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Determining Crossing Conductor Clearance Using Line-Mounted LiDAR

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SUMMARY

Maintaining proper transmission line clearance is required by the North American Electric Reliability Corporation (NERC). Locations where two lines cross or are co-located along a common right-of-way pose a difficult monitoring challenge: determining the clearance between the crossing lines. While the National Electric Safety Code details what these clearances should be and how they should be estimated based on a variety of criteria, these calculations do not provide confirmation of actual clearance or of the clearance itself. This becomes particularly important when the loading characteristics of the crossing lines vary significantly, or if future system changes may result in unpredictable clearances. In this case the sag characteristics of each line cannot be assumed to result in a consistent clearance value, as each line may be loaded differently as they are often on different circuits. The spatial difference of the lines can also result in different wind levels and a difference in the rate of cooling of the conductors.

ENMAX, a utility located in the Province of Alberta in Canada, faced this situation where a 138kV transmission line with Curlew conductor is located above a 25 kV distribution circuit using Hawk conductor for a distance of approximately 9.3 km. The pending energization of a new local 800MW generation source made knowledge of the clearance between the two circuits more critical as the additional generation will change power flows and result in very different load profiles on the 138kV transmission circuit.

ENMAX installed four transmission line conductor monitors containing built-in downward-looking LiDAR units to provide the line-to-ground clearance of each line. The difference in the line's clearances-to-ground provided clearance between the two circuits. The paper discusses ENMAX's situation, the operational characteristics of the monitors, their installation, the communication method used to collect the measurement information and pass it back to EMS, an algorithm used to filter out bad data caused by motor vehicles passing under the lines, and operational experience to date.

KEYWORDS
Clearance, LiDAR, conductor monitor, line crossing, conductor crossing, line clearance, dynamic line rating

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1. INTRODUCTION

Maintaining proper clearance-to-ground for transmission lines is a requirement of utilities by the North American Electric Reliability Corporation (NERC). While transmission line profiles are kept and maintained by utility engineering departments, and validated by periodic LiDAR measurements from helicopter or ground based measuring devices, these methods capture only point-in-time snapshots of clearance. One situation which is peculiarly problematic is when two lines cross or are co-located along a common right-of-way. In this case it is important to not only measure the clearance-to-ground of the lowest line, but also the clearance between the closest adjacent conductors of the two lines.

ENMAX, a utility located in the Province of Alberta in Canada, faced this situation where a 138kV transmission line is located above a 25 kV distribution circuit for a distance of approximately 9.3 km. The need to know, in real-time, the clearance between the two circuits was to become more critical when later in 2015 ENMAX's Shepard Energy Centre comes on line, bringing 800MW of additional power generation to the area[1].

2. CROSSING LINES; THE ISSUE OF CLEARANCE

The required clearances between crossing transmission lines of various voltages are well documented. In North America, Sections 233 and 235 of the National Electric Safety Code (NESC) [2] details the clearance requirements for crossing lines mounted on different supporting structures and the same supporting structures respectively. Examination of these sections highlights various issues that underscore the complexity of determining clearance:

- Conductor characteristics
- Ambient temperature and wind assumptions (for conductor movement)
- Insulator and structure deflection
- Sag, which itself is a function of conductor temperature, wind speed (for cooling), solar radiation, ice loading, etc.
- Application of various safety factors and configuration factors

Most if not all of these issues are also common to determining conductor thermal behavior as documented in the IEEE 738 [3] standard and the CIGRE 207 [4] brochure. Dynamic line rating (DLR) applications all depend on being able to accurately determine conductor clearance to what is below, whether in real-time or forecasted.

For both dynamic line rating and crossing conductors, "clearance-to-something" is the real issue. Both of the dynamic line rating standards and the NESC depend upon essentially a double estimation; the computation of conductor sag and the subsequent use of that parameter to estimate clearance. Sag is a value that is distinctly different than clearance. Sag is essentially the droop of a conductor below the straight line drawn between its two endpoints. Variables that affect sag:

- Conductor temperature and all that affects it; current, solar radiation, cooling associated with wind, the thermal insulating effects of ice and snow, etc.
- The location of the endpoints; insulator swing and tower movement from wind and conductor expansion/contraction, the weight effects of ice and snow loading, etc.

And yet sag does not give clearance, which also depends on the location of what it beneath; ground, snow cover, vegetation growth, and human activity (construction of buildings or vehicles).

