Overhead Conductor Motion During Short Circuits

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***Abstract* - It is widely recognized that all conductors experience motion when subjected to the passage of high currents. This is due to the forces exerted by the magnetic fields produced by current flow in the conductor. This paper examines factors which affect the degree of conductor motion in overhead lines. Several cases are examined to illustrate potential systems design trends which may affect distribution system reliability when conductor motion parameters are ignored. A finite element model is used to estimate the amount of conductor motion under various conditions. It is demonstrated that conductor motion can have an adverse impact on system reliability and power quality.**

I. INTRODUCTION

The majority of overhead electric distribution conductors are suspended between support structures and consequently have sag which is a function of conductor weight and the tension in the conductor. In any system the conductor position at any point is affected not only by the force of gravity and conductor tension, but also by wind pressure and the magnetic forces exerted by the currents in the conductors. While these inter-conductor forces have minimal influence under normal load currents (<1,000A). These forces can introduce perceptible motion into suspended conductors under fault current conditions where currents may approach or exceed 10,000 amperes.

The factors that influence dynamic conductor motion include the following:

- Conductor Unit Weight (lbs. per ft.)
- Fault Current in Conductor (amperes)
- Duration of Fault Current (seconds)
- Conductor Spacing
- Conductor Tension & Sag
- Mechanical Damping

Since most overhead distribution conductors are uninsulated, a natural consequence of excessive conductor motion is contact and arcing between conductors operating at different potentials. These can be either phase conductors or neutral conductors.

It is known that the magnetic forces between conductors carrying high currents act to repel the conductors one from another. Thus, parallel conductors will initially swing away from each other. However, having rotated to a position of higher potential energy, they will tend to swing past their original at-rest position when currents are removed. This is due to inertia. Conductors may well come into contact with each other if the conductors are spaced at a distance less than half of the horizontal component of the displacement during the short circuit event. While the circuit will have been deenergized as the conductors reach their maximum displacement; if the circuit protective equipment has reclosed during the return swing time, the contact will result in a new fault event. Since the new fault will be at a location closer to the source than the initial fault location, the second (and subsequent) fault currents will be higher in magnitude, thus creating conditions conducive to other conductor swing events of even greater magnitude closer to the power source. The overall result is the possibility of additional operations of protective devices if there is conductor contact at the time of reclosing. Also, the potential horizontal displacement of the conductors may introduce additional right-of-way requirements in areas with minimal wind loading conditions.

The importance of acknowledging conductor swing under short-circuit conditions is amplified by several trends in the electric utility industry. These include:

- Larger substations that increase available fault currents.
- Closer conductor spacing in order to minimize aesthetic impact of overhead lines.
- Increased customer sensitivity to momentary interruptions and voltage dips.
- Increased conductor sag due to the use of larger conductors while maintaining distribution tension limits.

All of these factors have an impact on the effects of short-circuit currents on conductors. Conductor motion is proportional to the magnitude of the fault current. Conductor motion is inversely proportional to the distance between the conductors. Conductor sag is directly proportional to the unit weight of the conductor if the tension is held constant.

II. BASIC EQUATIONS

The factors that impact the amount of conductor swing are all well documented within the electric utility industry. These include the basic amount of sag under static conditions, the amount of force applied to a conductor by current flow, and the horizontal displacement of the conductor under a lateral force. What has been seldom been considered in routine distribution line design is the combined effect of these phenomena under short circuits.

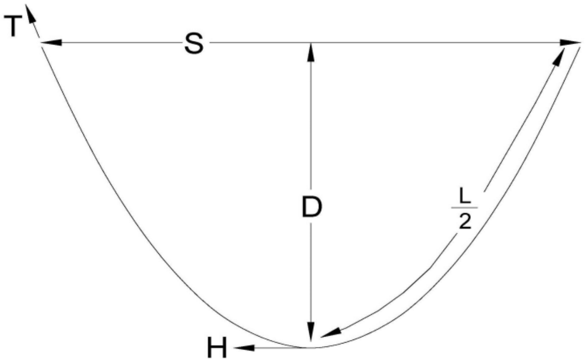
- Catenary Shape - The sag in a conductor is defined by the characteristics of a catenary. See Equation 1a. For most calculations this can be simplified to the form of a parabola. See Equation 1b.

$$y(x) = \frac{H}{w}\left[\cosh\left(\frac{wx}{H}\right) - 1\right] \quad \text{(Equation 1a)}$$

$$D = \frac{wS^2}{8H} \quad \text{(Equation 1b)}$$

Where D is the sag of a level span, S is the span length, H is the conductor tension and w is the unit weight of the conductor. See Figure 1. [3,4,6]

