PRACTICAL ASPECTS OF HARDWARE FOR COMPACT LINES

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1.0 Introduction

In recent years there has been an increased interest in the use of compact transmission lines due to environmental and economic factors. In general, measured EMF can be reduced by reducing the distance between phases in a compact transmission line. However, in designing a compact transmission line there are certain minimum electrical phase to phase and phase to ground clearances that must be maintained. These clearances are determined by minimum required phase to phase insulation, energized hardware size, mid span phase separation and maintenance requirements. If the spans are short, or mid span phase spaces are used, much of the minimum phase to phase spacing is governed by minimum insulation requirements. Further reduction in phase to phase spacing must be accomplished by minimizing the size of the energized hardware.

In the past, many transmission lines have been designed and constructed using standard hardware components with very little thought to minimizing hardware size or providing for future live-line maintenance. The size of standard hardware components is not critical for most EHV transmission lines. However, compact transmission lines will utilize insulator designs and geometries that do not lend themselves to standard yoke plates and hardware components. As to live-line maintenance, it could be argued that a compact transmission line will only be maintained de-energized. However, the experience of most utilities suggests that all transmission lines should be designed for live-line maintenance. In general, transmission lines that are not critical and can be taken out of service today, will be critical tomorrow.

The design of compact transmission lines will require a trade off between minimum phase to phase separation utilizing compact hardware designs, and the need for live-line maintenance considerations, articulation of the hardware and minimum strength rating of the hardware. This paper will discuss some of the practical aspects of hardware for compact transmission lines; however, many of the topics are equally applicable to EHV

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transmission lines [1, 2]. Some typical hardware designs and specific recommendations are presented that allow for minimum phase to phase separation and for efficient use of live-line maintenance techniques.

2.0 Insulator and Hardware Loads

Compact transmission lines will, most probably, utilize new insulator geometries and combinations of insulators. Any one insulator assembly may utilize both tension or suspension type insulators and post or strut type insulators. Both ceramic and nonceramic insulators may be used in the same assembly. In general the transmission engineer will need to analyze insulator and hardware loads of non standard insulator arrangements in order to minimize both insulator and hardware size.

Most new insulator arrangements can be made up from combinations of I-string, V-string and U-string insulator assemblies. This section will summarize the loads on I- and V-string insulators and show the steps required to calculate loads and displacements in a U-string insulator arrangement.

2.1 I-string and V-string Insulator Assemblies

The loads on insulators and hardware in I-and V-string insulator assemblies are easily calculated. Figure 1 shows resulting insulator loads, t_{AL}, and insulator swing, ϕ, caused

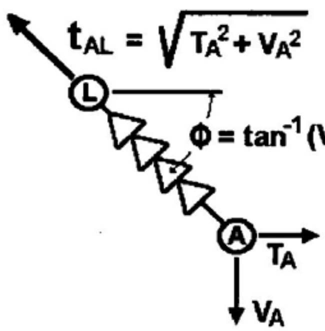

Figure 1: I-string insulator assembly.

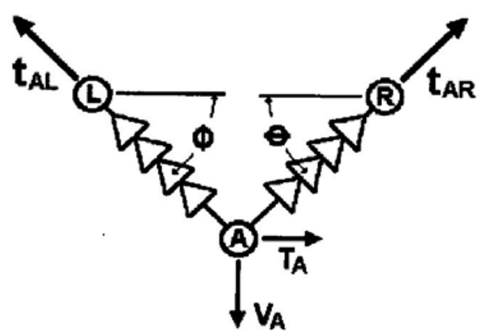

Figure 2: V-string insulator assembly.

by transverse, T_A, and vertical, V_A, loads on Phase A. Figure 2 shows those same transverse and vertical loads acting on Phase A supported by a V-string insulator

$$t_{AL} = (V_A + T_A \tan\Theta)/(\sin\Phi + \cos\Phi\tan\Theta) \qquad (1)$$

$$t_{AR} = (V_A - T_A \tan\Phi)/(\sin\Theta + \cos\Theta\tan\Phi) \qquad (2)$$

arrangement. Equations 1 and 2 give the resulting insulator loads from Phase A to the left insulator attachment point, t_{AL}, and the right insulator attachment point, t_{AR}. If both insulators in a V-string are tension only insulators, a V-string will become an

I-string if tension t_{AR} is equal or less than zero. If post or strut type insulators are used for the V-string assembly, the reaction t_{AR} in Figure 2 can be negative.

