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Design and Analysis of 400KV Extra High Voltage Power Transmission Lines in Lebanon

Hassan Amin Osseily
Lebanese International University LIU
The International University of Beirut BIU
Electrical and Electronics Department
Beirut Lebanon
Hassan.osseily@liu.edu.lb

Abstract: This paper aims to design and analyze an overhead AC extra high voltage transmission line in Lebanon, using ACSR conductors, to meet the growing demand for the future. The optimal design will consider various factors to achieve the best system efficiency and performance, while complying with regulations and safety standards, including EHV voltage level, conductor size, number of conductors per phase, cable sag, and other factors, as well as estimating and describing environmental impacts such as conductor surface potential gradient, corona loss, radio interference, and audible and random noise.

Keywords: Power Transmission Lines, Corona Effect, EHV, Overhead Lines OHL

I. Introduction to Power Transmission Lines in Lebanon

High voltage transmission allows the usage of smaller conductor sizes, which reduces the cost of the transmission line infrastructure. Furthermore, high voltage transmission also reduces the amount of current flowing through the transmission line, which leads to less heating and power loss. This is important for maintaining the stability and reliability of the power system. In addition, high voltage transmission allows for higher power transfer capability, which is essential for meeting the increasing demand for electricity in today's modern society [1]. It also enables the integration of renewable energy sources, such as wind and solar power, which are typically located in remote areas and require long-distance transmission to demand load centers. Overall, high voltage transmission plays a crucial role in the efficient and reliable delivery of electricity from power plants to consumers, helping to ensure a stable and resilient power system. Figure 1, shows the general power diagram including the transmission system [3].

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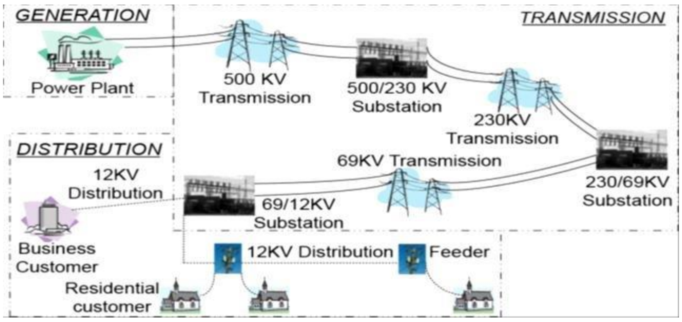

Figure-1: Power system diagram showing primary and secondary feeders' transmission.

The issue of electricity blackouts and poor quality power supply in Lebanon is a well-known problem that has persisted for many years. The insufficient power generation capacity in the country has led to frequent blackouts and energy shortages, causing significant disruptions to daily life and hindering economic development. The reliance on aging power plants, lack of investment in infrastructure, and political instability have all contributed to the electricity crisis in Lebanon. The government has struggled to address these challenges and implement long-term solutions to improve the reliability and quality of the power supply. Figure-2, shows the technical losses and the power shortage in Lebanon.

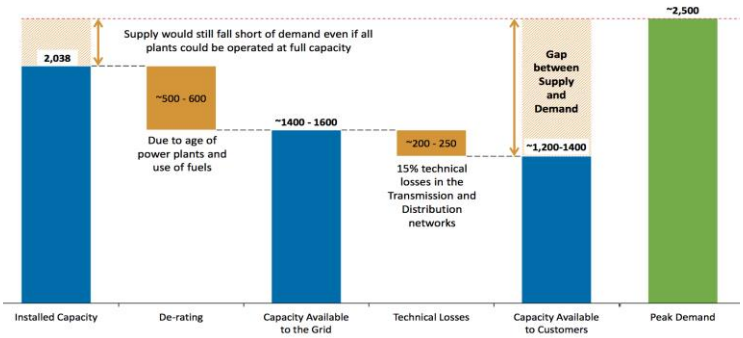

Figure-2: Technical losses and power shortages in MW (2009).

One of the main Lebanese power problems is the high TL technical losses as shown in Figure-3; these losses are a result of resistance and iron core losses in metallic lines that connect power plants to end users. These losses are expected to be roughly 15% of total electricity produced in Lebanon, a greater figure than 8-10% losses experienced in efficient systems in western countries. Higher losses in Lebanon are primarily due to lack of power line rehabilitation and incomplete infrastructure works that can jeopardize the grid's ability to operate efficiently.

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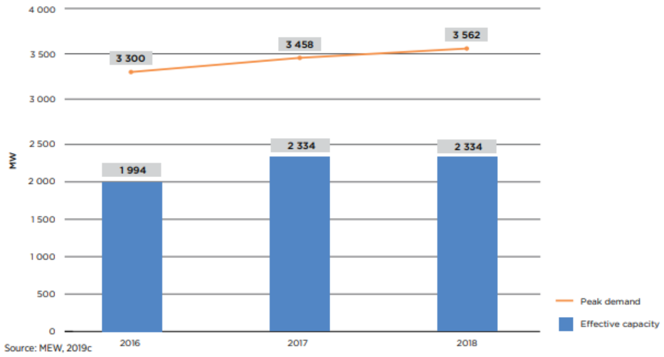

Figure-3: Installed capacity versus peak demand.

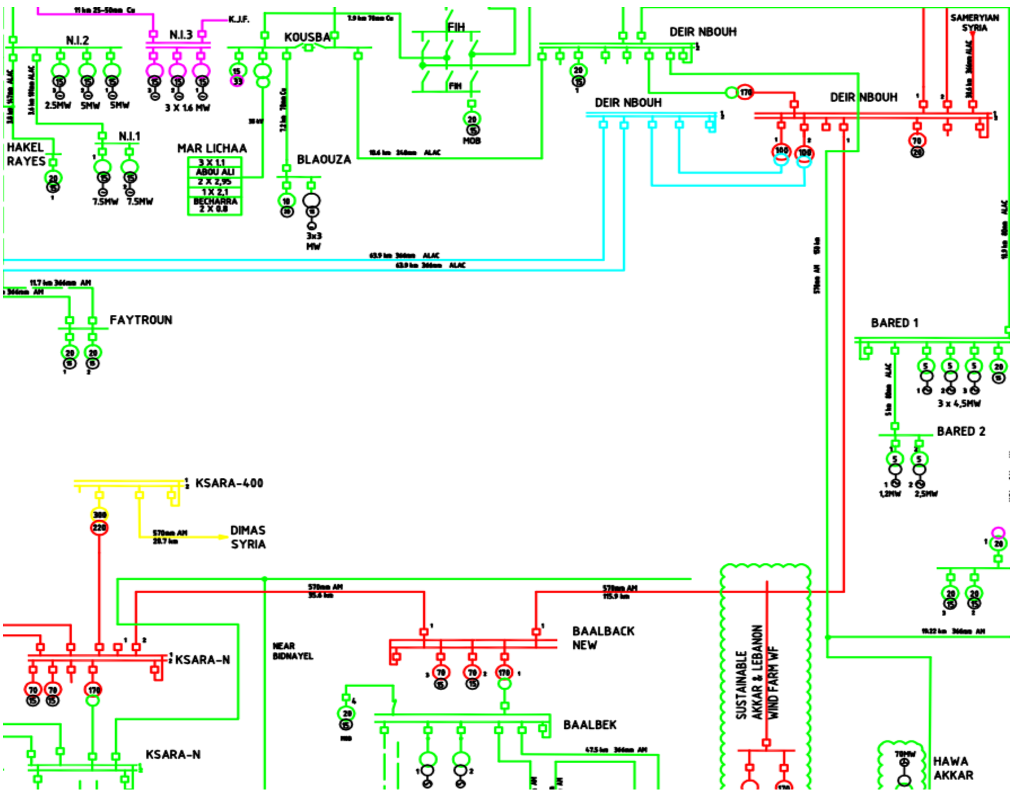

Figure-4: Single line diagram for the 220 KV Lebanese grid.