FIGURE 1 - CATENARY PARAMETERS

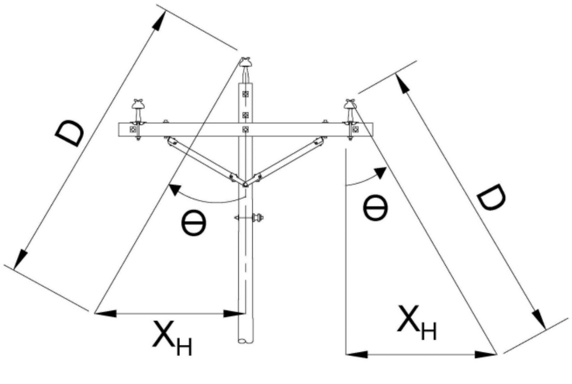


- Magnetic Force Between Conductors - In 1820, Ampere demonstrated that forces exist between two conductors that are carrying current. In the case of two parallel conductors carrying symmetrical short-circuit currents the average force between the conductors is found by using the results of Equation 2.

$$F = \frac{4.49\, I^2 10^{-8}}{d}\; lb/ft \quad \text{(Equation 2) [2]}$$

Where F is the force in pounds per foot of conductor, d is the spacing between the conductors in feet and I is the symmetrical short-circuit current.

FIGURE 2 - CONDUCTOR SWING



- Conductor Displacement - Methods of determining wind displacement of overhead conductors is well established. Assuming that the conductor is cylindrical and the wind is perpendicular to the axis of the conductor, the force imposed by the wind is…

$$F_H = 0.00256\left(\frac{d}{12}\right)(V_w)^2 \quad \text{(Equation 3) [4,8]}$$

where:

d = *conductor diameter, in*
V_w = *wind speed, mph*
F_H = *horizontal wind force, lbs/ft*

The result of wind is the angular rotation of the catenary according to Equation 4a. See Figure 2. This results in the horizontal displacement of the low point of the sag according to Equation 4b.

$$\theta = tan^{-1}\frac{F_H}{W_c} \quad \text{(Equation 4a) [3,4,6]}$$

where:

W_c = *conductor weight per unit length, lbs/ft*

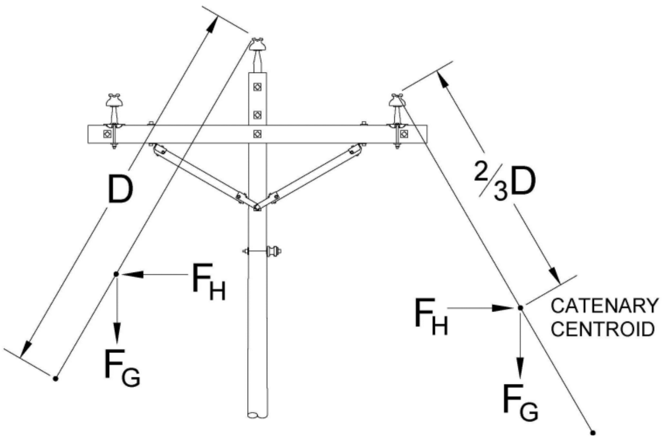
$$X_H = (D)\,(sin\theta) \quad \text{(Equation 4b)}$$

where:

X_H = *horizontal deflection at midpoint of span, ft*
D = *midpoint sag of conductor at specified wind and conductor temperature, ft*

Where X_H is the displacement at midspan and D is the midpoint sag of the conductor at the time of the fault.

FIGURE 3 - FORCES ON CONDUCTOR



- Development of Swing Envelopes - In order to determine the conductor displacement under short-circuit conditions, an analysis is made of the forces acting upon the conductor(s). These forces are illustrated in Figure 3. The horizontal force is the magnetic repulsion between the conductors and the gravitational force (weight of conductor) is acting vertically. For a straight conductor these forces would be applied at the conductor, but for a suspended conductor in the shape of a catenary, these forces are applied at the centroid of the catenary (2/3 D) in order to calculate the effective rotational force.

Given that conductor swing is a highly dynamic phenomenon and the magnetic forces are inversely proportional to the distance between the conductors, a finite element approach was used to determine the position of the conductor as it progressed in time. This approach was used and experimentally verified in the EPRI *Transmission Line Reference Book, 115-138kV Compact Line Design* [2]. EPRI found that time increments of 100 samples per second gave less than 1% error in maximum conductor deflection. The calculation time increment used here was 0.01 seconds. For high currents that produce high conductor velocities, it may be desirable to use smaller time increments in calculating the conductor motion.

