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Optimal Design of Overhead Transmission Line Towers in Relation with Environmental and Land Ownership in Kenya

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Abstract: **Over the next decade, substantial extensions of the transmission infrastructure in Kenya and related investments are needed in order to accommodate increasing loads and generation of renewable electricity in line with policy targets. Overhead lines (OHL) are the reference technology for transmission of electrical power. However, the construction of new OHL and general reinforcement of the transmission system requires acquisition of way leave easement which raises considerable concerns to local communities and have cost implications especially with skyrocketing prices of land in Kenya.**

The feasibility of optimal design of OHL to reduce right of way width and potential technology alternatives to OHL is likely to be discussed publicly in all future transmission development proposals. In response to these concerns, the Board of Directors, Kenya Electricity Transmission Company Ltd commissioned a Study on optimal design of OHL for transmission of electrical power.

Recent concerns of the public about possible health effects of magnetic fields has resulted in an increased emphasis on the use of compact transmission lines as a means of managing (i.e. reducing) magnetic fields. This paper examines how compact transmission configurations and optimal conductor selection will result in reduction of way leave corridor.

Keywords: **Overhead lines (OHL), Electricity Transmission Company.**

1. INTRODUCTION

1.1. Background of the study:

Kenya Electricity Transmission Company (KETRACO) was incorporated in December 2008 as a State Corporation 100% owned by the Government of Kenya. The Mandate of the KETRACO is to plan, design, construct, own, operate and maintain new high voltage (132kV and above) electricity transmission infrastructure that will form the backbone of the National Transmission Grid & regional inter-connections. It is expected that this will also facilitate evolution of an open-access- system in the country.

The transmission development plan indicates the need to develop approximately 10,345KM of new lines at an estimated present cost of USD 4.48 Billion. This will mean quite expansive acquisition of way leave. Experience indicates that way leave issues could be one of the main hindrances to KETRACO delivering its mandate in line with LCPDP.

It is advantageous to both transmission line developers and to landowners to minimize the space required for a transmission line. This is the basic idea behind compact transmission line design. Compact transmission lines are not fundamentally different from traditional transmission lines, but because they are designed to take up less space, they require some considerations that may not be necessary when designing transmission lines with more traditional form factors.

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Traditional transmission lines were designed very conservatively - with wide spaces between phase conductors which made the risk of phase-to-phase flashovers very low, and left surface voltage gradients at very low levels. They had simple wooden frame designs which were cheap and easy to build.

1.2. Statement of the Problem:

Over time, public opposition to the construction of new lines has increased, and the sophistication of such opposition has grown. The public's concerns over the construction of new overhead transmission lines in residential and scenic areas are summarized in Figure 1.2-1, which is taken from a study entitled "Perception of Transmission Lines" written by Thomas Priestly and Kenneth Craik and sponsored by an international group of utilities [9]. As summarized in this bar chart, people are concerned about a wide range of issues, but the their major concerns centre on the appearance of these lines ("Aesthetics" and "Property Values") particularly near residential areas and on fear of being near them ("Health" and "Safety").