The present TL operating voltage in Lebanon is 220 KV. The distance of the longest path of TL is 150 Km connecting DEIR NBOUH with KSARA, and designed to transfer around 300 MW of power. Lebanon near future expectations especially with the start of oil and gas extraction will be bright, at that stage industrial revolution may occurs, in addition to growth in population, the increase in uses of electrical cars, and the proposed governmental future plans related to electricity sector in Lebanon where renewable energy may be major source for producing extra megawatts, then a suitable transmission system will be necessary where the

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existing will not be able to carries the demand. Assuming the future energy capacity to be transferred on the longest line in Lebanon is increased in the future, and then EHV becomes necessary for transferring the maximum power possible of the desired capacity with lowest possible losses. Figure-4 shows the Single line diagram for the 220 KV Lebanese grid

Lebanon major electricity problem is due to the gap between supply and demand, where energy demand in 2016 was anticipated to be over 22,000 GWh, up 54.8 percent from 2010, when demand was estimated to be 15,934 GWh . **Error! Reference source not found.**. Another important issue is substantial technical losses, despite recent attempts by the ministry, EDL and distribution service providers to repair the undeveloped grid, both transmission and distribution grids have losses equivalent to 16.5 percent **Error! Reference source not found.**. Figure-7, shows the Lebanese Transmission line network.

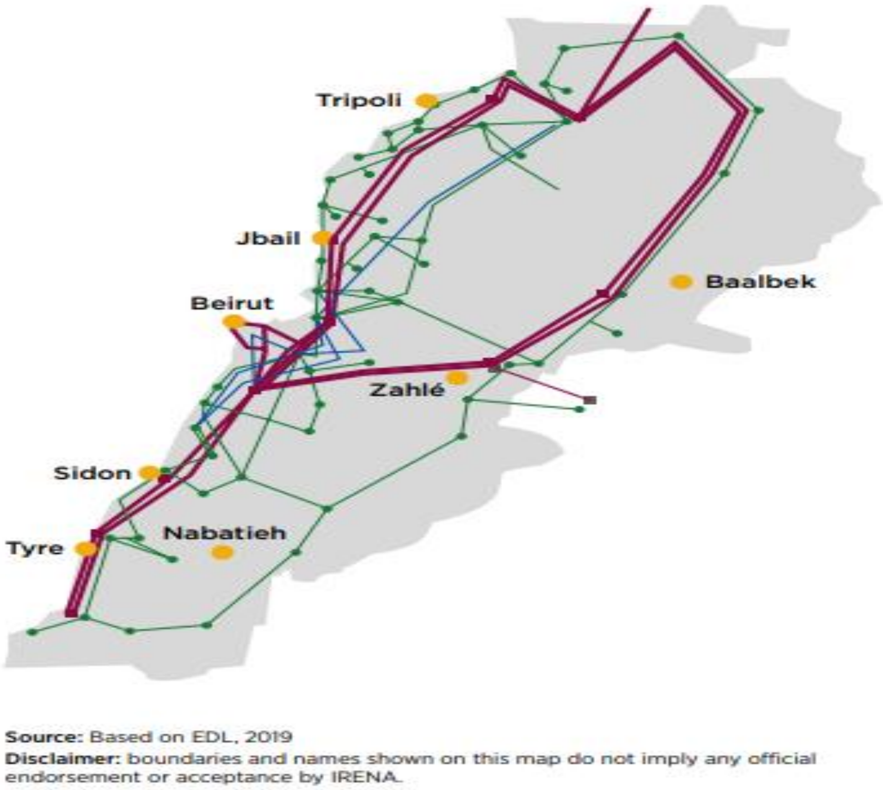

Figure-5: EDL transmission network.

Lebanon electricity sector suffer since 1990 due to many reasons one of which is high technical losses on transmission and distribution grids which is equivalent to 16.5 %, **Error! Reference source not found.** however the greatest voltage level of TL is 220 KV, so a design of extra high voltage overhead transmission line in this project is proposed to meet the transfer of desired energy in future. As per ANSI standard 220 KV is considered as high voltage where

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EHV is 345KV and above has impact in fault transmission lines that lead to use of fault detection techniques.

II. COMPONENTS OF EXTRA HIGH VOLTAGE LINES 400KV

- **Transmission line Conductor type**

In this paper, the conductor is selected of ACSR type; aluminum conductor steel reinforced as seen in figure-6, it's commonly used in overhead transmission and distribution lines because it provide a great combination of conductivity and strength, allowing for the largest possible spans and the least amount of sag between towers. Conductor size will be calculated and selected in the design phase [5].

Figure-6: Aluminum conductor steel reinforced conductor.

- **Transmission line insulator**

Overhead line insulators (Figure-7) are required to withstand both electrical and mechanical stresses. In addition, the surface leakage path must have sufficiently high resistance so as to avoid any current leakage to earth. In a puncture, the discharge occurs from conductor to pin through the body of the insulator. When the voltage exceeds 33 KV, suspension type insulators are recommended. The suspension type insulator comprises of number of porcelain discs that are connected in series by metal links forming a string. Number of discs will be calculated in the design section.

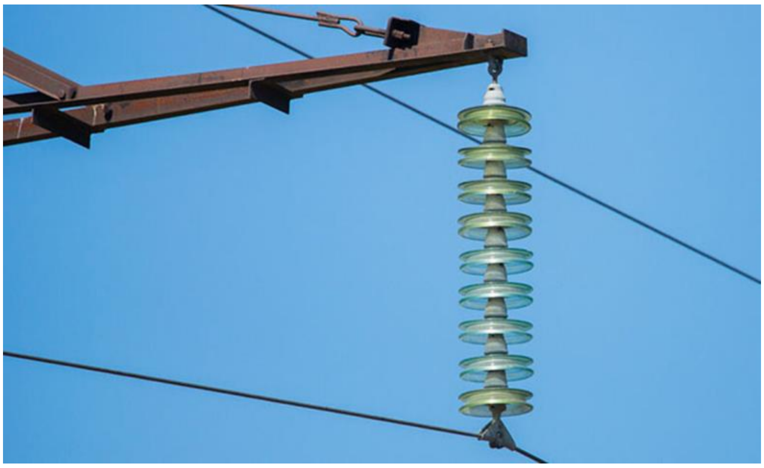

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Figure-7: Suspension type insulator suspended below the cross arm.

- **Transmission line spacer**

Spacers are used for Spacing the number of conductors apart to form a larger effective single conductor (Figure-8). Where spacers are provided to maintain distance between sub-conductors, and resist the force due to wind and magnetic forces during a short circuit.