It is assumed that the conductor length within the span remains the same even though the forces acting on the conductor may cause some elongation. Likewise, it is considered that the conductor temperature remains constant since the thermal time constant of the conductor is large relative to the duration of the short circuit current. Also, mechanical damping within the conductor was considered negligible during the first displacement.

III. NESC REQUIREMENTS

NESC Rule 235B.1.b includes requirements for horizontal separation between conductors. Rule 235B.1.b and Tables 235-2 and 235-3 relate the allowable clearances to the conductor size and the amount of sag in the span. This section of the Code language existed prior to the 1960's. Since that time the electric systems commonly in service have evolved greatly in capacity and characteristics. It is probable that this Code section was principally intended to address the problem of conductor contact precipitated by wind. [3] Section 235 of the NBS Handbook 81 (1961), predecessor to the NESC, contained equations and tables defining "Minimum horizontal separation at supports between line conductors of the same or different circuits". [9] Separation values given in these tables are essentially the same as those currently specified in the 2012 NESC. Review of the NESC Interpretations shows that there have been no questions raised about the applicability of these horizontal separation tables to distribution (or transmission) line design. This is in spite of the fact that line designs have tended to become more compact and typical distribution short-circuit forces have increased by an order of magnitude between 1960 and 2015, particularly for utilities with long radial circuits.

Motion induced by wind is a different problem from motion induced by the magnetic forces associated with short circuit currents. Wind forces act in the same direction so conductors have some degree of motion in the same direction, thus reducing the probability of contact. Also, wind forces are more gradual in nature and are more sustained than short-circuit forces.

Here it is important to recognize that the NESC is a "…standard of safe practices." (Rule 010.C) instead of a "design specification" (Rule 010.D). Factors that determine good system design in many cases exceed the requirements to produce a design that is acceptable solely for public safety criteria.

IV. CASE STUDIES

A. 'Slack Spans'

Most utilities designing according to Rural Utility Service (RUS) guidelines will seldom purposefully install spans with significantly reduced tension. However, certain space limitations in congested areas can lead to consideration of "slack spans" as a method of reducing guying requirements. Such a practice can introduce the possibility of contact between conductors. This is because the reduced tension increases sag and thereby allows greater conductor displacement than similar installations with normal design tensions. Also, even "slack spans" with reduced guy tension can cause long-term creep of the supporting poles and this will increase the conductor sag beyond that which was present at the time of installation.

As an example, consider a 50' span of 477 AAC conductor with 5' of sag. This may be extreme, but similar conditions have been observed in some urban areas. The theoretical conductor tension with this amount of sag will be approximately 30 lbs compared with a 'normal' sag of 0.23' (3") if the conductor is at a 'normal' line tension of 2000 lbs that is often used in distribution lines. Raising the tension to 50 lbs will result in sag of 2.8' (34"). NESC Table 235-3 requires 22" of horizontal spacing for a conductor of this size with 5' of sag. Similarly, the horizontal clearance requirement for 3' of sag is only 18". In both cases the NESC minimum requirements are clearly inadequate to prevent conductor contact if swing even approaches the magnitudes expected under short-circuit conditions.

B. Compact Construction

All utilities are faced with demands to reduce the amount of space occupied by overhead lines. These demands range from the aesthetic to the lack of available space for pole lines near substations. A natural result of these pressures is to reduce clearances between energized conductors; either through the use of armless construction or the installation of more conductors (Figure 4B) on each crossarm.

C. Increased Short-Circuit Currents

As load density has increased, utilities have typically installed transformers with higher capacity in order to optimize substation economics. The increased substation transformer size along with increased conductor sizes have produced higher available fault currents on distribution circuits. In the 1960's rural utilities often had 7500 kVA transformers served from 35 kV subtransmission lines. Today, as population density increases and commercial loads become more prevalent, similar areas may be served by 20 (or 30) MVA transformers served by 115 kV transmission lines. For 7.2/12.5 kV systems this increases maximum available fault currents from <3700A to >11,000A at the substation bus. During this time distribution circuit conductors have increased from #4 ACSR to 336 kcmil - or even 556 kcmil ACSR. The lower impedance of the distribution circuit conductors has brought high fault currents to an even greater area of the distribution system.

D. Multiple Circuits on Pole Line

Almost all electric utilities encounter locations where multiple circuits must be accommodated on a single pole line. Typical of this is RUS DC-C1 (Fig. 4B) where two circuits are supported on two crossarms. Another example with similar spacing is RUS C9 (Fig. 4A) where both the phase and neutral conductors are supported on a single arm. Both of these configurations introduce another dimension to the problem. This is the possibility of a short circuit between two conductors resulting in the involvement of a third conductor, either on the same circuit or on a previously uninvolved circuit.