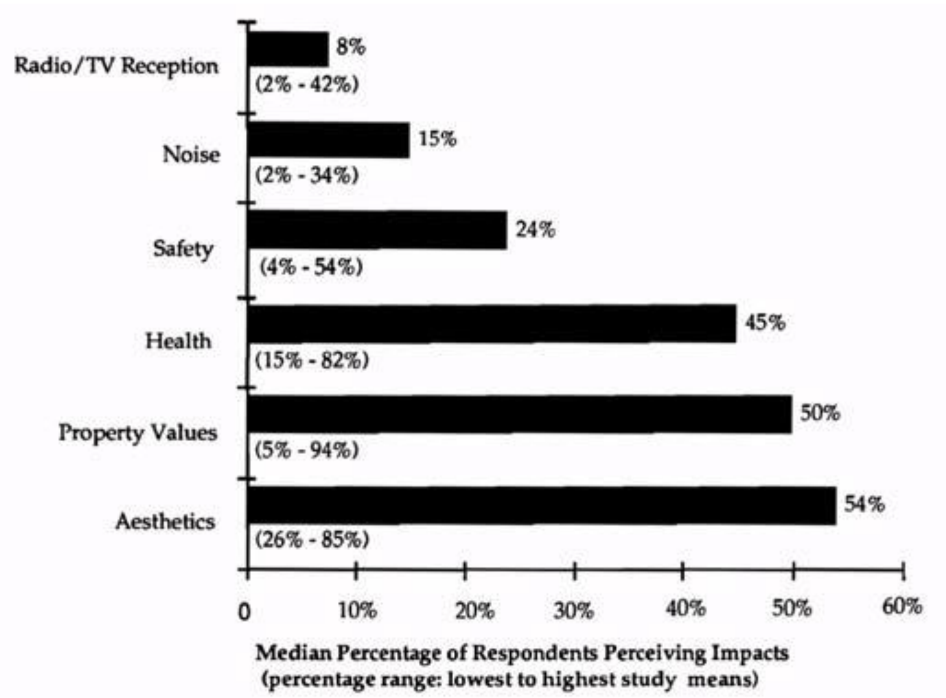

Figure 1.2.1 Public concerns about overhead transmission lines (Priestley and Craik 1993).

1.3. Objectives of the Research:

The objectives of this project were to:

- Model different configuration of 220kV double circuit overhead line tower using PLS Tower software and analyse weight.
- Study the output Scenarios for different conductors used in the 220kV Double Circuit tower for KETACO optimal design.
- Calculate the inclined sag, swing angle and the blowout which have a trigonometric relationship.
- Add blowout to the tower geometry and clearance calculations to determine the way leave requirements.

1.4. Scope of the Project:

The Project entailed a review of all the projects carried out within KETRACO. Desktop modeling and calculation was carried out

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2. LITERATURE REVIEW

2.1. Compact Transmission Line Design Considerations:

2.1.1. Introduction:

It is advantageous to both transmission line developers and to landowners to minimize the space required for a transmission line. This is the basic idea behind compact transmission line design. Compact transmission lines are not fundamentally different from traditional transmission lines, but because they are designed to take up less space, they require some considerations that may not be necessary when designing transmission lines with more traditional form factors.

Traditional transmission lines were designed very conservatively with wide spaces between phase conductors which made the risk of phase-to-phase flashovers very low, and left surface voltage gradients at very low levels. They had simple wooden frame designs which were cheap and easy to build.

In recent years, building new transmission lines has been difficult. Often, the biggest impediment to a transmission project is securing a right-of-way access. Landowners are hesitant to comply with developers who they may see as outsiders, without their interests in mind. Some people balk at the spectre of a transmission line cutting across their property, altering the perceived beauty of the landscape. Neighbours may fear that their property values will decrease. These concerns are very common.

This resistance has a cost to developers, who must go through a great deal of work to procure the easements necessary for new transmission lines. As a result, transmission developers have found ways to decrease the right of way necessary for new projects. This is often done by reusing existing right of way, occupied by existing distribution lines. Developers often choose to uprate existing transmission lines to higher voltages.

Compact line design is the result of this space-saving strategy. New transmission lines are designed to take up far less lateral space by utilizing modern materials and altering tower geometries. These structures in these modern designs are simpler and require less space, reducing their visual impact. These designs reduce phase-to-phase and phase-to-structure distances, which in turn increase voltage gradients on conductors and reduced flashover voltage thresholds. Methods first used in EHV transmission design are utilized in order to guarantee that audible noise (AN), radio noise (RN), and EM fields are kept at acceptable levels.

The horizontal cross-section of compact lines is decreased using several methods. Triangular and vertical arrangements of phases are used, rather than horizontal arrangements, in order to decrease the width of the lines. Steel pole structures and composite insulators are often used as well. These materials have increased strength, and can be used to support the lines with less material.

Figures below show a traditional support structure, as well as several typical compact structures.

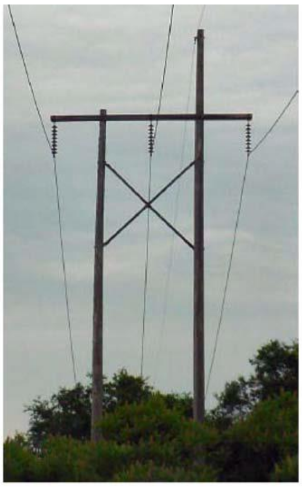

Figure 2.1-1 Conventional 115-kV line with 3650mm phase-phase spacing.

Figure 2.1-2 Compact line in a residential area.