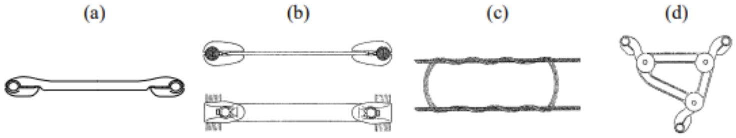

Figure-8: Various types of spacers used in the transmission line industry: (a) rigid type, (b) articulated type, (c) flexible type, and (d) spacer-damper type.

(a) And (b) are often used except in twin-bundle conductors in the jumper cable, but (c) used in twin-bundle conductors. Now when (a), (b), and (c) are used in twin bundle conductors, they find themselves associated with the Stockbridge damper type mounted on each of the sub-conductors. The spacer-damper type is the most used in transmission line conductors, even though some controversy exists on the twin-bundle conductor not being effective in mitigating wind energy. Spacer-dampers often consist of a rigid frame, which is hafted by a clamp (arm) by means of rubber bushing as noted in Figure-9.

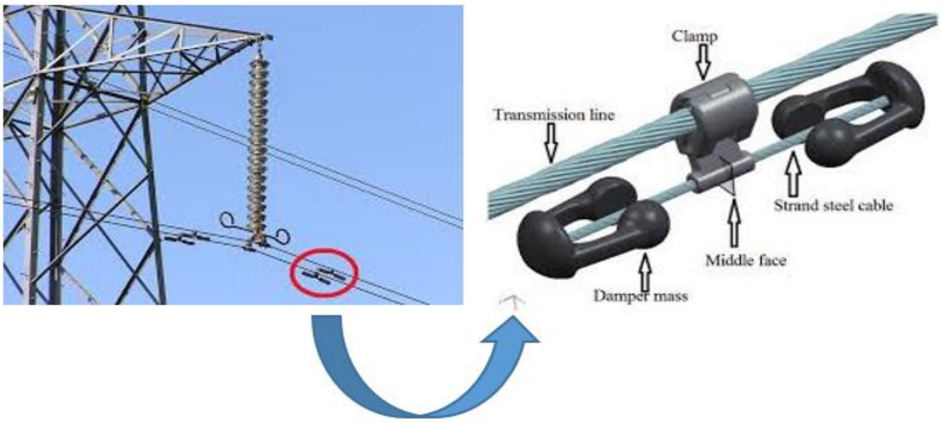

Figure-9: A Stockbridge damper is used to reduce wind-induced vibrations on overhead power lines' slender constructions.

- **Transmission tower type**

Waist-type tower is selected in this study as seen in Figure-10; this is the most prevalent form of transmission tower. It can handle voltages between 110 and 735 kV. These towers are simple to erect and are ideal for power lines that cross very uneven terrain.

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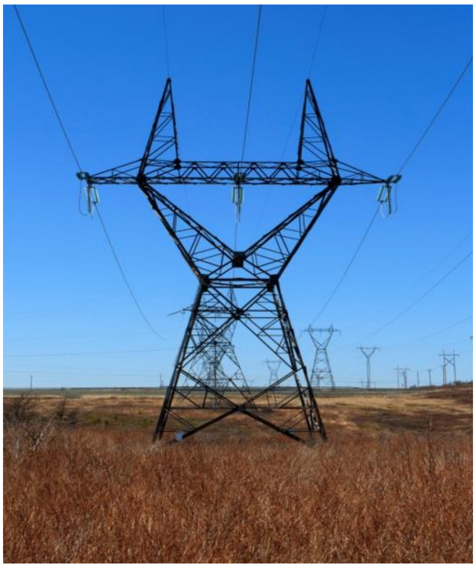

Figure-10: High voltage transmission waist type tower

III. Design Parameters of Extra High Voltage Lines 400kV

When it comes to extra high voltage the behavior of transmission line differs and additional constrains are taken into consideration for optimum design. The requirements below are to be selected before starting the design:

- The demand load that needs to be transmitted on the line.
- The distance of power to be travelled.
- Frequency of the system (50 HZ).
- Transmission line environmental impacts.

Accordingly, the following parameters are calculated and selected to meet the system's criteria:

- EHV transmission line resistance, capacitance, and inductance.
- Transmission line economic voltage selection.
- Conductor size selection.
- Number of sub conductors per phase and its equivalent spacing.
- Environmental impacts from transmission line such as surface gradient, radio interference, audible noise and random noise.
- Conductor vertical and horizontal clearance.
- Tower insulator size and type.

The design calculations and parameters should be within the acceptable limits as per the electrical codes and standards. The design criteria according to site specification and requirements are:

- Total line length L=150 Km
- Type of conductor ACSR

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- Towers span 350 m.
- Transmitted power capacity P=400MW at 0.85 lagging
- Ambient temperature 25$C°$
- Wind speed 60 $miles/hours$
- System frequency at 50 HZ

a) ***Block Diagram of 400 Kv Transmission Line Design***

The diagram below in Figure-11, shows the system design construction which is divided to 3 sections, first is the parameters related the conductor design, second is the tower design and insulator, finally the environmental effects on the conductor.

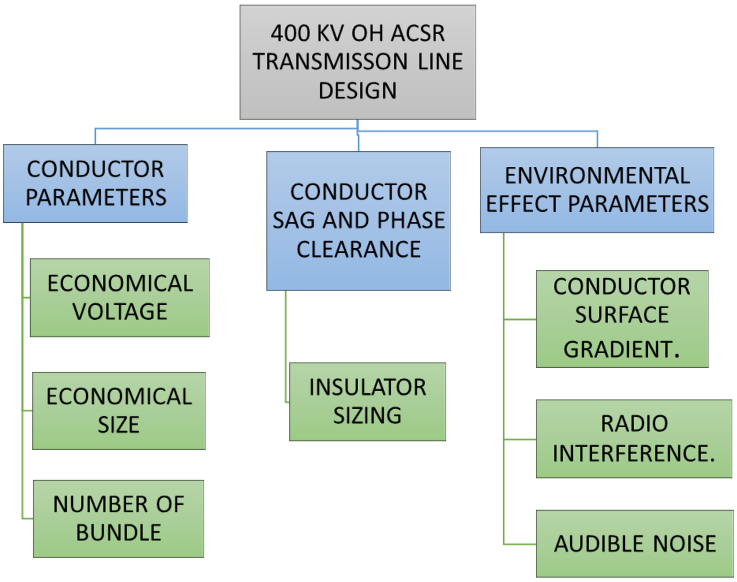

Figure-11: Block Diagram of 400KV Transmission Lines

b) ***Main Design Equations That Will Be Applied In Design***

c) ***<u>Economic Voltage Selection</u>***

It's critical to choose the right voltage level for a transmission line because it has a lot of implications in terms of operation, a wrong selection will be very expensive and difficult to change in future. The most economical voltage is calculated using the following empirical formula:

$$\boldsymbol{v = 5.5\sqrt{l + \frac{load\ in\ kva}{150}}}\ (\text{KV}) \qquad (1)$$

Where,

L = line length of TL in mile,

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Accordingly the transmission line voltage will be selected.

ii) Conductor Size Selection

According to Central Electricity Authority regarding EHV transmission lines bundle conductors (minimum of two sub conductors per phase) shall be used for satisfactory performance.

