile tool.

Illustration4. Elevation profile of the selected route

It is obtained that the average elevation of the area is 441,742 meters.

$$\log(h) = \log(76) - \frac{elevation_{avg}}{18336} \quad (11)$$

Calculando h:

$$\log(h) = \log(76) - \frac{441.742}{18336} = 71.89 \; cm \; of \; Hg$$

For the temperature value, a temperature investigation was carried out in 2018 [7], where the following result was obtained:

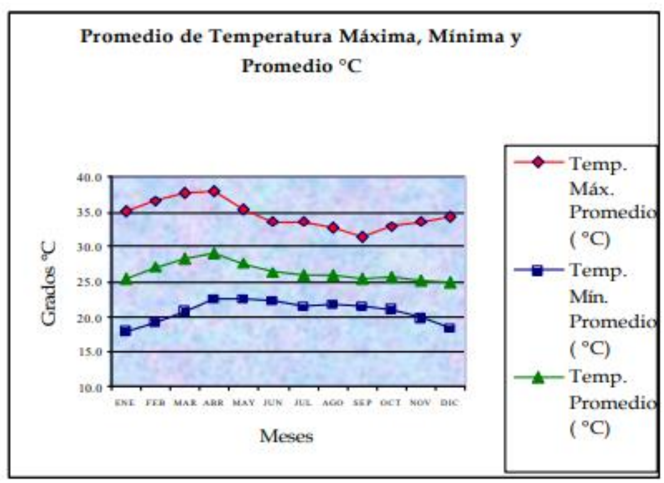

Illustration5. Average temperature 2018

Observing the trend of the average temperature, a value of 24°C will be taken.

Calculating the correction air factor:

$$\delta = \frac{3.921(71.89)}{273+24} = 0.949$$

In addition, it will be necessary to calculate the critical disruptive voltage, which is given by the following formula:

$$U_c = 84 * m_t * m_c * r * log\left(\frac{DMG}{r}\right) * \delta \quad (12)$$

Donde:

m_t: Meteorological coefficient, to take into account the effect produced by humidity, reducing the U_c value. Its values are 1 for dry weather and 0.8 for humid weather according to [8].

m_c: Conductor roughness coefficient, in the case of cables [8], its average value is 0.85.

Calculating the critical disruptive voltage in dry weather:

$$U_c = 84(1)(0.85)(1.27)log\left(\frac{9.1974}{0.0127}\right)(0.949) = 246.1\ kV$$

According to [6] the maximum voltage will be 230 kV, since the critical breakdown voltage is greater than the line and nominal voltage, there will be no corona effect in dry weather.

For wet weather, the corona effect is calculated as follows:

$$U'_c = 0.8U_c \qquad (12.1)$$

$$U'_c = 0.8(246.1) = 196.88\ kV$$

When making the comparison, it is found that the critical breakdown voltage in dry weather is lower than the maximum and nominal voltage of the line, so there will be losses due to corona effect, these losses are calculated according to (9) which results in a power loss per conductor of:

$$P = \frac{241}{0.949}(60+25)\sqrt{\frac{0.0127}{9.1974}}\left[\frac{245}{\sqrt{3}} - \frac{196.88}{\sqrt{3}}\right]^2 * 10^{-5}$$

$$P = 6.21\ {}^{Kw}/_{Km}$$

Therefore, the conductance loss

$$G_k = \frac{P}{\left(\frac{U_c}{\sqrt{3}}\right)^2} * 10^{-3} \qquad (13)$$

$$G_k = \frac{6.21}{\left(\frac{196.88}{\sqrt{3}}\right)^2} * 10^{-3} = 4.81x10^{-7}\ {}^{S}/_{Km}$$

The importance of the corona effect analysis can be seen, since it provides a power loss value which must be considered in case of wanting to make modifications to the power transport.

D. Mechanical calculation and change of state equation for arrow calculation

The conductors of power lines are generally cables, for the most part heterogeneous, that is, they are made up of groups of conductors of different materials (combination of aluminum and steel conductors, copper and steel, etc.). Therefore, the mechanical calculation of these conductors must be done based on the elasticity modulus and the expansion coefficient, corresponding to the proportion in which the aluminum and steel are found (these values are provided by the manufacturer). The atmospheric influences that determine the mechanical behavior of cables are temperature variations and the force of the wind on conductors and fittings.
All the modifications that must be considered in the mechanical operation of the lines are reflected in a relationship between them [9], which is called “Equation of Change of State”.

$$t_x^2[t_x - (K - \alpha E \Delta\theta)] = a^2 \omega^2 \frac{E}{24} m_x^2 \qquad (14)$$

Where:

α:Linear expansion coefficient of the cable$[°C^{-1}]$
$\Delta\theta$:It corresponds to the difference of two temperatures to which the cable may be subjected successively.$[°C]$
t:cable unit tension$\left[\frac{Kg}{mm^2}\right]$
a:Vain$[m]$
E: Modulus of elasticity of the cable$\left[\frac{Kg}{mm^2}\right]$
ω: cable weight$\left[\frac{Kg}{mm^2}\right]$
m: overload coefficient$[adimensional]$

In (14) you can see the existence of a subscript “x” which will indicate the working hypothesis. This hypothesis refers to the climatic conditions to which the driver will be subject, and will indicate the types of overload present in the line of work. according to the work area.

For the conditions in table 1, letters have been used to designate the types of overload in Kg/m, in this case P is used to designate the overload due to the own weight of the cable, H is used to designate ice overload and V It is used to designate wind overload according to the area where the line is located.