Traditional 'H-frame' structures were built of wood, and often utilized suspended ceramic insulators. Compact lines are typically built with tubular steel poles and composite insulators. Post-insulators are often used which provide structural support, requiring fewer steel pole arms. Some designs use v-shaped configurations of insulators to accomplish a similar function. Steel pole designs tend to be taller than h-frame structures, but take up less lateral space. An emphasis is placed on controlling the motion of conductors, so that they can be placed closer together without risking flashover. If desired, poles can be placed closer together in order to decrease span length, and thus decrease the physical motion of conductors. Phase-to-phase spacers may also be utilized. Insulators must be designed to adequately protect from flashovers. Phase-to-phase spacing must be designed to limit voltage gradients and EM fields. Bundling can be used at lower-than-traditional voltages in order to further limit surface gradients. Shield wires and well-calibrated surge arrestors are used to protect against lightning strikes.

As long as proper design considerations are followed, compact lines should operate no less reliably than traditional lines, and should not cause high numbers of complaints due to audible or radio noise. Design studies suggest that the cost of construction of these lines is not significantly higher than traditional designs. But, the decreased cross-section may make such lines seem more agreeable to neighbours and lease holders.

2.1.2. Phase Spacing and Conductor Motion:

The primary insulator for overhead transmission lines is air. Transmission lines are mechanically designed to maintain adequate air gaps under a variety of environmental conditions, in order to prevent phase-to-phase and phase-to-tower faults. Wind and ice phenomena can significantly impact the behaviour of conductors in the natural environment, so great care is taken to prevent these phenomena from reducing phase-to-phase spacing and causing faults.

Conductor loading due to ice should be considered for a variety of credible scenarios, in order to assure that phase-to-phase faults do not occur. In traditional horizontal phase arrangements, unequal ice loads are unlikely to cause phase-to-phase faults. Compact designs, however, frequently feature conductors aligned in the same vertical plane. Unequal loading of conductors, inaccurate tensioning, or excessive vibration may cause a conductor to stray into proximity of a conductor above it. On top of this, phase-to-phase spacing is reduced in these designs. For this reason, a study of conductor motion is very important in compact lines.

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2.1.3. Clearances:

Sufficient clearance must be guaranteed such that under most normal conditions, phase-to-phase clearance, phase-to-tower clearance, and phase-to-ground clearance is maintained. Phase-to-ground clearances are specified by the NESC for a number of circumstances [2]. This clearance is designed to account for peak operating voltages, switching-surge levels (transient peak voltages caused by switch openings and closings), and elevation, among other factors. Phase-to-tower clearances are maintained by utilizing adequate insulation. Post insulators and line insulator in bracing configurations are often used in compact transmission lines, so phase-to-structure clearances are fixed, and phase-to-tower clearances often do not depend on conductor motion.

Phase-to-phase clearance has been a topic of some study. All power lines must be designed to withstand lightening-induced surges and switching surges, under static conditions (no motion). The required phase-to-phase electrical clearance is calculated based on withstand voltages. An air gap of distance *dw* has a 98% withstand voltage *V*98% of *V*98% = *V*50% + 3delta, where delta represents the standard deviation of the withstand voltage of the air dielectric. Withstand voltage distributions (summarized by *V*50% and delta) have been studied for many different environments.

Many kinds of conductor motion can reduce phase-to-phase clearance, so it is important to consider these factors in the design of a transmission line. These are largely mechanical issues, caused by wind and ice cover. When considering conductors in motion, phase-to-phase clearances are based on power frequency voltages, rather than on switching surge or lightening surge voltages. It is assumed that the probability of both a transient surge occurring and two conductors in motion coming into close proximity of each other at the same time is very low.

A typical set of power-frequency withstand voltages is shown in Figure 2.1.3 [4] [5]. An air gap must have a withstand voltage greater than the maximum expected power frequency voltage *Vp* seen on a transmission line | typically, 1.05 *Vp*.

Figure 2.1.4 shows the results of a survey done by EPRI, using data from real compact transmission lines some of which were uprated from lower voltage transmission lines. The Phase Spacing Ratio is the ratio of the actual phase-to-phase spacing distance *da* over the spacing required to insulate against a peak power frequency voltage *dpf*. While, overall, it shows that compact transmission line phase spacing in compact line is decreased, the value of that decrease varies significantly between individual lines.