- The current I is calculated using the following formula:

$$I = \frac{P}{\sqrt{3} * Pf * V} \text{ (A)} \quad (2)$$

Where,
P : Maximum Power,
Pf : the Power factor,
V : Line voltage.
Accordingly, the size and number of conductors per phase is selected.

iii) TL Parameters

As mentioned previously extra high voltage TL is defined by its parameters (R, L, and C) and calculated as follows:

- Skin effect R_{AC}:
  For skin effect calculations refer to **Error! Reference source not found.**.
- The average inductance per phase is [5]:

$$L = 0.2 ln \frac{GMD}{GMR_L} \text{ mH/Km} \quad (3)$$

$$X_L = 2\pi f L \; \Omega/Km \quad (4)$$

$$GMD = \sqrt[3]{Dab * Dbc * Dac} \quad (5)$$

$$GMR_L = \sqrt{D_s * d} \quad \text{(III.3)} \quad (6)$$

Where,
GMD = Geometric mean distance between conductor centers,
GMR_L= GMR of two sub conductors,
D_s = GMR of sub conductor,
d = Spacing between bundles,
Dab, Dbc, Dac = Horizontal spacing between phase conductors.

The spacing of the conductors in an overhead TL is directly proportional to the inductance as the space between phases increases the inductance in the line increases.

- The Average line to neutral capacitance per unit length is [5]:

$$C = \frac{0.0556}{ln\frac{GMD}{GMR_C}} \; \mu F/Km \quad (7)$$

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$$X_C = \frac{1}{2\pi f C}\ \Omega.Km \quad (8)$$

$$GMR_C = \sqrt{r * d} \quad (9)$$

Where,

r = radius of sub conductor.

The spacing of the conductors in an overhead TL is inversely proportional to the capacitance as the space between phases increases the capacitance of the line decreases.

iv) Surge Impedance Loading

SIL is one of the important parameters calculated throughout the design of EHV TL; it helps to find out the maximum load capacity of TL in MW at unity power factor and calculated as follows [5]:

$$SIL = \frac{|KV_{R(L-L)}|^2}{Z_C}\ (MW) \quad (10)$$

Where,

$KV_{R(L-L)}$= receiving end line to line voltage,

Z_C= Characteristic impedance.

$$Z_C = \sqrt{\frac{L}{C}}\ (\Omega) \quad (11)$$

v) Conductor Surface Gradient and Corona loss

The surface potential gradient is critical design parameter which determines the level of corona loss, audible noise and radio inference. That's why at high voltage level it is recommended to use bundled conductors [4] where it helps in reducing the corona losses [2].

- Maximum surface gradient formula [5]:

$$g_{MAX} = g_{AV}\left[1 + \left(\frac{d}{D}\right)(N-1)\right]\ (KV_{rms}/cm) \quad (12)$$

- Bundle diameter D formula:

$$D = \frac{S}{\sin\frac{\pi}{2}}\ (cm) \quad (13)$$

- Outer phases average conductor gradient formula:

$$g_{AV} = \frac{Q}{2\pi\varepsilon_0 r}(Kv_{rms}/cm) \quad (14)$$

- Average density on one conductor of phase bundle formula:

$$Q = \frac{CV}{N}(KC_{rms}/cm) \quad (15)$$

Where,

d= sub conductor diameter in cm,

N= number of sub conductors per phase,

S= bundle spacing in cm,

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r= sub conductor radius in cm.

$$\varepsilon_0 = 2\pi\left(\frac{1}{36\pi}\right) * 10^{-9}$$

- Corona loss formula [5]:

$$P_{c(3\emptyset)} = P_{FW} + 0.3606 * K * V * r^2 * \ln(1 + 10\rho) * \sum_1^{3N} E^5 \quad (4)$$

- Peak surface gradient on the centre phase conductor [5]:

$$E = \frac{V*\left[1+(N-1)*\frac{r}{R}\right]}{N*r*\ln\left[\frac{2H}{r_{eq}*\sqrt{\left(\frac{2H}{S}\right)^2+1}}\right]} \ (Kv_{rms}/cm) \quad (5)$$

Where,
P_{FW}= total fair weather loss in KW/Km (1 to 5),
K=5.35*10^{-10} for 500 KV to 700 KV,
K=7.04*10^{-10} for 400 KV,
V= rms line to line conductor voltage in KV,
ρ= rain rate in mm/hour,
r=conductor radius in cm,
N= number of conductors per phase.

$$r_{eq} = R\left(\frac{N*r}{R}\right)^{\frac{1}{N}} \ (cm) \quad (6)$$

- Bundle radius for 2 sub conductor in cm:

$$R = \frac{B}{2} \ (cm) \quad (7)$$

B= Bundle spacing in cm.

vi) <u>Conductor Disruptive Critical Corona Voltage</u>

Disruptive critical voltage of conductor defines the minimum value of voltage at which corona effect occurs.

- The corona critical voltage of bundle conductor is[5]:

$$V_c = \sqrt{3} m_0 m_1 \delta^{\frac{3}{2}} * 48.8 * \frac{nr}{1-\frac{2(n-1)}{S}\sin\frac{\pi}{n}} * \left(1 + \frac{0.301}{\sqrt{rd}}\right) \log \frac{D}{\frac{1}{r^{\frac{1}{n}} * S^{\frac{n-1}{n}}}} (Kv) \quad (8)$$

Where,
n= number of conductors per phase,
m_0= conductor factor (1 for polished, 0.92-0.98 for dirty conductors, 0.8-0.87 for standard conductors),
m_1= weather factor (0.8 for rainy weather, 1 for fair weather),
δ= air density factor,

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D= conductors phase spacing in cm,
d= conductor diameter in cm,
r= radius of conductor in cm,
S= space between sub conductor in cm.

vii) ***Audible Noise and Radio Interference***

- **Audible noise** is described by sound pressure level SPL and can be found by applying Bonneville Power Administration of USA formula for number of sub conductors per phase equal or less than two as follows [5]:

$$SPL = 10 \log_{10} \sum_{i=1}^{3} 10^{0.1AN(i)} \, db(A) \quad (9)$$

$$AN(i) = 120 \log_{10} E_{am}(i) + 55 \log_{10} d - 11.4 \log_{10} D(i) - 115.4 \quad (10)$$

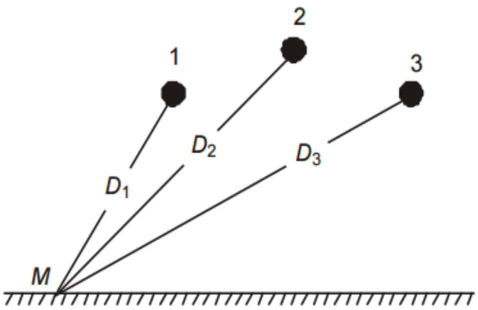

Figure-12: Calculation of AN level of line by B.P.A. Formula.

Where,
$E_{am}(i)$= average maximum surface voltage gradient belonging to phase i in KV/cm,
d= sub conductor diameter in cm,
N= number of sub conductors per bundle,
$D(i)$=aerial distance from phase i to the location of the microphone in m.