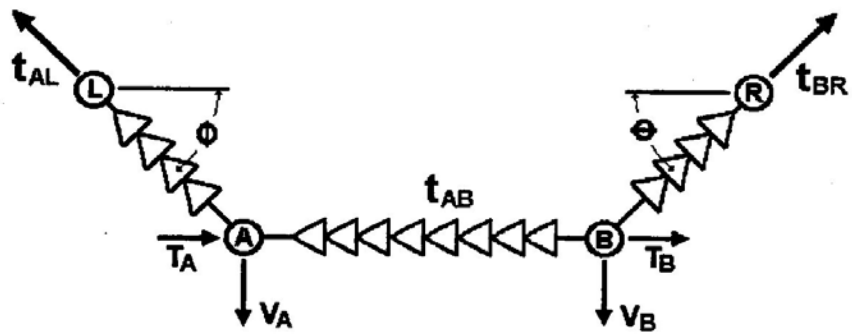

Figure 3: U-string insulator assembly

2.2 U-string Insulator Assemblies

A typical U-string insulator assembly is shown schematically in Figure 3. Unlike the V-string assembly, a U-string assembly will move and swing about its left and right attachment points, **L** and **R**, when acted upon by any transverse load (**T_A** and **T_B**) or a difference in vertical loads. This movement will result in a change in insulator geometry as shown in Figure 4. Note that in its initial position Phase **A** and **B** are separated by a horizontal insulator and hardware assembly of length l_{AB} resisting a tensile load of t_{AB}. Phase **A** is supported and insulated from its tower attachment point, **L**, by an insulator and hardware assembly of length l_{AL} resisting a tensile load of t_{AL}. Likewise, phase **B** is supported and insulated from its tower attachment point **R** by an insulator and hardware assembly of length l_{BR} resisting a tensile of compressive load of t_{BR}.

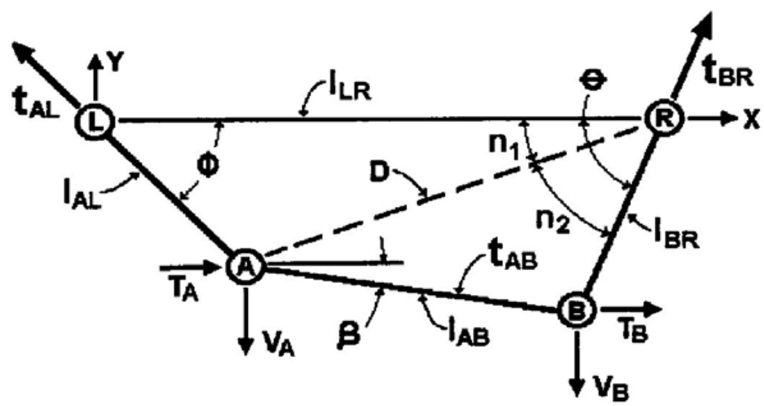

Figure 4: Motion of a U-string insulator assembly

In the design of a compact transmission line it is important to analyze the insulator movement in this U-string, which might result in insufficient electrical clearance. In addition, this insulator movement will result in an increase in the loads that the insulators and hardware must resist. In order to analyze this movement and resulting load distribution in the U-string assembly, it is best to write an iterative computer program to solve for the static equilibrium of the U-string assembly, modeling it as though it were a mechanical four-bar linkage [3].

For numerical calculations the following procedure is probably best:

1.Sum the forces in the X and Y direction at Phase **B**, assuming the initial geometry to be correct. Thus, the insulator loads t_{AB} and t_{BR} are determined as if Phase **B** were supported by a V-string.

2.Sum the forces in the X and Y direction at Phase **A** as shown in Figure 5 where the angle ϕ is calculated so that the sum of the forces is equal to zero. Thus, the X-component of t_{AL} is given in equation 3 and the Y-component of t_{AL} is given in equation 4. The new angle ϕ' is given in equation 5.

