Compact Transmission Line Design Considerations

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Chapter 1

Compact Transmission Line Design Considerations

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 [1].

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. Neighbors 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 structure 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.

Figure shows a traditional support structure, as well as several typical compact structures. 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. As in and , 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 lightening 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 neighbors and lease holders.

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 behavior of conductors in the natural enviroment, so great care is taken to prevent these phenomena from reducing phase-to-phase spacing and causing faults.

Methods for calculating sag due to steady-state ice and wind loading were covered in Chapter 3. 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.

1.2.1 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 d_w has a 98% withstand voltage $V_{98\%}$ of $V_{98\%} = V_{50\%} + 3\sigma$, where σ represents the standard deviation of the withstand voltage of the air dielectric. Withstand voltage distributions (summarized by $V_{50\%}$ and σ) have been studied for many different environments. Figure 1.1 compares the insulation requirements for power frequency voltage (on contaminated insulators), switching surges, and lightening surges[3]. Insulators must be selected to withstand these transient voltages, as should phase spacing. The magnitude of lightening surge voltages

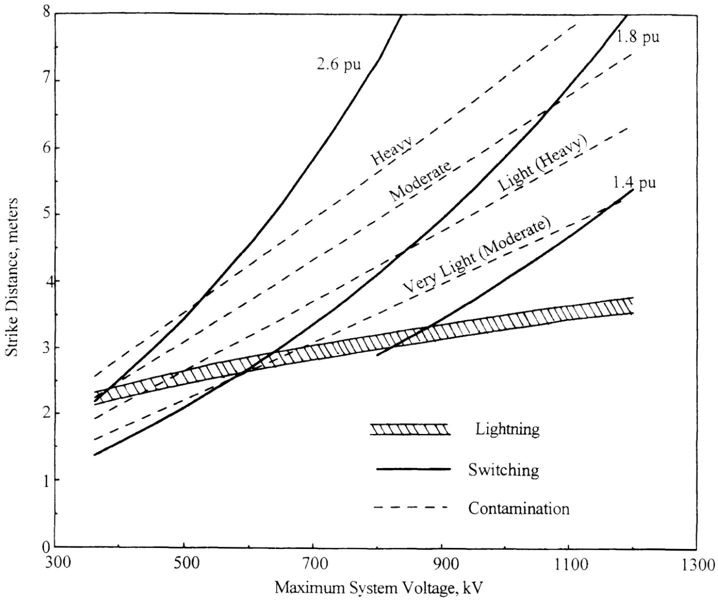

Figure 1.1: $V_{50\%}$ Insulation Levels for Power Frequency Voltage, Switching Surges, and Lightening Surges

can be modeled based on the electrical properties of the transmission line and protective systems. The same can be done with switching surges. Typically, these values will be described as a probability distribution, and calculated as described above. More on insulation requirements will be described in section **??**.

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 occuring 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 Figure1.2 [4] [5]. An air gap must have a withstand voltage greater than the maximum expected power frequency voltage V_p seen on a transmission line — typically, 1.05 V_p.

Figure 1.3 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 d_a over the spacing required to insulate against a peak power frequency voltage d_{pf}. 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.

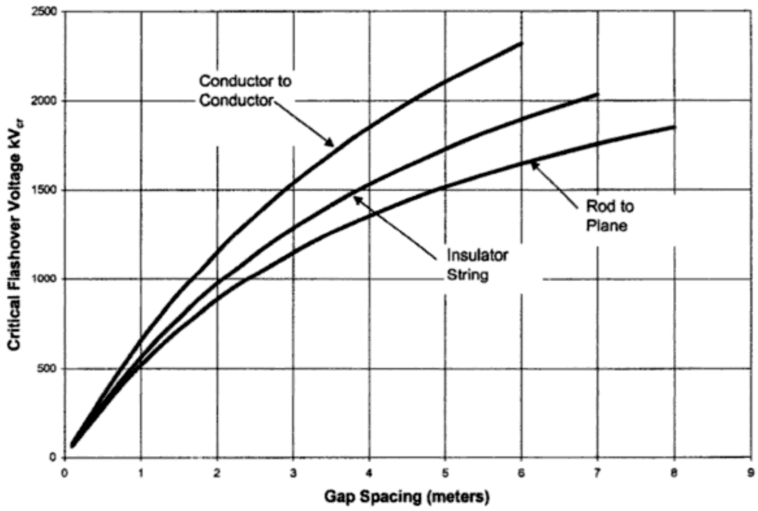

Figure 1.2: $V_{50\%}$ Critical Flashover Voltages

1.2.2 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 behavior will be significantly damped by the weight of the conductor itself.