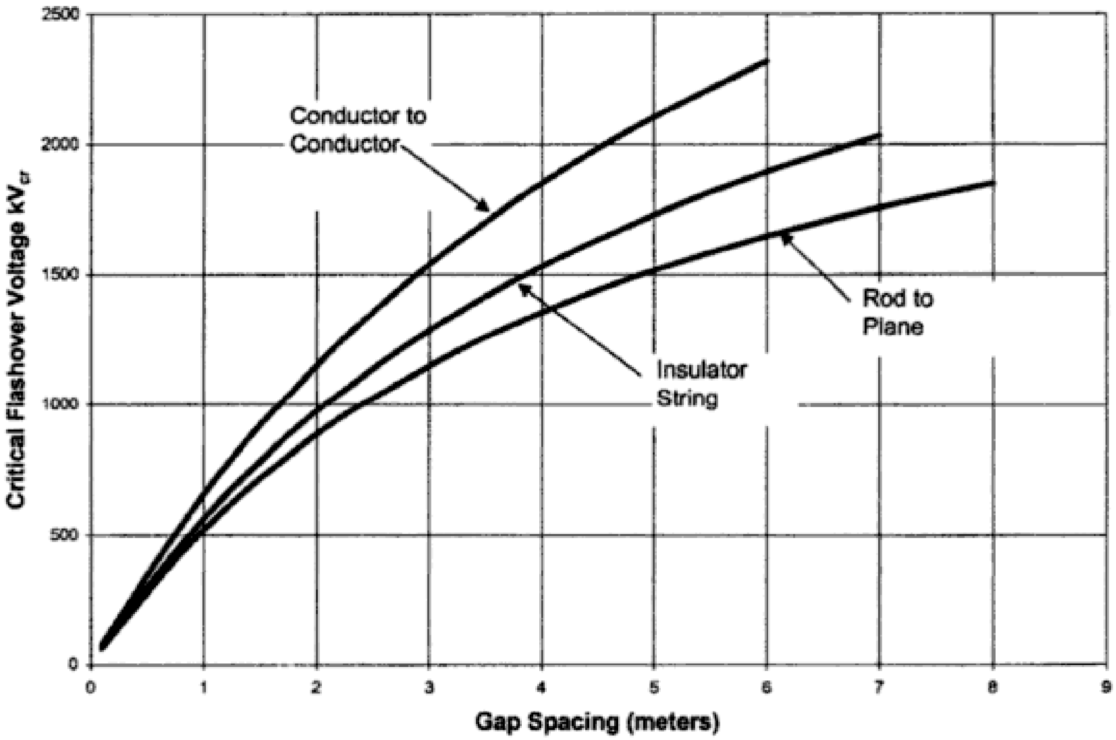

Figure 2.1.3: V50% Critical Flashover Voltages

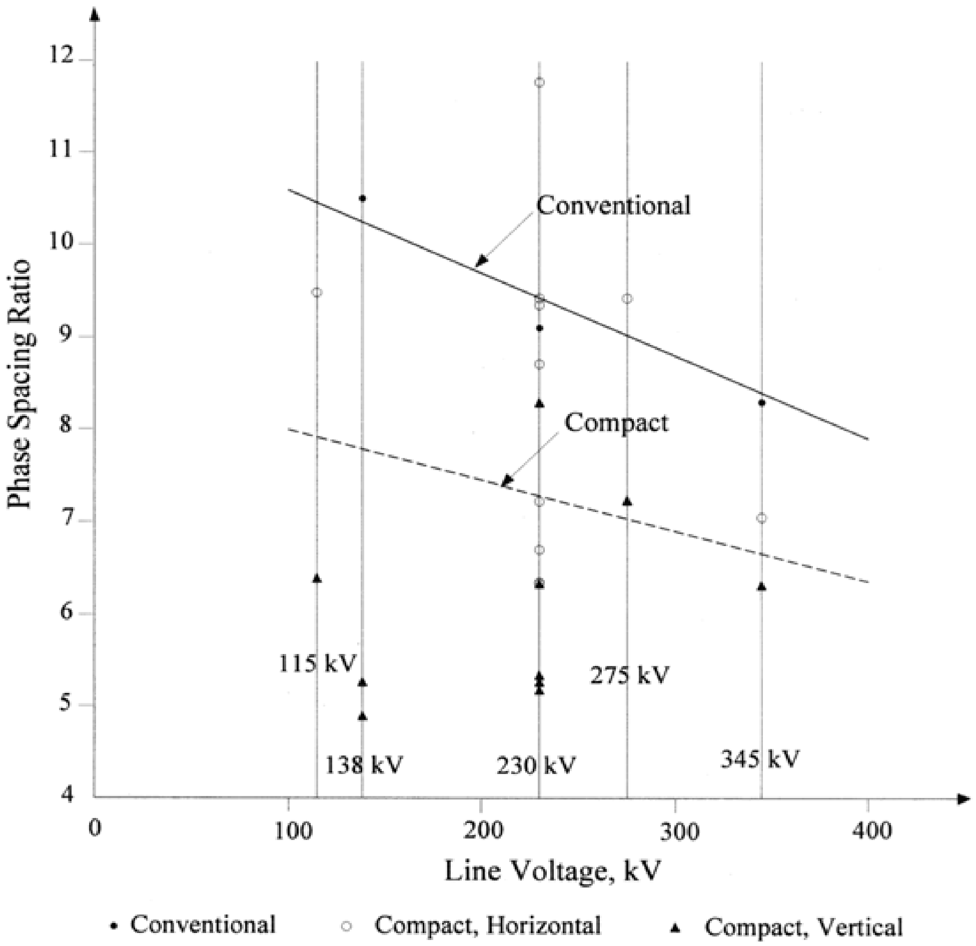

Figure 2.1.4: ***dpp* / *d*98%, for Traditional and Compact Transmission Lines**

2.1.4. Types of Conductor Motion:

Wind and ice loading can cause a variety of types of conductor motion around which or against which a line will be designed.

Blowout:

Blowout is the most basic conductor motion. Blowout refers to the magnitude of the horizontal displacement of a conductor, due to wind. This is most commonly caused by steady winds. Gusts of wind can cause more dynamic blowout, though the behaviour will be significantly damped by the weight of the conductor itself.

Wind will exert pressure on a conductor, orthogonal to the conductor itself. Wind speeds should be selected to represent the highest wind speed expected over a period of time.

Blowout should be calculated for the maximum sustained wind speed. This is the method used in the NESC estimation of force due to wind. Further work by CIGRE has suggested that this method consistently leads to overestimations of force. There are more accurate methods for calculating force due to wind, but this method guarantees that actual blowout less than those designed for. Trapezoidal (compact) conductors and self-damping conductors have been shown to have lower drag coefficients than traditional stranded conductors, and will likely be less impacted by wind pressure.

To calculate blowout, a transmission line is modelled as a point mass on a pendulum. Specify the per-distance weight of the conductor and per-distance force on the conductor. Then, set the moment of the pendulum to zero, and solve for the angle θ as shown in Figure 2.1.5 Blowout angle and blowout distance *dbo* are calculated from:

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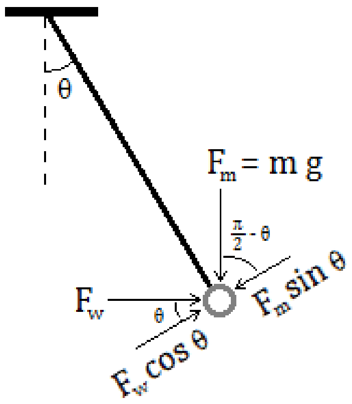

Figure 2.1.5: Blowout Pendulum Model