FIGURE 4A - RUS C1

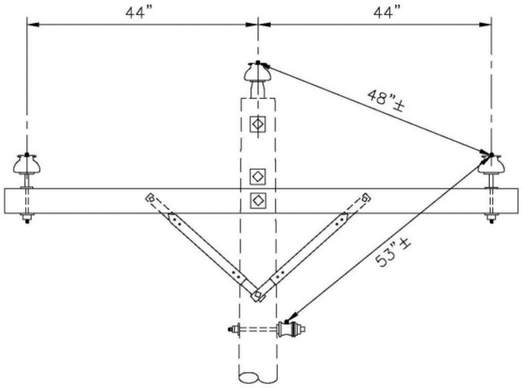
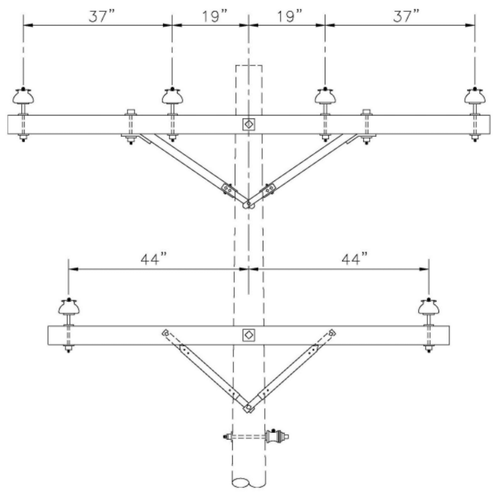


FIGURE 4B - RUS DC-C1



E. Increased Conductor Sag Under Load

While conductor sags most often discussed are those that are present during installation, it is also important that we consider those 'final' sags that exist after creep and those sags that are present when the conductor is operating near rated capacity. Examples of various conductor sags for a 250' span at various temperatures are found in Table 2. The increase in sag due to the conductor creep is relatively minimal, but creep plus the thermal effect of load currents is much more significant.

It is important to recognize the conditions that are most often used to determine the ampacity of conductors in most reference books. These are commonly for a conductor operating in an ambient temperature of 25°C with a 75°C conductor temperature. It is assumed that there is a wind of 2 FPS perpendicular to the conductor. Many times, particularly during summer peak loads, conditions are much different. The most common difference is the ambient temperature which often approaches 40°C (104°F). This alone can reduce the conductor ampacity by 20% if the 75°C conductor temperature limit is observed. Another very important factor is the wind direction relative to the conductor. See Table 1 for a comparison of ampacities by relative wind direction. All of these factors are important because they affect the conductor sag; and conductor sag is the most important factor in evaluating the probability of contact under short-circuit conditions.

Table 1

Conductor Ampacity				
Wind Angle	**Book***	**90°****	**45°****	**0°****
1/0 ACSR	243	198	182	121
4/0 ACSR	366	294	271	180
336 ACSR	519	419	386	262
556 ACSR	711	571	526	369

- All values at 75°C conductor temperature with 2 FPS wind.

* 25°C Ambient
** 40°C Ambient

F. Delayed Clearing Times and Reclose Times

Conductor motion is dependent not only on the magnitude of the short-circuit current, but also on its duration. This is because the horizontal swing of the catenary raises the potential energy of the conductor; thus the total motion is a function of the force and the time that the force is present. With high fault currents on typical systems, the first protective device operation will clear the fault in as little as 6 cycles (0.10 seconds). However, subsequent operations of a feeder recloser may have delayed clearing in order to coordinate with downstream devices. During these delayed operations clearing may be closer to 0.2 seconds for fault currents on the order of 10 kA. For faults of approximately 3 kA, durations will be closer to 1.0 seconds.

The reclosing times of distribution circuit protection equipment is a consideration, particularly in the analysis of suspected conductor clash events. First, the subsequent faulting of two initially faulted conductors at a second location will occur if the circuit is reenergized at a time when the two conductors have swung past their at-rest position and are in contact. Second, if the circuit is reenergized when the initially faulted conductors have returned to their initial post-fault swing point while the original fault still exists, the reenergization may impart additional energy to the conductor swing and further increase the magnitude of the swing. This can bring about a problem that previously had not existed if conductor clearance was adequate to accommodate the first swing caused by the initial fault.

G. Improper Conductor Installation

While installation specifications will call for particular sags, it is not unusual to find that the conductors have been installed at a lower tension. This produces sags that are greater than those envisioned during the design process. For purposes of discussion, Table 2 gives the sags associated with various conditions for conductors installed with 75% of the design tension. This can have a marked effect on the probability of conductor clash. While this may be considered by some to be unusual, we have encountered situations where the sag was double the value that would have existed if the reduced design tension of 2000 pounds had been used for 556.5 kcmil ACSR conductor.