- **Radio interference** generated by each phase can be found by applying CIGRE formula [5]:

$$RI_i = 3.5g_m + 6d - 33 \log_{10} \left(\frac{D(i)}{20}\right) - 30 \, (db) \quad (11)$$

Where,
g_m= maximum surface voltage gradient on conductor in KV/cm,
d= conductor diameter in cm,
$D(i)$= aerial distance from conductor to the point where RI is evaluated in m.
Line RI level can be found as follows:

1. If one of the RI levels is greater than the rest by 3 dB, then it will be the line RI level in fair weather condition.

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2. Otherwise the line RI level is [5]:

$$RI = (avarage\ of\ the\ two\ highest + 1.5)\ (db)$$
(12)

3. At 1 MHZ, the RI level is 6 dB lower than at 0.5 MHZ.
4. In rainy weather condition 17 dB is added.

IV. Calculation of Extra High Voltage Lines 400kV

In this section factors affecting mechanical design of OHTL will be calculated, presented by the minimum permissible horizontal spacing between TL phases and its corresponding minimum sag.

i. Conductor Sag

The sag of the selected conductor is calculated as follows [5]:

Considering symmetrical spans of 350 $meter$

Worst case wind speed is considered $v = 60\ miles/hours$

$The\ wind\ pressure\ on\ cylindrical\ surface\ p = 0.00256v^2 (lb/ft^2)$

$p = 9.216\ lb/ft^2$

$d_c\ is\ the\ conductor\ diameter\ in\ (ft)$

$The\ horizontal\ wind\ force\ exerted\ on\ conductor\ P = p * d_c$

$= 9.216 * 0.104 = 0.958\ lb/ft$

Referring to Moose ACSR conductor specifications in **Error! Reference source not found.**,

Ultimate breaking strength of conductor is given $U_S = 159.6\ Kn = 35879.6\ lb$

Weight of conductor per unit length $W_C = 1998\ Kg/Km = 1.3425\ lb/ft$

Minimum sag in feet is $d = \frac{W_e L^2}{8T}\ (ft)$

Where,

$W_e\ is\ the\ effective\ load\ acting\ on\ the\ conductor\ in\ (lb/ft)$

$L\ is\ conductor\ length\ between\ two\ supports\ in\ (ft)$

$$T\ is\ conductor\ tension\ in\ (lb) = \frac{U_S}{safety\ factor = 2}$$

$$W_e = \sqrt{P^2 + W_c^2} = \sqrt{0.958^2 + 1.3425^2} = 1.649\ lb/ft$$

$$T = \frac{35879.6}{2}\ lb$$

Substitute to get

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$$d = \frac{1.649(1148.29)^2}{8(17939.8)} = 15.15\, ft = 4.6\, meters$$

ii. TL Required Phase Clearance

Minimum required horizontal clearance between phases for horizontal configuration TL is [5]:

$$minimum\ clearance = 0.3\frac{inch}{KV} + 8\left(\frac{1}{12}S\right)^{\frac{1}{2}}$$ (For line conductor's ≥ 2 AWG)

$$Sag\ S = 181.8\ inches$$

- **For 400 KV:**

$$minimum\ clearance = 0.3 * 400 + 8\left(\frac{1}{12} * 181.8\right)^{\frac{1}{2}} = 151.13\ inches$$
$$= 3.83\ meters$$

iii. Insulation between Tower and Conductor

1.1.1.1. Electrical Calculation

The number of required insulator disks is calculated as follows [5] :

Considering the following specification of a porcelain disk insulator

$$Disk\ height = 140\ mm$$
$$Disk\ diameter = 165\ mm$$
$$Disk\ rate\ voltage = 11\ Kv$$
$$Disk\ Ultimate\ strength = 45\ KN$$

- **For 400 KV:**

$$Target\ withstandvoltage = \frac{maximum\ system\ voltage}{\sqrt{3}} * 1.2 = \frac{400}{\sqrt{3}} * 1.2$$
$$= 277.12\ Kv$$

$$Number\ of\ disks\ needed = \frac{277.12\ Kv}{11\ Kv} = 26\ disk\ connected\ in\ series.$$

$$length\ of\ string = 140\ mm * 26 = 3.6\ meters$$

1.1.1.1. Mechanical Check

The selected insulator disk should be able to handle all tensions exerted due to weight and wind [5]:

$$Disk\ Ultimate\ strength = 45\ KN$$
$$Disk\ tension\ proof\ load = 22\ KN$$
$$Weight\ of\ conductor\ per\ meter = \frac{1998\ Kg/Km}{1000} = 1.99\ Kg/Km$$
$$Weight\ of\ conductor\ for\ span\ of\ 350\ m = 1.99\ Kg * 350\ meters * 9.8$$
$$= 696.5\ Kg * 9.8N/Kg = 6.825\ \text{KN}$$
$$Weight\ of\ wind\ \ exerted\ on\ inulator\ string = p * area\ of\ inulator$$

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$p = 9.216\ lb/ft^2 = 0.4405\ KN/m^2$

$area\ of\ inulator\ \ for\ 400\ Kv = 3.6 * 0.165 = 0.594\ m^2$

$Weight\ of\ wind\ \ exerted\ on\ 400\ Kv\ inulator\ string = 0.4405 * 0.594$
$= 0.261\ KN$

$Total\ Weight\ of\ 400\ Kv\ insulator\ to\ hold = \sqrt{0.261^2 + 6.825^2}$
$= \ 6.829\ KN * 2\ number\ of\ subconductor = 13.65\ KN$

b. OHTL Technical Calculations

Design data according to site specification and requirements:

- Total line length L=150 Km.
- Type of conductor =ACSR.
- Installation method= OH horizontal transposed configuration.
- Transmitted power capacity P=400MW at 0.85 lagging.
- System frequency at 50 HZ.
- Bundle space S=45cm.
- Phase to phase clearance=10 meters.

1.1.1. Economic Voltage Selection

Selection of transmission line voltage is determined by applying the following formula:

$$v = 5.5\sqrt{l + \frac{load\ in\ kva}{150}}\ (\mathrm{KV})$$

Load in KVA=470.5 MVA,
Power factor=0.85 lagging,

$$v = 5.5\sqrt{93.2 + \frac{470588.23}{150}} = 312.6\ KV$$

The selected voltage is 400 KV since it is the nearest standard voltage.

i.Conductor Selection

After selecting the voltage, selection of conductor size and number of conductors per phase and it’s spacing according to the ampacity of the conductor.

P=400 MW
Line to line voltage=400 KV
Power factor=0.85
Current per phase conductor is calculated as:

$$I = \frac{P}{Pf * V * \sqrt{3}}(A)$$

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$I = \frac{400MW}{\sqrt{3}*400KV*0.85} = 679.235$ A.