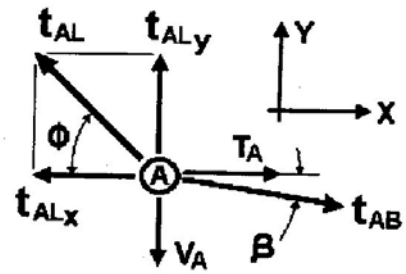

Figure 5: Forces acting on the yoke plate at phase A of the U-string assembly.

$$t_{AL_x} = T_A + t_{AB}\cos\beta \qquad (3)$$

$$t_{AL_y} = V_A + t_{AB}\sin\beta \qquad (4)$$

$$\Phi' = \tan^{-1}(t_{AL_y} / t_{AL_x}) \qquad (5)$$

3.If the difference between the initial angle ϕ and the new computed angle ϕ' from equation 5 is too large to stop the iteration process, then allow the U-string to move to a position which better approximates equilibrium by changing the initial angle ϕ. With this new angle ϕ compute the diagonal D of the quadrilateral (see Figure 4) using the cosine law in equation 6.

$$D^2 = l_{LR}^2 + l_{AL}^2 + 2\, l_{LR}\, l_{AL}\cos(\pi - \Phi) \qquad (6)$$

Next compute the angles n_1 and n_2 (see Figure 4) by further application of the cosine law as shown in equations 7 and 8.

$$\cos n_1 = (D^2 + l_{LR}^2 - l_{AB}^2)/(2D\, l_{LR}) \qquad (7)$$

$$\cos n_2 = (D^2 + l_{BR}^2 - l_{AB}^2)/(2D\, l_{BR}) \qquad (8)$$

From angles n_1 and n_2 compute the angle θ from equation 9 and compute the remaining geometry of the four-bar linkage. With this new geometry repeat steps 1 and 2 until the change in geometry is insignificant.

$$\theta = n_1 + n_2 \tag{9}$$

2.3 Combined I-, V- and U-string Insulator Assemblies

Using the equations and computational procedures of Section 2.1 and 2.2, a compact transmission line insulator and hardware assembly such as the one shown in Figure 6, can easily be analyzed. Table 1 gives the initial geometry of a compact transmission line similar to the one shown in Figure 6, and the geometry and insulator loads after two load

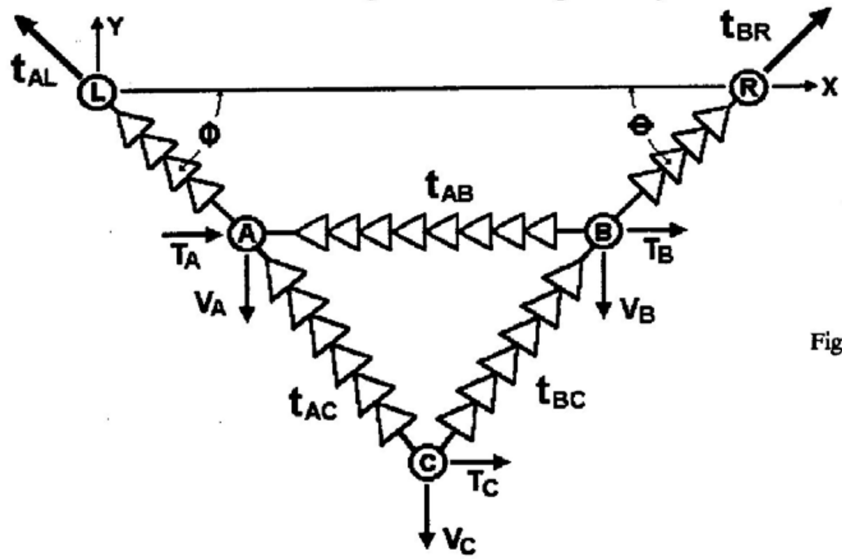

Figure 6: An inverted delta compact transmission line insulator assembly composed of I-, V-, and U-string insulator assemblies.

	INITIAL	CASE 1	CASE 2
LOADS			
$V_A=V_B=V_C$	—	3160	761
$T_A=T_B=T_C$	—	981	1700
TENSIONS			
t_{AL}	—	8622	5611
t_{AB}	—	4004	1889
t_{AC}	—	2875	1863
t_{BC}	—	709	0
t_{BR}	—	4942	120
GEOMETRY (x,y)			
L	0 , 0	—	—
R	157 , 0	—	—
A	42 , -42	43.5 , -40.4	54.7 , -23.1
B	115 , -42	116.5 , -43.4	123.1 , -48.8
C	78.5 , -105.2	77.4 , -105.1	121.3 , -53.0

Table 1

Loads, insulator tensions and movement of the inverted delta assembly shown in Figure 6 cases are applied. Note that for this initial compact transmission line geometry, post or strut-type insulators are required between the Phases **A**, **B** and **C**, in order to maintain electrical clearance under the heavy wind loading case 2.