The difficulties associated with accurately determining and designing for proper clearance between conductors is underscored in one widely distributed report that for one utility, fully 60% of all documented transmission clearance issues were the result of distribution crossings [5].

Here, the problem facing ENMAX was particularly challenging:

- The transmission and distribution lines had very different loading profiles.

- After the Shepard Energy Centre is on-line, the 800MW of additional power generation in the area would change power flows and result in very different load profiles on the 138kV transmission circuit than before.
- Again, after the Shepard Energy Centre is on-line, identified system contingencies could result in greatly increased conductor sag.

Since clearance is what ultimately matters, ENMAX chose to approach the potential problem with the co-located 138kV and 25kV lines by actually measuring the clearance between the lines in real-time.

3. CONDUCTOR MOUNTED LiDAR

To accomplish the required real-time direct conductor clearance, ENMAX chose to use a novel conductor mounted monitor called the TLM® conductor monitor. This device provides a complete picture of conductor behavior including actual conductor clearance-to-ground, conductor temperature, line current, and vibration. The TLM monitor directly provides accurate, actionable, clearance-to-ground distance. See Figure 1.

Figure 1: TLM Conductor Monitor

Figure 2: Location of LiDAR measurement taken from installed conductor monitor

The distance of the nearest object to the conductor is measured using an on-board LiDAR (i.e., Light Detection And Ranging) sensor providing a highly accurate (+/-0.3% at 40m) line clearance measurement regardless of tower or insulator motion, varying span lengths, or other line conditions [6]. See Figure 2.

The particular application need facing ENMAX required knowledge of the clearance between the co-located138kV and 25kV lines along line for a length of 9.3km. The sensor's LiDAR unit performs a measurement sweep perpendicular to the conductor as part of its method to correct for conductor rotation due to heating, conductor swing, and to adapt to under build and undergrowth. However, this sweep does not allow for the accurate measurement from the 138kV line directly to the 25kV line below; the 25kV conductor presents too small of a target. To address this situation, it was decided to mount a sensor in the lowest phase of the 138kV line and the nearest phase of the 25kV circuit. See Figures 3 and 4. Measurements would then be taken from each conductor to ground, with the difference between the two measurements being the clearance between the conductors.

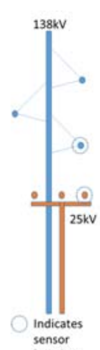

Figure3 (left): Photo of parallel 138kV and 25kV lines

Figure 4 (right): End view perspective

4. INSTALLATION AND COMMISSIONING

The initial project involved the installation of two TLM monitors each in two locations, for a total of four TLM monitors. Being pilot installations, the locations were chosen by ENMAX based on ease of access and proximity to the substation in which the communication gateway was installed, eliminating the need for any repeaters. Both spans were along the same straight right-of-way, so both spans were exposed to similar conditions. The spans were 115m and 107m in length. Even though the two sites were physically close, the presence of a small body of water resulted in a 5km drive between the installation sites. The monitors were installed using bare hand, live line installation methods. See Figure 5. The total elapsed time from arrival on site of the contractor crew to their departure was four hours. Figure 6 shows one set of the TLM conductor monitors immediately after installation.

Figure 5: Live line installation of sensor

The monitors are self-powered from the magnetic field associated with the line's current. Closing the clamp-style monitor body energizes the power supply charging circuit. This allowed the monitors to immediately begin communicating via built-in 915 MHz mesh radios to each other, and ultimately to a rack-mounted communication gateway that had been previously installed in a nearby substation. The communication gateway was set up to communicate to ENMAX's SCADA system via DNP 3.0 protocol. The mesh radios allow direct communication from one TLM monitor to the next at distances up to 2km, depending upon terrain. Because of the proximity of the four monitors, only one communication gateway was required to collect the data and interface with ENMAX's SCADA system. Note that up to 100 TLM monitors could be used with one communication gateway.