Referring to **Error! Reference source not found.** the selected conductor is Moose 54/7 of size 597 mm^2 and 667 current carrying capacity. 2 bundle conductors per phase are needed to transmit the required amount of current.

ii.TL Parameters

As mentioned previously extra high voltage TL is defined by its parameters (R, L, and C) and calculated as follows:

Referring to **Error! Reference source not found.**,

Resistance at 20 °C, $R_{dc} = 0.05595\ \Omega/\text{Km}$

At 65 °C:

$$\frac{R_{65\,°C}}{R_{20\,°C}} = \frac{T + t2}{T + t1}$$

$$R_{65\,°C} = (0.05595)(\frac{228 + 65}{228 + 20})$$

$$R_{65\,°C} = 0.06691\ \Omega/\text{Km}$$

$$R_{65\,°C} = 0.10768\ \Omega/\text{mile}$$

- **Skin effect R_{ac}:**

$$Rac = K * Rdc$$

$$x = 0.063598\sqrt{\frac{\mu f}{Rdc}}$$

$$x = 0.063598\sqrt{\frac{1 * 50}{0.10768}}$$

$$x = 1.37$$

Referring to **Error! Reference source not found.** and applying linear interpolation:

$$k = 1.01470 + \left(\frac{1.01969 - 1.01470}{1.4 - 1.3}\right)(1.37 - 1.3)$$

$$k = 1.01819$$

$$R_{ac} = 1.01819 * 0.06691 = 0.06812\ \Omega/\text{Km}$$

$$R_{eq} = 0.03406\ \Omega/\text{Km}\ \ \text{(For two bundles)}$$

- **Inductance L:**

Dab, Dbc, Dac = 10 m

d = 0.45 cm

$$L = 0.2ln\frac{GMD}{GMR_L}\ \text{mH/Km}$$

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$$GMD = \sqrt[3]{Dab * Dbc * Dac} = \sqrt[3]{10 * 10 * 20} = 12.59 \text{ m}$$
$$GMR_L = \sqrt{D_s * d}$$
$$D_s = 6.9499 * r = 0.01226\ m$$
$$GMR_L = \sqrt{0.01226 * 45 * 10^{-2}} = 0.07428 \text{ m}$$
$$\therefore L = 0.2ln\frac{12.59}{0.07428} = 1.0267 \text{ mH/Km}$$
$$X_L = 2\pi f L = 0.322\ \Omega/Km$$

- **Capacitance C :**

r = 31.77 mm
$$C = \frac{0.0556}{ln\frac{GMD}{GMR_c}}\ \mu F/Km$$
$$GMD = \sqrt[3]{Dab * Dbc * Dac} = \sqrt[3]{10 * 10 * 20} = 12.59 \text{ m}$$
$$GMR_C = \sqrt{r * d} = \sqrt{\frac{31.77 * 10^{-3}}{2} * 0.45}$$
$$GMR_C = 0.0845 \text{ m}$$
$$\therefore C = \frac{0.0556}{ln\frac{12.59}{0.08455}} = 0.0111\ \mu F/Km$$
$$X_C = \frac{1}{2\pi f C} = 0.286 * 10^6 \Omega.Km$$

iii. TL Modeling (T model)

Since 150 Km line length lies on medium transmission line, the equivalent TL circuit will be represented by forming T network (Figure-14) and the circuit parameters will be calculated accordingly [5].

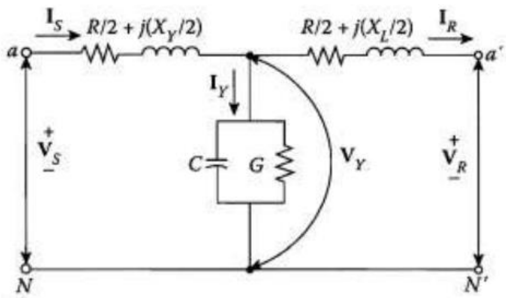

Figure-14: T Modeling Circuit of a Transmission Line

- **Calculations of A B C D parameters :**

$$Z = R_{eq} + jX_L = (0.03406 + j0.322) * 150 = 5.1 + j48.3\ \Omega$$

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$Y = j\omega C = j * 2\pi f * 0.0111 * 10^{-6} * 150 = j5.2281 * 10^{-4}\ S$

$A = D = 1 + \frac{1}{2}YZ = 0.987 + j1.326 * 10^{-3}$

$A = D = 0.987\angle 0.077°$

$B = Z + \frac{1}{4}YZ^2 = 5.0357 + j43.2297 = 48.26\angle 84.01°$

$C = Y = j5.2281 * 10^{-4} = 5.228 * 10^{-4}\angle 90°$

$\begin{bmatrix} V_S \\ I_S \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_R \\ I_R \end{bmatrix}$

- **Power flow through transmission line :**

Voltage at sending end:

$V_S = AV_R + BI_R$

Current at sending end:

$I_S = CV_R + DI_R$

Assuming the receiving end voltage as reference with phase angle $\theta = 0°$

$V_{R(L-N)} = \frac{400Kv}{\sqrt{3}} = 230.94\angle 0°\ KV$

The receiving-end current is

$I_R = \frac{400MW}{\sqrt{3} * 0.85 * 400KV} = 679.235\angle - 31.79°$ A

$\begin{bmatrix} \boldsymbol{V_{S(L-N)}} \\ \boldsymbol{I_S} \end{bmatrix} = \begin{bmatrix} \mathbf{0.987\angle 0.07°} & \mathbf{48.26\angle 84.01°} \\ \mathbf{5.228 * 10^{-4}\angle 90°} & \mathbf{0.987\angle 0.07°} \end{bmatrix} \begin{bmatrix} \mathbf{230,940.1\angle 0°} \\ \mathbf{1018.8\angle - 31.79°} \end{bmatrix}$

$V_{S(L-N)} = 249.398\angle 6.027°\ KV$

$V_{S(L-L)} = 431.970\angle 36.02°\ KV$

$I_S = 615.553\angle - 22.11°$ A

The sending end power factor is

$\theta_S = 6.027° - (-22.11°) = 28.137°$

$\cos\theta_S = 0.881°$

The complex power at receiving end is expressed as (on per phase basis)

$S_R = P_R + jQ_R = V_R {I_R}^*$

$S_R = 133.330 + j82.636\ MVA$

$P_R = 133.330\ MW,\ Q_R = 82.636\ MVAR$

The complex power at sending end is expressed as (on per phase basis)

$S_S = P_S + jQ_S = V_S {I_S}^*$

$S_S = 135.375 + j72.396\ MVA$

$P_S = 135.375\ MW,\ Q_S = 72.396\ MVAR$

- **<u>TL efficiency and voltage regulation :</u>**

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$\left|V_{R(L-N)}\right|$ At no load = $\left|\frac{V_{S(L-N)}}{A}\right| = 252.682\ KV$

$V_{R,FL} = V_{R(L-N)} = 230.94\angle 0°\ KV$

$$Percentage\ of\ voltage\ regulation = \frac{\left|\frac{V_S}{A}\right| - |V_{R,FL}|}{|V_{R,FL}|} * 100 = 9.414\%$$

Efficiency of transmission line is

$$\eta = \frac{\sqrt{3}V_R I_R \cos\theta_R}{\sqrt{3}V_S I_S \cos\theta_S} * 100$$

$$= \frac{\sqrt{3} * 230.94 * 10^3 * 679.235 * 0.85}{\sqrt{3} * 249.398 * 10^3 * 615.553 * 0.881} * 100$$

η =98.5%

$$Percentage\ of\ voltage\ drop = \frac{|V_S| - |V_R|}{|V_S|} = \frac{261.010 - 230.94}{261.010} * 100$$

$$= 7.4\%$$

iv.Surge Impedance Loading (SIL)

The characteristic impendence is calculated as follows:

$$Z_C = \sqrt{\frac{L}{C}} = \sqrt{\frac{1.0267 * 10^{-3}}{0.0111 * 10^{-6}}} = 304.13\ \Omega$$