Wind will exert pressure on a conductor, orthogonal to the conductor itself. For high-speed winds, that pressure can be estimated to be equal to [2]:

$$P = \frac{\rho}{2} V^2 \tag{1.1}$$

Where

P — Pressure, in Pa

ρ — Air density, in kg/m^3. Typically, around 1.225 kg/m^3

V — 5-minute average wind speed at conductor height, in m/s

Wind speeds should be selected to represent the highest wind speed expected over a period of time. From the pressure calculated in 1.1, the force exerted on the conductor per unit length can be calculated:

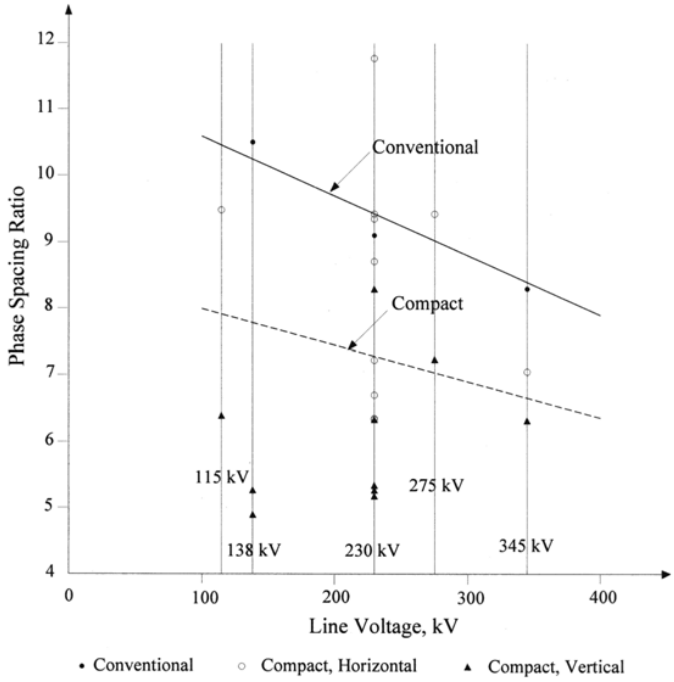

Figure 1.3: d_{pp} / $d_{98\%}$, for Traditional and Compact Transmission Lines

$$F_w = P\frac{d}{100}C_f, \tag{1.2}$$

where d is the diameter of the conductor in cm, C_f is a force coefficient (assumed to be 1.0 for conductors), and F_w is force per unit length, in N/m. 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 guarrantees 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 modeled 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 1.4. Blowout angle θ and blowout distance d_{bo} are calculated from:

$$F_w \cos\theta = F_m \sin\theta$$

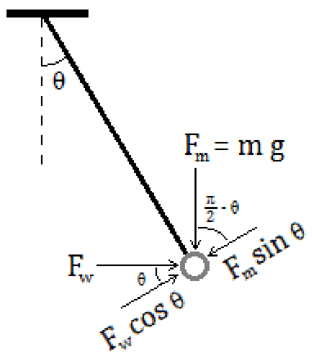

Figure 1.4: Blowout Pendulum Model

$$\frac{F_w}{F_m} = \frac{\sin\theta}{\cos\theta}$$

$$\theta = \arctan\frac{F_w}{F_m} = \arctan\frac{F_w}{mg} \quad (1.3)$$

$$d_{bo} = S\sin\theta \quad (1.4)$$

Where

F_w — Force exerted by wind per unit length, in N/m

F_m — Weight of the conductor per unit length, in N/m

m — Mass of the conductor, per unit length, in kg/m

g — Acceleration due to gravity, 9.81 m/s^2

θ — Blowout angle

S — Total sag distance of span, under given windloaded conditions, in m

More detailed models of conductor blowout can include the length, cross-section, and weight of insulators as well.

Example

A 200-MW transmission line with nominal voltage of 161-kV is constructed with ACSR 'Dove' 556.5-kcmil conductors. The sag distance of the conductor is 10-ft. Find the conductor blow-out for a wind speed of 50-mph, given:

$$d = 0.927in \quad (1.5)$$

$$w = 0.766lb/ft \quad (1.6)$$

The imperial version of 1.1 is:

$$P = 0.00256V^2 \quad (1.7)$$

$$F_w = P\frac{d}{12}C_f \tag{1.8}$$

Where

P — **Pressure, in** lbs/ft^2

V — **Wind speed, in** mi/hr

F_w— **Force due to wind, in** lbs

d — **Diameter of conductor, in** in

C_f— **Force coefficient, usually assumed to be 1.0 for stranded conductors**

$$P = 0.00256(50)^2 = 6.40lbf/ft^2$$

$$F_w = \frac{0.927}{12}6.40 = 0.494lbf$$

$$\theta = \arctan\frac{F_w}{w} = \arctan\frac{0.494}{0.766} = 32\deg$$

$$d_{bo} = 10\sin 32\deg = 5.4ft$$

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[6] [7]. This is consistant 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, it's 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 behavior. Research on this 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, Galloping

1.2.3 Right of Way

1.3 EM Considerations

Audible Noise, Radio Noise, Corona, EM fields

1.3.1 Phase Spacing

1.3.2 Insulation

1.4 Protection Considerations

Lightening, shield wires, arresters, etc.

1.5 Electrical Considerations

Reduced Reactance

1.6 Conclusion

$$ExampleEquation \tag{1.9}$$

Where

α — Description, in *units*

β — Description, in *units*

γ — Description, in *units*

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