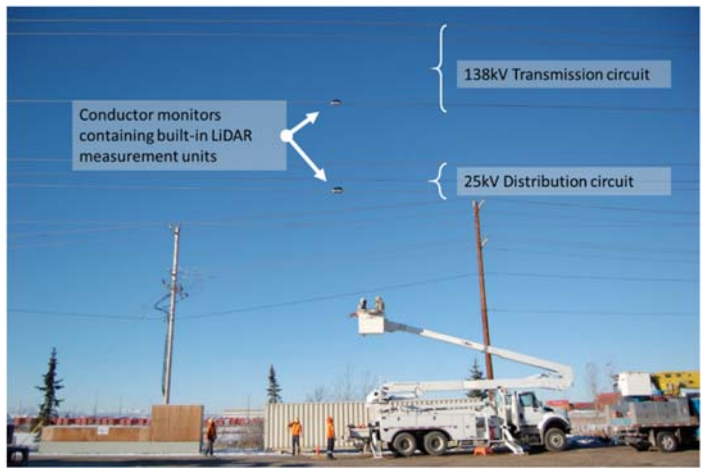

Figure 6: Installation of two line-mounted LiDAR measuring units on co-located transmission and distribution circuits

5. TRAFFIC ISSUE AND RESOLUTION

A site survey was completed before the installation. Figure 7 shows the environment around the line and where the conductor monitors would be installed. The lines are adjacent to a fairly busy light industrial commercial area with a fair amount of vehicle traffic. Although the sensors at each site are located roughly vertical from each other, it was identified that passing vehicular traffic may result in a sudden change in the reported distance to ground of the conductors, and during the vehicle's transit, possibly even a step change in the reported conductor-to-conductor clearance. See Figure 8.

The TLM conductor monitors pass along their raw data to the communication gateway which collects the raw data and processes it to fit the application. In this case the gateway was programmed with an algorithm that looks for step changes of 1m or greater in either the line-to-ground clearance reported by a given conductor monitor, or in the difference between monitor sets, which represents the line crossing clearance. If such a step difference is seen, the gateway reports the measurement through SCADA but also reports via a separate SCADA point that the data is suspect, allowing ENMAX's SCADA system to disregard that measurement.

6. EXPERIENCE

The system as described is now operational and is providing continuous, real-time clearance data between the 138kV and 25kV distribution lines. At the time of this paper, ENMAX is only monitoring the data and no operational actions are being taken.

Figure 7: Commercial / Industrial environment conductor clearance monitor installation

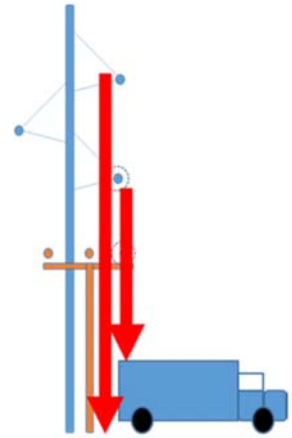

Figure 8: Possible step distance reporting error due to vehicular traffic

Figure 9 shows the measured clearance between the two lines at one of the TLM monitor locations for a one day period, June 8, 2015. The dashed line is the nominal NESC required clearance per Table 233-1. The actual clearance ranges from 3.7m to 6.0m during the course of the day, or a 2.3m change between the two lines. As would be expected, examination of the underlying data shows most of the change is due to the 138kV line; only 0.3m of clearance difference was due to the 25kV distribution line. While there were moderate winds present in the afternoon that could result in some blowout, for the conductor used, this would account for approximately 0.5m of this difference. The current on the 138kV line ranged from 111A to 319A over the day. This change would not result in appreciable sag for the size of the conductor used. Therefore this change in clearance over the course of the day seemed much greater than expected.