The natural loading of TL is:

$$SIL = \frac{\left|Kv_{R(L-L)}\right|^2}{Z_C} = \frac{|400|^2}{304.13} = 526.089\ MW$$

c. TL Environmental Effects Calculations

In this section the choice of moose conductor selected will be checked by calculating the environmental impact for the conductor.

i.Conductor Corona Voltage

The corona critical voltage of bundle conductor is:

$$V_C = \sqrt{3}m_0 m_1 \delta^{\frac{3}{2}} * 48.8 * \frac{nr}{1 - \frac{2(n-1)}{S}\sin\frac{\pi}{n}} * (1 + \frac{0.301}{\sqrt{rd}}) \log\frac{D}{\frac{1}{r^{\frac{1}{n}} * S^{\frac{n-1}{n}}}}$$

Where,

n =2

$m_0 = 0.8$

$m_1 = (0.8\ in\ rainy, 1\ in\ fair\ weather)$

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$\delta = 1$
$D = 1000\ cm$
$d = 3.17\ cm$
$r = 1.58\ cm$
$S = 45cm$

$$V_C = \sqrt{3} * 0.8 * 0.8 * 1^{\frac{3}{2}} * 48.8 * \frac{2 * 1.58}{1 - \frac{2(2-1)}{45}\sin\frac{\pi}{n}} * (1 + \frac{0.301}{\sqrt{1.58 * 3.17}}) \log\frac{1000}{\frac{1}{1.58^{\frac{1}{2}} * 45^{\frac{2-1}{2}}}}$$

$$V_{C(L-L)} = 54.095 * \frac{2 * 1.58}{0.955} * 1.134 \log 8432.08 = 796.88\ KV$$

ii.Conductor Surface Gradient

Surface gradient for the conductor is calculated using the following formula:

$$g_{MAX} = g_{AV}\left[1 + \left(\frac{d}{D}\right)(N-1)\right]\ (KV, rms/cm)$$

Where,

$$g_{AV} = \frac{Q}{2\pi\varepsilon_0 r}(KV, rms/cm)$$

$d = 3.17\ cm$
$r = 1.585\ cm$

$$D = \frac{S}{\sin\frac{\pi}{2}} = 45\ cm$$

$N = 2$

$$Q = \frac{CV}{N}(KC, rms/cm)$$

$Capacitance = 1.11 * 10^{-11} F/m$
$phase\ rms\ voltage\ V = 230.9\ (KV, rms)$

$$Q = \frac{CV}{N} = \frac{1.11 * 10^{-11} * 230.9}{2} = 1.2817 * 10^{-9} Kc, rms/cm\ for\ each\ subconductor$$

$$g_{AV} = \frac{Q}{2\pi\varepsilon_0 r} = \frac{1.602 * 10^{-9}}{2\pi\left(\frac{1}{36\pi}\right) * 10^{-9} * 1.585} = \frac{1.602 * 10^{-9}}{8.805 * 10^{-11}} = 14.55\ KV, rms/cm$$

$$g_{MAX} = 18.19\left[1 + \left(\frac{3.17}{45}\right)(2-1)\right] = 15.57\ KV, rms/cm$$

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iii.Corona Power Loss

Using Anderson, Baretsky, and McCarthy formula:

$$P_C = P_{FW} + 0.3606 * K * V * r^2 * \ln(1 + 10\rho) * \sum_{1}^{3N} E^5$$

$P_{FW} = 1\ to\ 5\ KW/Km$

$K = 7.04 * 10^{-10}$

$V = \frac{400}{\sqrt{3}}\ KV$

$E = Peak\ surface\ voltage\ gradient\ on\ the\ centre\ phase\ condcutor\ KV/cm$

$\rho = rain\ rate\ in\ mm/hour = 5\ mm/hr$

r=1.58 cm

$N = 2$

$H = 12\ meters$

Calculating for E

$$E = \frac{V * \left[1 + (N-1) * \frac{r}{R}\right]}{N * r * \ln\left[\frac{2H}{r_{eq} * \sqrt{\left(\frac{2H}{S}\right)^2 + 1}}\right]}$$

$$r_{eq} = R\left(\frac{N * r}{R}\right)^{\frac{1}{N}}$$

$$r_{eq} = 0.225\left(\frac{2 * 0.158}{0.225}\right)^{\frac{1}{2}} = 8.43\ cm$$

$$R = \frac{B}{2} = \frac{45}{2} = 22.5\ cm\ is\ the\ bundle\ radius$$

$S = 10\ meter\ is\ the\ phase\ spacing$

$$E = \frac{\frac{400}{\sqrt{3}} * \left[1 + (2-1) * \frac{1.58}{22.5}\right]}{2 * 1.58 * \ln\left[\frac{2 * 1200}{8.43 * \sqrt{\left(\frac{2 * 1200}{1000}\right)^2 + 1}}\right]} = \frac{230.9 * 1.0702}{14.839} = 16.655\ KV/cm$$

$$peak\ to\ peak\ E = 16.65 * \sqrt{2} = 23.55$$

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3 phases Power loss due to corona discharge is

$$P_{C(3\emptyset)} = 5 + 0.3606 * 7.04 * 10^{-10} * 400 * 1.58^2 * \ln(1+50) * 6 * 23.5^5$$

$$P_{C(3\emptyset)} = 47.8\ KW/Km$$

$$i_C = \frac{P_C}{\sqrt{3} * V} = \frac{47.8}{\sqrt{3} * 400} = 0.069\ A/Km$$

$$P_{C(3\emptyset)} = 47.8 * 150 = 7.17\ MW$$

iv.Audible Noise of Corona

Measuring the sound pressure level at 25 meters distance far from the middle phase of the transmission line at ground level,

$D(1)$=19.2 m,

$D(2)$=27.73 m,

$D(3)$=37 m,

Outer phases g_m=15.57 KV/cm,

Centre phase g_m=16.655 KV/cm,

d=3.17 cm,

Audible noise is calculated for each phase as follows:

$$AN(1) = 120\log_{10} 15.57 + 55\log_{10} 3.17 - 11.4\log_{10} 19.2 - 115.4 = 40.6\ db$$

$$AN(2) = 120\log_{10} 16.6 + 55\log_{10} 3.17 - 11.4\log_{10} 27.73 - 115.4 = 42.12\ db$$

$$AN(3) = 120\log_{10} 15.57 + 55\log_{10} 3.17 - 11.4\log_{10} 37 - 115.4 = 37.35\ db$$

Total sound pressure level is:

$$SPL = 10\log_{10}\sum_{i=1}^{3} 10^{0.1AN(i)}\ db(A)$$

$$SPL = 10\log_{10}(10^{5.225} + 10^{5.387} + 10^{4.9004}) = 45.212\ db$$

v.Radio Interference

RI generated by each phase of the transmission line is calculated as follows:

Right of way is 50 meters, so measuring point is at ground level at 25 meters far from the middle phase of the transmission line,

$D(1)$=19.2 m,

$D(2)$=27.73 m,

$D(3)$=37 m,

Outer phases g_m=15.57 KV/cm,

Centre phase g_m=16.655 KV/cm,

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d=3.17 cm,

$$RI_1 = 3.5(15.5) + 6(3.17) - 33\log_{10}\left(\frac{19.2}{20}\right) - 30 = 43.855\ db$$

$$RI_2 = 3.5(16.655) + 6(3.17) - 33\log_{10}\left(\frac{27.73}{20}\right) - 30 = 42.6\ db$$

$$RI_3 = 3.5(15.57) + 6(3.17) - 33\log_{10}\left(\frac{37}{20}\right) - 30 = 34.69\ db$$

In fair weather condition:

$RI = \left(\frac{43.855+42.6}{2} + 1.5\right) = 43.22\ db$ At 0.5 MHZ

$RI = 43.22\ - 6 = 37.22\ db$ At 1 MHZ

In rainy weather condition:

$RI = 43.22\ + 17 = 60.22\ db$ At 0.5 MHZ

$RI = 37.22\ + 17 = 54.227\ db$ At 1 MHZ

d. Reducing Corona Losses Effect

Corona losses effect can be reduced by increasing the spacing between phases of the transmission line, recalculation is done by using the design formulas considering 13.5 and 15 meters space between phases give the results shown in Tabl.