More detailed models of conductor blowout can include the length, cross-section, and weight of insulators as well. Blowout due to gusts will likely be accompanied by some differential motion. Conductors will not all blow out to the same distance, with the same speed, or at the same time, due to the variability of wind across time and space. Two conductors in the same plane may not be affected to the same degree as each other - especially if the leading phase causes significant turbulence in the wind stream. Differential motion refers to the speed and distance of the displacement of one conductor in reference to the other. Analytical and experimental studies have shown that, in general, the magnitude of differential displacement between two phases in a transmission line will usually be less than 10% of the magnitude of blowout. This is consistent with the goal of reducing the horizontal spacing between phase conductors.

Partial Ice Loading and "Jumping":

Ice loading of conductors impacts their sag, reducing phase-to-ground clearance. It is also important to look at the effect of unequal ice loading between phases. Unequal ice loading can cause one phase to sag closer to another, decreasing the phase-to-phase spacing. A typical calculation will assume maximum ice loading on one strand, an error distance between calculated sag and in-service final sag, and no ice loading on the strand below. Under these assumed static conditions, the distance between phase conductors must be greater than the acceptable withstand distance for a maximum switching surge.

If a significant amount of ice is suddenly shed from a conductor, its elasticity will cause it to "jump". These jumps can be very large - up to 10 feet vertically, in some cases. Care should be taken to maintain vertical conductor spacing, even in cases of unequal ice loading and jumping behaviour. Research on these phenomena was done on a test line in Saratoga, New York, and jump distances are presented as a series of empirical curves and correction factors in EPRI's first book on compact line design [8]. Jumping is not as significant an issue in more traditional transmission designs, where phases are arranged horizontally.