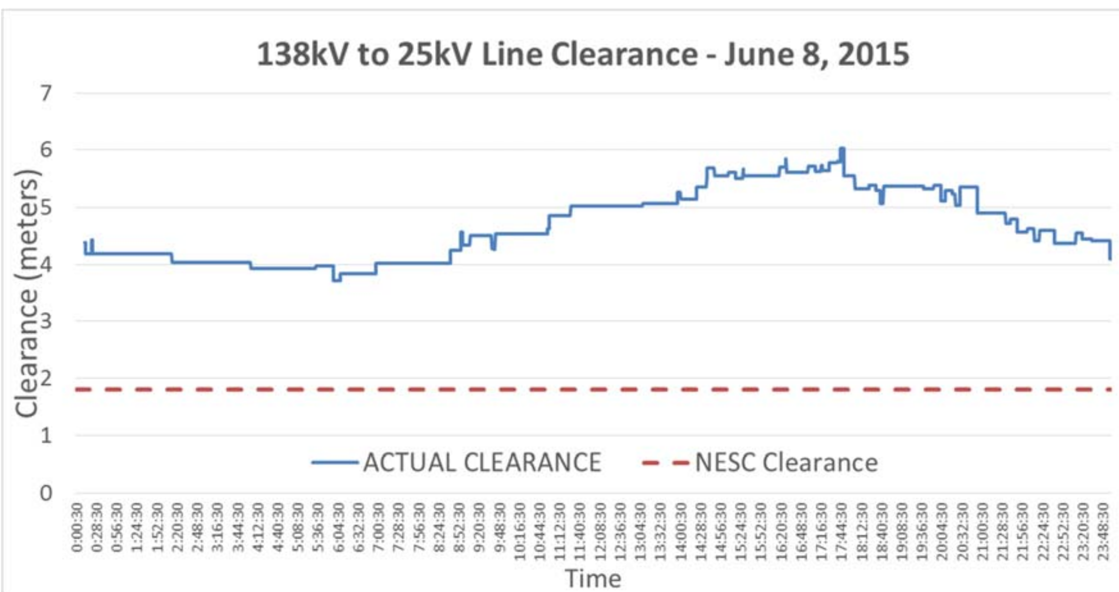

Figure 9: Measured clearance on June 8, 2015 between the 138kV and 25kV lines at Span A based on one conductor mounted LiDAR-based monitor pair

As mentioned previously, two sets of spans were monitored. As the 25kV line clearance to ground varied little, the focus was brought to the 138kV spans. Figure 10 shows the clearance to ground over the course of the day of each of these two spans, marked Span A and Span B. Recall that both spans are roughly equal length at 115m and 107m (Span A and B respectively). Note that Span A is the span for which the conductor-to-conductor clearance is shown in Figure 9.