V. Simulation and Analysis of the Results of Extra High Voltage Lines 400KV

A brief power flow analysis is done by Etap simulation on the existing longest 220 KV line in Lebanon connecting DEIR-NBOUH with KSARA which is designed to transfer maximum per phase current of 880 as shown in item number 6 in **Error! Reference source not found.**. Simulation result shown in Figure-15, shows the TL voltage drop and power flow at 200 MW load. Extra high voltage transmission line is one of the good solutions in reducing the losses in the process of sending high ranges of power over long distances. Protection systems, switchgears, and transformers where not covered in the design. For best application of EHV TL system, feasibility, reliability and stability studies should be done on the whole grid including the distribution lines.

a) TL Power Flow Analysis Results

The calculation and simulation using ETAP software give results that include the power flow analysis at both 220 and 400 KV TL voltage levels. The power flow calculation results at TL voltage levels 400 KV is presented as follows in Table-1:

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Table-1: Power flow results at 400 KV voltage level.

Voltage level (KV)	**400**	**Voltage level (KV)**	**400**
3 phase real power at sending end (MW)	405.99	**Recieving end line voltage (KV)**	400
3 phase reactive power at sending end (MVAR)	217.17	**Sending end power factor**	0.881
3 phase real power at receiving end (MW)	399.99	**Recieving end power factor**	0.85
3 phase reactive power at receiving end (MVAR)	247.908	**Surge impedance loading (MW)**	526.089
Sending end phase current (A)	615	**TL efficiency (%)**	98.5
Sending end line voltage (KV)	431.97	**TL voltage regulation (%)**	9.4
Receiving end phase current (A)	679.235	**TL voltage drop (%)**	7.4

b) TL Calculated Results:

TL Calculation Results at 400 KV in Table-2

Table-2: Calculation results for selected voltage level (400 KV EHV AC TL).

Selected voltage (KV)	400
Size of conductor (mm^2)	597
Number of sub conductors per phase	2
Corona voltage	796.88
Number of insulator discs	26
AC Resistance (Ω /Km)	0.06812
Inductance (mH/Km)	1.0267
Inductive reactance(Ω/Km)	0.322
Capacitance (μF/Km)	0.0111

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Capacitive reactance (Ω.Km)	$0.286 x 10^{6}$
Surge Imepdance Z_0 (Ω)	304.13
Surge Impedance loading (MW)	526.089

ii. TL Environmental Effects Results at 400 KV

Table-3: Calculation results of environmental effects on 400 KV TL.

Maximum bundle gradient (KV/cm)	**Outer phases**	15.5
	Centre phase	16.6
Audible noise (dB)	**AN(1)**	40.6
	AN(2)	42.12
	AN(3)	37.35
Sound pressure level (dB)		45.2

Reducing TL Environmental Effects at 400 KV

Table-4: Corona losses effect with respect to TL phases spacing.

	Phase Spacing (m)		
	10	13.2	15
Geometric mean distance GMD (m)	12.59	16.63	18.89
Average Inductance (mH/Km)	1.0267	1.082	1.107
Average Capacitance (μF/Km)	0.0111	0.0105	0.0102
Outer phases average surface voltage gradient (KV/cm)	14.5	13.7	13.3
Outer phases maximum surface voltage gradient (KV/cm)	15.57	14.7	14.3

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Maximum surface voltage gradient on the centre of conductor (KV/cm)	16.65	15.8	15.5
Disruptive critical corona voltage (KV)	796.88	821.3	832.63
TL Corona power loss (MW)	7.17	5.74	5.28
TL Total power loss (MW)	14.24	12.81	12.35
Audible noise (dB)	45.2	41.89	40.74
Radio interference in fair weather at 1 MHZ (dB)	37.22	34.34	33.09

Tower and TL Clearance

Table-5: TL required clearance.

Tower Span (m)	350
TL Sag (m)	4.6
Minimum horizontal phase-phase clearance (m)	3.83
TL phase to ground minimum clearance (m)	12
Right of Way (m)	52

Simulation Results

Power flow analysis is simulated using ETAP software at both 220 and 400 KV levels.

400 KV Design Simulation Result

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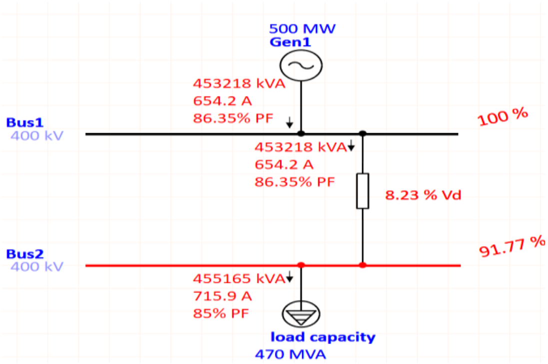

Figure-15: ETAP power flow simulation at 400 KV under 400 MW load.

DEIR NBOUH-KSARA 220 KV TL Simulation Results

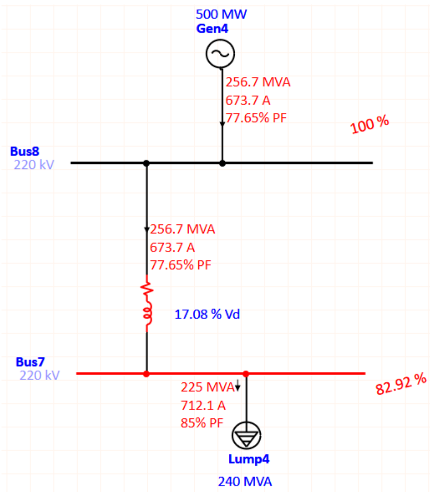

Figure-16: ETAP power flow simulation at 220KV under 200 MW load.

VI. Conclusion

In this paper, the analysis and design of 400 KV transmission line have proposed where the importance of extra high voltage in transmission systems is obvious in making system more efficient with fewer losses and lower voltage drop. However, the proposed design that was done is one of multiple designs that can be applied depending on the factors affecting the applicability and the existing transmission system performance followed with other configurations and results. However, to properly study the feasibility of the project further studies and analysis on both double circuit and addition of 220 KV TL to the existing must be studied and compared. Besides, EHV TL projects are considered governmental nonprofit project in which a cost benefit analysis is required, based on mentioned analysis results a valuable decision will be taken accordingly either to go or not to go with replacement of 230KV by 400KV lines.

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