Vibration:

Conductor vibration can occur with lines of any form factor, so it is a well-studied set of phenomena. There are several varieties of conductor vibration which can occur. Vibration is caused by wind, and can change significantly in character, depending on temperatures and ice cover.

Aeolian Vibration is a resonant oscillation caused by vortex shedding by a conductor exposed to a steady wind [8]. This resonance Wake-induced Oscillation termed as Galloping.

3. METHODOLOGY

3.1. Design of Steel Lattice Overhead Transmission Tower:

3.1.1. Introduction:

Towers were modelled using the PLS Tower design software. This was achieved by actual input of tower geometry and importing of parameters from projects already actualized by KETRACO. A model was prepared for a 220kV tower with different configuration namely:

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- Vertical configuration
- Horizontal configuration
- Delta (Danube) Configuration

Work of carrying out tower design was in three stages. The first stage involved modelling of the towers which involved direct data input into PLS tower and import of existing designs parameters. The next stage involved analysis of the tower models and optimisation of the tower configuration to get an optimal tower outline. The third stage involved the design and optimisation of members sizes to get optimal structure weight.

3.1.2. Tower Modelling:

Angles with truss which can resist both tension and compression forces were modelled. At this stage of the project, the research team decided to adopt parameters electrical properties used in Mombasa Nairobi line 220kV double circuit towers. Thus, the model was done using ACSR Hawk 30/7/29.2mm conductor type and Sediver insulator 2539mm long.

3.1.3. Optimisation of Tower model:

Once a model was created, it was checked for common mistakes using the **Model/Check** command. Once the model has been checked, its analysis was performed with the **Model/ Run** command. Best practices were borrowed from experience and approaches adopted by other designers in selecting of member sizes.

3.1.4. Conductor Selection and Easement Width Calculation for KETRACO 220kV Optimum Line:

Conductor Selection:

The optimum choice of conductor for lines below 220kV is governed by the current carrying capacity of the conductor. For lines above 220kV the optimum choice is governed primarily by the corona performance of the line. We note that:

- Conductors with larger diameters have lower electrical stress levels and better corona performance
- Bundling of conductors has the same effect as increasing the conductor diameter

NB: Bundled conductors are easier to handle than large conductor of equal

Two different conductors, ACSR Hawk and ACSR Lynx were considered in our analyses. Configurations for four different scenarios were analyzed:

Scenario A	Scenario B	Scenario C	Scenario D
ACSR Lynx	**ACSR Lynx**	**ACSR Hawk**	**ACSR Hawk**
Single Conductor	**Twin Bundle**	**Single Conductor**	**Twin Bundle**

The Input matrix below was used to specify tower, system and conductor parameters for the calculations.

	Geometry - Vertical			Geometry - Horizontal	
H_1	Height of cond 1 (m)	**30.1**	x_1	Center to Conductor 1 (m)	**4.65**
H_2	Height of conductor 2	**24.4**	x_2	Center to Conductor 2 (m)	**4.73**
H_3	Height of conductor 3	**18.5**	x_3	Center to Conductor 3 (m)	**4.98**
H_4	Height of cond 4 (m)	**30.1**	x_4	Center to Conductor 4 (m)	**-4.65**
H_5	Height of conductor 5	**24.4**	x_5	Center to Conductor 5 (m)	**-4.73**
H_6	Height of conductor 6	**18.5**	x_6	Center to Conductor 6 (m)	**-4.98**

	System			Conductor	
	Description	**Value**		**Description**	**Value**
U_L	System Voltage (kV)	**220**	Name	Conductor Type	**ACSR**
U_{max}	Maximum System Voltage (kV)	**245**	Type	Conductor Name	**Hawk**
C	# circuits	**2**	E_c	Emmisivity of conductor	**0.5**
P	Power transfer (MVA)	**400**	α_s	Solar absorption coefficient	**0.5**
Row	Wayleave (m)	**40**	α	Temp Coeff of Resistance per^{0}C	**0.00403**
f	System frequency (Hz)	**50**	m_0	Surface irregularity factor	**0.82**
frad	Radio frequency (MHz)	**10**	n	Conductors per phase	**1**
			s	Subconductor separation (cm)	**40**

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Easement Width Calculations:

For the optimized conductor, the Easement Width was then calculated to determine the minimum way leave requirement. The input parameters for the easement width calculations are as follows:

VOLTAGE(kV):	**220**
ELECTRICAL SAFETY CLEARANCE (m):	**3.5**
1/2 Tower Width (m).	**4.73**
Insulator length (m):	**3.40**
Conductor:	**Hawk**
Average span of (m):	**350**

4. RESULTS AND DISCUSSION

4.1.1. Tower Model:

The figure 4.1.1.1 below shows danube configuration of the tower developed in PLS tower.