3.0 Yoke Plate and Clamp Design

Standard yoke plates cannot be easily adapted to work with compact transmission lines. If minimum phase separation is required then special yoke plates should be designed.

The maximum loads acting on a yoke plate can be determined from the information presented in Section 2.0. From this information, and allowing for articulation of the suspension clamp, a yoke plate of minimal size can be designed which will resist failure due to bearing stresses, shear tear out, bending stresses or buckling. Figure 7 shows an example of such a specially designed yoke plate used at Phase **B** position of the compact transmission line shown in Figure 6. Note that all the loads, whether they are tensile or compressive, tend to have their resultant act through the conductor attachment point **B**. Therefore, since the sum of the moments about point **B** is equal to zero, the yoke will not rotate and thus will maintain the geometry of the compact transmission line.

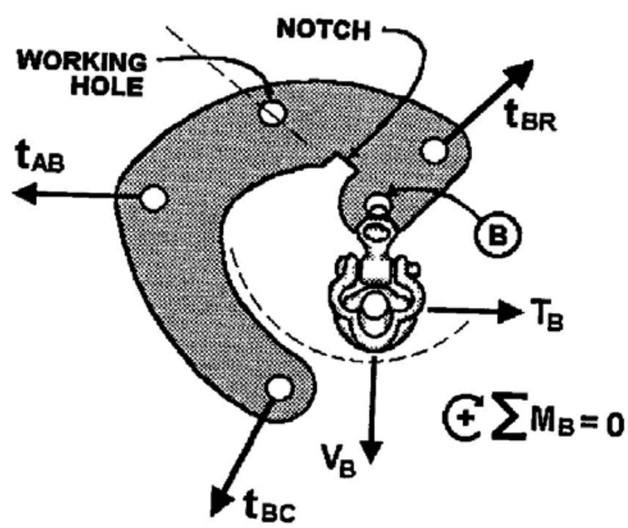

Figure 7: Forces acting on a specially designed yoke plate at phase B of Figure 6.

Maintenance holes, notches and rigging holes should be designed into the yoke plate. The working hole, located at the top of the yoke plate in Figure 7 allows a single pole strain carrier to lift the yoke plate at Phase **B**, up and to the left tower attachment point, **L**. Using an identical yoke plate at Phase **A**, allows that yoke plate to be lifted up and to the right tower attachment point, **R**. This removes any load in the insulator connecting Phases **A** and **B** and allows this insulator to be removed, using hot-stick techniques.

The notch in the yoke plate of Figure 7 allows the load to be removed from the insulator connecting Phase **B** to the right tower attachment point, **R**, using a two-pole strain carrier. These notches facilitate the placement of a two-pole strain carrier yoke plate and prevent the hardware yokes from moving or slipping on the strain carrier yoke. Clearance must be allowed for placement of these strain carrier yokes which are typically 5 inches wide and require a 1 inch wide and 1/2 inch deep notch in the hardware for proper seating.

The addition of these holes and notches during the fabrication of these yoke plates adds very little to the initial cost of the hardware since all the holes are normally drilled simultaneously and notches can easily be added to flame cut templates. However, substantial savings can be realized due to more efficient hot-stick maintenance procedures.

Standard suspension clamps are not recommended for compact transmission lines when minimum phase separation is required. One reason is that typical EHV suspension clamps require 30% to 40% less space then standard suspension clamps as illustrated in Figure 8. This reduced space also decreases the size and thickness required of the yoke plate shown in Figure 7, thus further reducing phase spacing. A second reason for using EHV suspension clamps is that the electric fields between phases can be quite high for a compact transmission line design. Therefore, the possibility of corona emanating from the U-bolts and sharp corners of standard suspension clamps is eliminated.