TABLE 1
HYPOTHESES FOR CALCULATING ARROWS

	Zone or hypothesis	Temperature	Conditions
Maximum traction	A B C	-5°C -15°C -20°C	P+V P+H P+H
Maximum arrow	Wind Temperature Ice	-20°C +15°C +50°C	P+V Q P+H
	Daily tension (TCD)	+15°C	Q
Vibratory phenomena	Voltage in cold hours (THF)	-5°C	Q
	Minimum vertical arrow	-20°C	Q

The arrow (see figure 6) is the distance between the straight line that passes through the two attachment points of a conductor on two consecutive supports, and the lowest point of this same conductor.

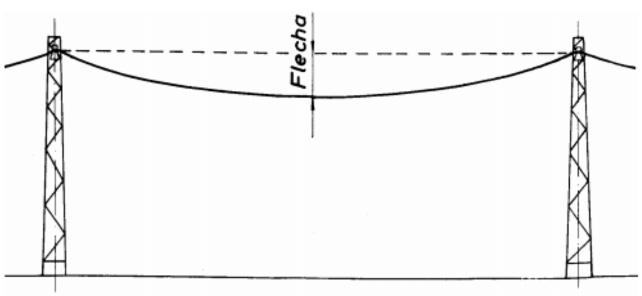

Illustration6. Arrow of a transmission line

The objective of the change of state equation is to obtain the unit voltage of the line under the conditions established by Table 1. Subsequently, with the tensions obtained, the effects of the temperatures and overloads of the work zone on the line will be calculated.
The arrow calculation is given by the following equation:

$$f = \frac{a^2 \omega}{8 t_x} m_x \quad (15)$$

Where:

a: Span between supports, in the case of the selected route it is planned to place the structures with a span of 500 meters

m_x: Overload coefficient according to the conditions of the area according to table 1. It is calculated according to (16).

$$m_x = \frac{p_x}{p} \quad (16)$$

Where p_x it is calculated according to the data in [11].

From the data available in [2] for the Gull conductor, the coefficient of linear expansion, modulus of elasticity, breaking load and self-weight of the cable are extracted.

These data will be necessary to determine the arrows in the conditions of zone A, which has overload from the own weight of the cable and the wind.
With the tension and characteristics initially obtained with the change of state equation, the calculations will be carried out for the rest of the hypotheses. The results obtained can be seen in Table 2, where the unit stresses and arrows are shown under the climatic conditions of each zone (excluding the initial one).

At the same time, a value must be selected for the safety factor, this value has been selected from three, which means that, by dividing the breaking load by the multiplication of the unit stress by the conductor section, we must obtain a higher value, which will indicate that there will be no damage to the structures.

TABLE 2
CALCULATION OF DEFLECTIONS, UNIT STRESSES AND SAFETY COEFFICIENT

Zone or hypothesis	Unitary voltage $\left[{Kg}/{mm^2}\right]$	Arrow $[m]$	Security coefficient
A	9.73	15.16	3
Wind Temperature Ice	9.17 6.22 14.51	16.07 16.78 17.44	3.18 4.68 2.01
Daily tension (TCD)	6.93	15.09	4.21
Voltage in cold hours (THF)	7.42	14.07	3.91
Minimum vertical arrow	7.85	13:30	3.71

It can be seen that, for ice conditions, the characteristics establish a safety factor lower than that established; however, in the country there are no overload conditions due to ice, therefore, it can be neglected.

E. Isolation coodination

Critical flashover voltage: It is the voltage at which flashover or electric arc occurs. It is calculated based on the lightning isolation coordination selected. The selected value was taken according to the nominal voltage level set at the beginning according to [10].

It is given by the equation:

$$VCF = \frac{BIL}{0.961} \quad (17)$$

$$VCF = \frac{750}{0.961} = 780.43\ kV$$

The voltage obtained above indicates that the basic insulation level (also called BIL) will prevent damage from excessive discharges in the line for values below the VCF. If greater protection is needed, the test voltage level must be changed.

It has been experimentally determined that, at voltages greater than 300 kV, the overvoltage effect is more severe due to waves due to switching operations than due to atmospheric discharges.

This is due to two main reasons:

1. Switching overvoltages increase, in principle, proportionally with the system voltage, while those due to lightning remain more or less constant.
2. The cost of insulation is considerable in electrical networks and therefore it is important to reduce the insulation as much as possible.

It is possible that surges could be very high and lead to failure of the insulation of equipment connected to said network with destructive results. It is therefore imperative that power systems be designed in such a way that expected surges fall below the insulation support capacity of the equipment, resulting in excessive cost. Therefore, the possibility of destructive equipment failure due to surges must be made to a minimum in the design of electrical networks. This procedure is based on the coordination of expected surges with the support capacity of the equipment.

Therefore, the basic objective of overvoltage protection of power systems must be to avoid the disruption of insulation and the interruptions that occur as a consequence or damage to the equipment.

III. ConclusiON

The design of transmission lines is an extensive process, which not only covers the electrical characteristics, but also the mechanical ones, since it is important to analyze the stresses to which the conductors will be subjected under the climatic conditions that were studied here. After carrying out all the calculations of geometric mean distance, fundamental and derived electrical characteristics, power losses due to corona effect, study of arrows and insulation coordination, it can be concluded that the purpose of the previous design of a transmission line is to analyze the feasibility to place a line with initial parameters, such as transport power and voltage level in a certain area, and in the event that considerable losses occur, try to solve these problems with existing methods.

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V. ABOUT THE AUTHOR

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She was born on September 1, 1997 in Ilopango, San Sallvador, El Salvador. Graduated in electrical engineering from Don Bosco University with a specialty in power systems. She has work experience in electrical maintenance. In addition, she has been part of social projects as a renewable energy instructor at Science Girl Camp and a data scientist tutor in Data scientists, Costa Rica. Currently, founder of Project E (Instagram: projecte__)