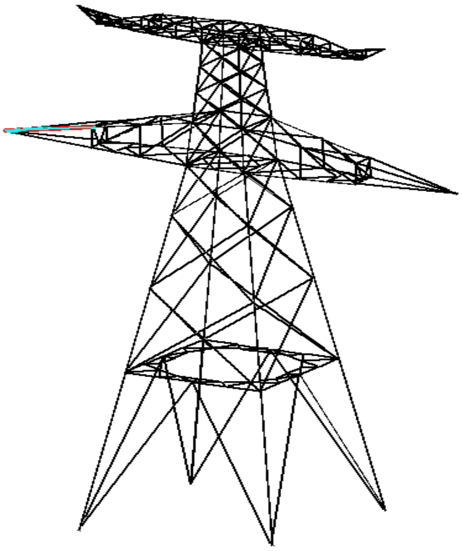

Fig 4.1.1. Danube configuration of tower

The figure 4.1.2 below shows vertical configuration of the tower developed in PLS tower.

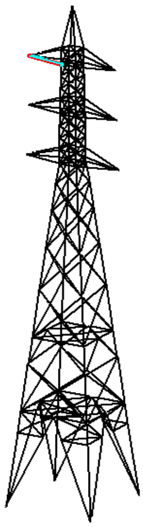

Fig 4.11.2 Vertical configuration of a double circuit tower

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The figure 4.1.1.3 below shows a horizontal configuration of a single circuit transmission line tower developed in PLS tower.

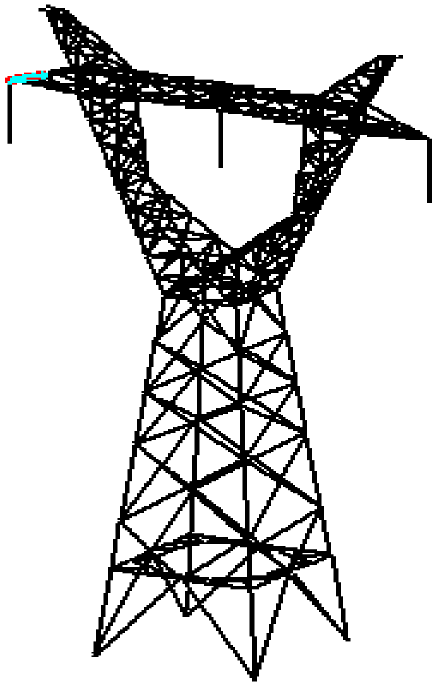

Fig 4.1.1.3 Horizontal configuration of a single circuit tower

From tower analysis, it was observed that there is no significant difference in weight between the vertical and danube tower configuration. For the same conductor type and environmental conditions, heavier cross arm members are required to resist moment in danube configuration but the towers are shorter as compared to vertical configuration which results to lighter cross arm members but taller towers due to electrical clearances. Tower models developed indicated that horizontal configuration is not feasible for double circuit towers unless where there are serious limitations to tower heights.

4.1.2. Conductor Selection:

The following are output scenarios for different conductors of the 220kV Double Circuit tower for KETACO's optimal design.

Parameter	**Description**	**Scenario/Values**			
		A	**B**	**C**	**D**
Type	Conductor Type	**ACSR**	**ACSR**	**ACSR**	**ACSR**
Name	Conductor Name	**Lynx**	**Lynx**	**Hawk**	**Hawk**
D	Conductor Diameter (cm)	**1.953**	**1.953**	**2.180**	**2.180**
Bundle	Conductors per Phase	**1**	**2**	**1**	**2**
Thermal Rating	Thermal rating capability (A)	**415**	**711**	**485**	**832**
SIL	Surge Impedance Loading (MW)	**529**	**1408**	**547**	**1474**
Emax	Max Electrical stress (kV/cm)	**25.47**	**19.02**	**22.07**	**17.35**
Emax/Ec	Electrical stress/Inception gradient (Allowable performance < 0.95)	**1.20**	**1.03**	**1.11**	**0.95**

From the results it is clear that the conductor in Scenario D, ACSR Hawk twin bundle, offers the optimum electrical corona performance. When the ratio of electrical stress to Inception gradient (Emax/Ec) is above 0.95, corona starts to occur. This leads to noise and losses.