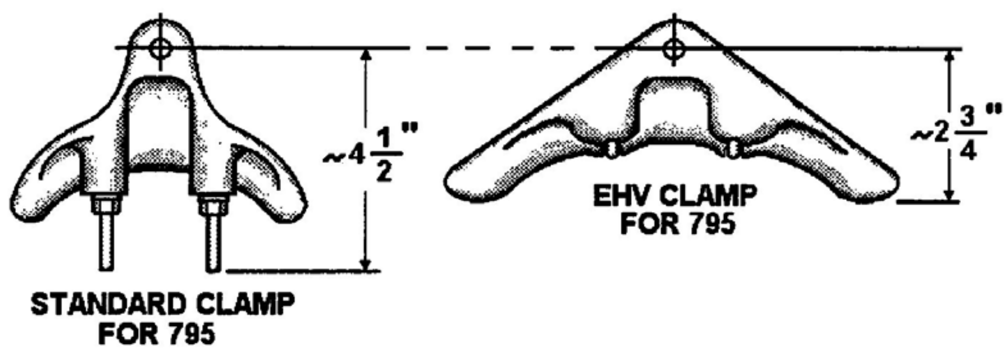

Figure 8: Comparison of standard and EHV suspension clamp dimension.

When specifying new designs of yoke plates, or when specifying any hardware, testing and quality assurance of these designs is imperative. Design tests should be performed to insure not only clearance and articulation of the complete assembly, but also mechanical strength. Clearance between insulators and hardware prior to installation of conductor should also be checked. Once these design tests have been verified, routine quality assurance testing of the hardware can be performed in accordance with the proposed new IEEE standard C135.61 on "Testing of Transmission and Distribution Line Hardware" [4].

4.0 Connecting Hardware

The type of connecting hardware between yoke plate and insulator and between insulator and tower will depend on the type of insulator used (i.e. ball and socket suspension, oval eye polymer suspension, pin and clevis suspension or clevis-clevis strut or post, etc.). In general, good articulation at the joint between insulator and hardware is important, since many hardware failures have occurred when the hardware becomes jammed and is not allowed to articulate during unusual loading conditions.

Consideration should also be given to live-line maintenance considerations at this connecting hardware.

4.1 Insulator-Yoke Plate Connecting Hardware

The best articulating joint for a polymer suspension insulator and a yoke plate is an oval-eye to an anchor shackle which connects to the yoke plate. However, since bare hand techniques generally cannot be used with compact transmission lines due to the close phase spacing, the use of an oval-eye to anchor shackle connection between insulators and yoke plates is not recommended.

Direct bolting of strut or post type insulators to yoke plates may be desirable when compressive loads are encountered; however, removal of these bolts using hot-sticks will be difficult.

Pin and clevis joints for tensile or compressive loads, and ball and socket for tensile loads, seem to be the best compromise between articulation and live-line maintenance requirements.

To aid in live-line maintenance procedures, shoulder live-line extension links connecting insulators and yoke plates may be used. However, if minimum phase separation is required, it should be noted that each one of these links will add a minimum of 5-1/2 inches in hardware length to any standard socket-clevis or clevis-clevis connection [5].

4.2 Insulator-Tower Connecting Hardware

Many of the same comments made in Section 4.1 also apply to the connecting hardware between the insulator and the tower connecting plate. However, the use of oval-eye to anchor shackle is ideal for this location. Directly connecting the suspension insulator to the tower plate is not recommended as articulation is limited and removal during live-line maintenance is more difficult. If space allows, the use of shoulder live-line extension links is recommended as they lend themselves to a two pole strain carrier, which is used to lift the yoke plate at the notch location, shown in Figure 6.

Additional working holes should be added to the tower attachment plate in order to locate and control maintenance loads on the tower. Without these working holes towers have been damaged due to improper rigging (refer to IEEE Standard 951, "Guide to the

Assembly and Erection of Metal Transmission Structures", Section 4.1 on "Construction and Maintenance Loads" for further discussion of tower working holes)[6].

5.0 Conclusion

The practical aspects of hardware design for compact transmission lines can be summarized as follows:

- Be creative in the geometic design of insulator assemblies that support the conductor for a compact transmission line.
- Using techniques described in this paper, analyze the actual loads and displacements that can occur in these new insulator-hardware assemblies.
- If minimum phase separation is required, design the yoke plates and hardware for these loads. Don't assume standard hardware can be adapted without sacrificing phase separation.
- Provide articulation at the interface and joints between insulators and yoke plates, and insulators and towers.
- Provide means in the yoke plate and hardware design for future live-line maintenance of the compact transmission line even if current plans call for only maintaining the line while de-energized.

References

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6.ANSI/IEEE Std.-951-1988, "IEEE Guide to the Assembly and Erection of Metal Transmission Structures".