Table 2

Typical 250' Span Conductor Sag - (FT.)

Conductor	Design	60°F Initial #	90°F	167°F	75% - 60°F Initial #	90°F	167°F
1/0 ACSR	1243	910	2.46	3.80	682	3.11	4.34
4/0 ACSR	2000	1394	3.00	4.33	1046	3.57	4.84
336 ACSR	2000	1172	4.09	6.02	879	4.69	6.48
556 ACSR	2000	1149	5.33	6.98	862	6.43	7.83
556 ACSR	3000	1812	4.22	6.12	1360	4.50	6.34

V. RELIABILITY AND PQ EFFECTS

A primary goal of a properly coordinated distribution system is to isolate the smallest area required to clear a fault. Also, the system should deliver the highest level of power quality that is practical under the conditions imposed by surrounding conditions. Conductor contact due to motion during short circuits can adversely affect system power quality by several means. First, unnecessary breaker operations can occur due to conductor clash on the source side of the initial fault. Given the right conditions of conductor sag and timing of the swing, the protective devices will have to operate to clear faults upstream from the initial fault site. This will mean an unnecessary momentary interruption to all customers on the circuit.

Second, each conductor contact event will produce a voltage dip on the substation bus that is serving the affected feeder. The magnitude of this dip will be a function of the fault current and the available fault MVA at the bus. Each subsequent contact, even if self-clearing, will produce additional voltage dips. Since the conductor sag is a relatively permanent condition, similar results will occur to the same customers for faults on the feeder. This repetition of momentary outages and voltage dips will exacerbate negative customer response.

VI. RESULTS

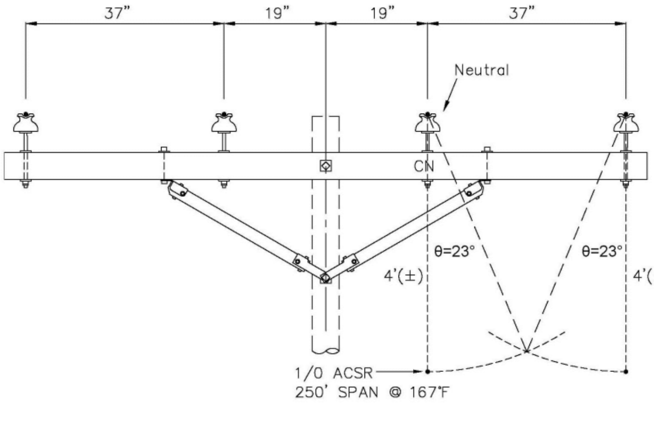
It is found that conductor separations that have served well for wind displacements can result in conductor contact following downline fault current events. While these contacts can be when the conductors have been deenergized by feeder breakers, there is the previously mentioned possibility of a subsequent fault if the feeder protection equipment recloses while the conductors are in their maximum rebound condition. Also, the faulted conductor may contact an energized conductor of an adjacent phase or circuit.

Calculations were performed for a variety of common conductor spacings. Fault currents of 3 kA for 58 cycles and 10 kA for 10 cycles were considered. A typical span of 250' was considered.

It was found that with an initial spacing of 37" a 1/0 ACSR conductor passing 3 kA for 58 cycles would displace 27" for a normal sag condition at 90°F, but would swing 45" if the conductor was initially installed at 75% of ‘normal’ and the conductor temperature was 167°F. This later condition would clearly produce conflict. A larger conductor such as 336.4 kcmil produced similar results.

When the conductors were subjected to a fault current of 10 kA for 10 cycles, the smaller conductors such as 1/0 ACSR through 336 ACSR achieved an angular displacement of approximately ninety degrees. In other words, they stood straight out (horizontal). Only larger conductors, such as 556.5 kcmil ACSR had displacement angles of less than ninety degrees, but the horizontal displacement varied from 57" to 73" at the evaluated sag conditions and temperatures. Of course, this too would produce conflict with only 37" of separation at the support structure.

FIGURE 5 - CONDUCTOR CONFLICT FOR A C9 STRUCTURE



VII. CONCLUSIONS

- Consider conductor temperature under load currents when determining maximum sags.

- Consider maximum operating sags and available short circuit currents when evaluating allowable span lengths, design tensions, and conductor spacing.

- Include measurements of actual conductor sag/tension during inspections of conductor installations.

- When investigating the occurrence of apparent miscoordination, consider the possibility of conductor clash on the source side of suspected fault locations.

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