4.1.3. Easement Width Calculations:

The inputs are used to calculate the inclined sag, swing angle and the blowout which have a trigonometric relationship. The blowout is then added to the tower geometry and clearance calculations to determine the way leave requirements. The results are as follows: Figure 4.1.3 gives a diagrammatical presentation of the results. Details of the calculations are available in appendix 1.

Inclined sag (m):	**8.64**
Swing Angle θ (Deg):	**33.0**
Calculated ½ Wayleave (m):	**14.8**
Required Wayleave = (m):	**30**

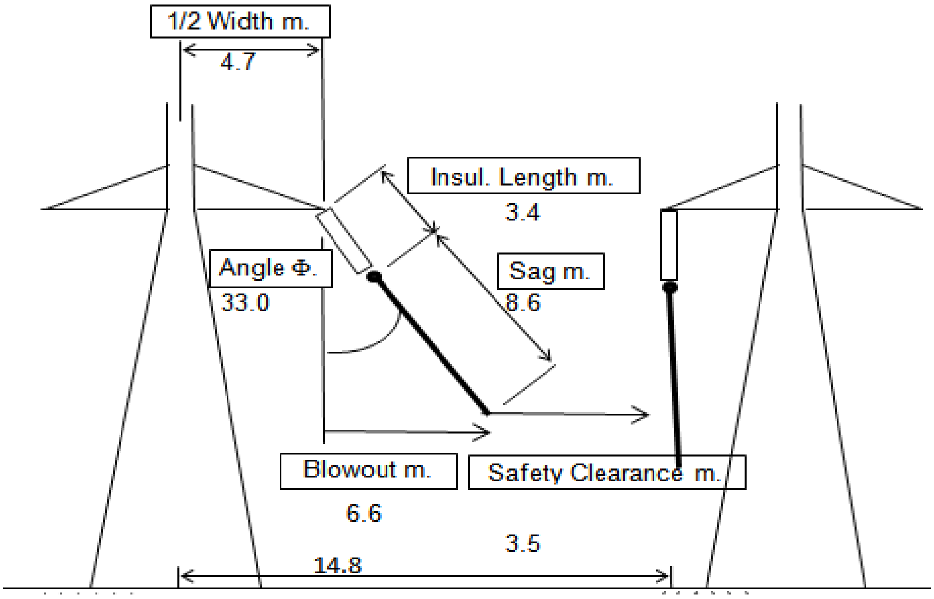

Fig 4.1.3 Illustration calculation of required way leave

5. CONCLUSION AND RECOMMENDATION

The results show that with optimization of tower geometry and conductor selections, it is possible to significantly reduce the way leave requirements for future transmission lines.

The compact line footprint can be further reduced in a variety of ways without sacrificing reliability or increasing cost dramatically. Design of more compact lattice towers will produce immediate benefit to KETRACO while implementing projects.

One of the keys to further compaction is reducing the percentage of sag of the phase conductors. Further research is suggested to be carried out to compare the cost of using tower poles.

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APPENDICES

Appendix 1: Calculations

Calculations 1: Corona Calculations

Maxwell potential coefficients (Matrix)

Pii=1/2πε0 *ln(2hi/GMR)

Pij=1/2πε0 *ln(Dij'/dij)

Determining charge Matrix from Maxwell potential coefficients

[Q] = [P]-1[V]

Eave = Q/2πε0nr

Determining maximum Phase stress (gradient) and Corona inception gradient

Emax = Eave[1+(n-1)r/R]

Ec= 21.21*cond_Sfac*alt_corr*(1+0.301/(cond_GMR*alt_corr)^0.5)

Calculations 2: Inclined Sag and Blowout

Wind Pressure =some utilities use standardised pressures; = 990 Pa

Swing Angle F = 90*ATAN(Force_wind/Conductor_weight_kg_m)/PI() = 33.04 deg

Tension @ full wind = obtained from sag tension calculations = 41.83 kN

Conductor weight =0.98 kg/m

Force due to Wind Pressure = Pressure*Diameter/(9.80665*1000) = 2.20 kg/m

Resultant weight with Wind Pressure= SQRT((Pressure*Diameter/(9.80665*1000))^2+Conductor_weight_kg_m^2) =2.41 kg/m

Inclined Sag @ min temp,full wind Pa =

(Resultant_weight*9.80665*Average_span_of_m.^2)/(8*Tension_full_wind*1000) = 8.64 m

Blowout m. =(Insulator_length_m.+Inclined_Sag)*SIN(Swing_Angle_F_Deg.*(PI()/180)) = 6.57m