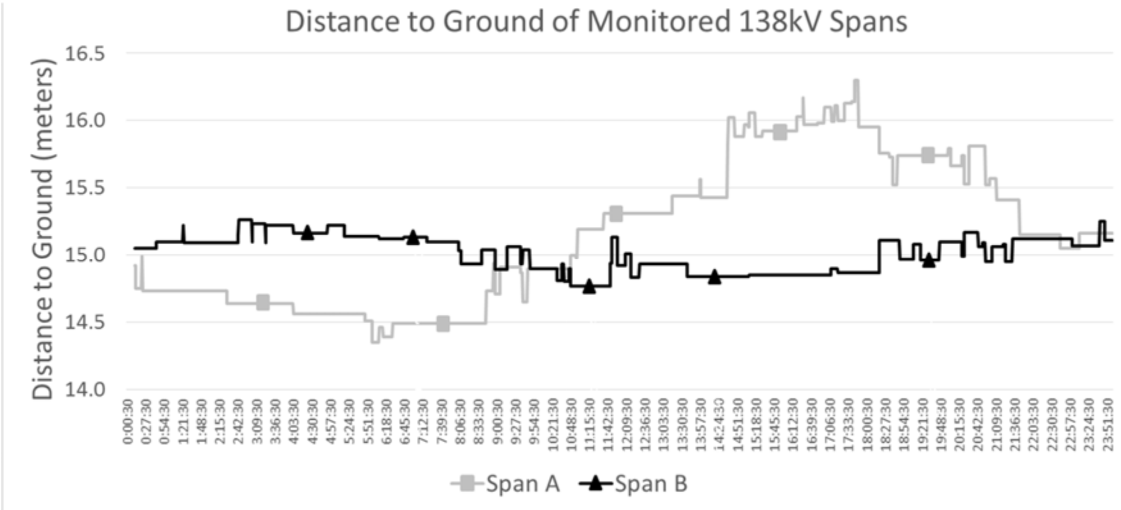

Figure 10: Distance to ground of 138kV lines for monitored Spans A and B

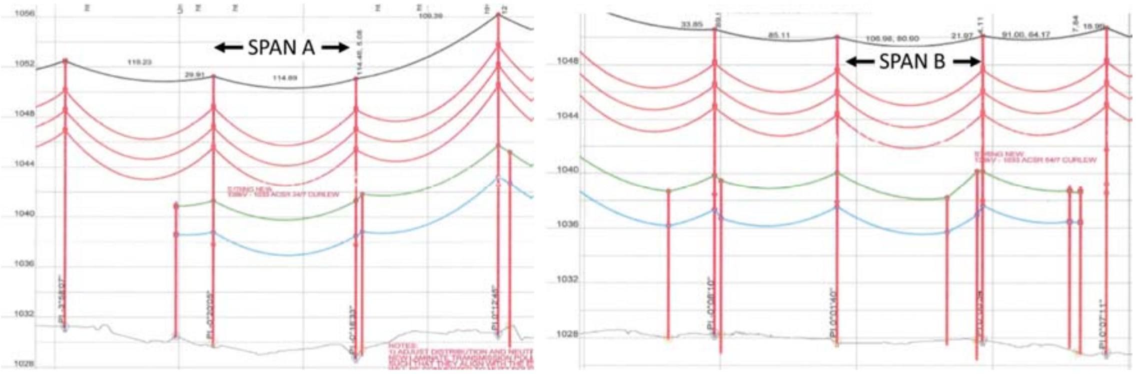

Figure 11: Plan profiles of monitored Spans A and B

Here we can see that the behaviour of Span A is quite different than that of Span B. To explain this, it is useful to examine the plan profiles of both spans as shown in Figures 11.

- Figure 10 shows the clearance to ground of Span B varies little over the course of the day (0.5m). However, as expected, in the afternoon as the conductor heats due to ambient temperature (approaching 32C from 3-5pm) and the modest current increase, the sag is greatest (lowest clearance). Note that the spans adjacent to Span B are at essentially the same elevation; all the spans will behave similarly.
- The clearance to ground of Span A has much more variation (1.8m). In addition, the variation is opposite that of Span B; that is, in the warm afternoon, the clearance to ground increases, meaning sag is decreasing.
- This behaviour is explained by examination of the plan profile in Figure 11. The spans on either side of Span A are at greater elevation; the span on the right in particular. As those elevated spans heat up (similar to Span B), those spans will sag more, exerting a pulling force on the flexible polymer brace post insulators on either side of Span A, lifting the conductor. As a point of reference, depending on initial tension an outward deflection of the brace post insulators on Span A by 0.1m each will result in approximately a 1.5m increase in the conductor height.

6.1. Geometry Aspects

Two sets of geometrical issues need be addressed. The first concerns the angle at which the LiDAR sensor is looking. The second is related to any lateral movement of the conductor. The latter is highlighted as a result of the observed wind.

6.1.1. LiDAR Angle Correction

The LiDAR units in the conductor monitors are fixed. Therefore the LiDAR measurement is initially based on the direction the monitor is facing. To ensure the measurements are always made in reference to the downward facing direction the monitors contain tilt and roll sensors. The reported distance to ground is corrected for theses measured angles. See Figure 12.

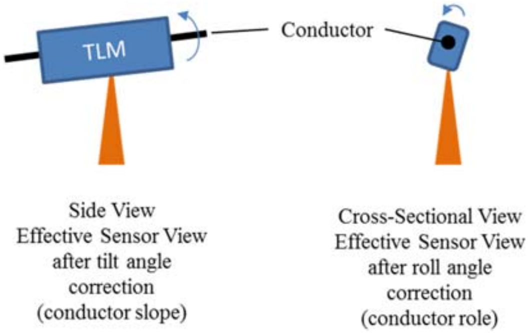

Figure 12: Tilt and Roll Correction

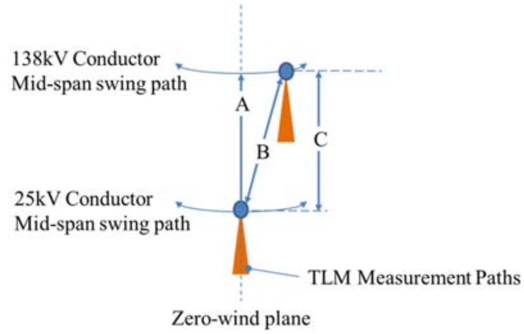

Figure 13: Lateral Conductor Movement Geometry

6.1.2. Lateral Conductor Movement Error

Recall that the overall concern is in measuring to ensure conductor clearances are not violated. The most critical case is when there is no, or very little, wind. This, with high current flow, will cause the most critical minimum clearance condition and the difference between the two LiDAR measurements will give the true conductor clearance. This is indicated by Line A in Figure 13.

The second geometric issue arises from conductor movement due to wind. Conductors in wind are not stationary; they will swing back and forth as the wind blows and gusts and the conductor will follow their own swing paths as shown in Figure 12. Therefore it is possible that the 138kV and 25kV conductors will not be in the same plane at the time of any given measurement. Recall that the algorithm used simply subtracts the tilt/roll corrected 138kv line distance-to-ground from the equivalent 25kV line distance-to-ground. This is shown as Line C in the Figure.

As it is possible for the LiDAR units to take their measurements at any time, it is possible an instantaneous error in measured clearance will occur, as Line C is shorter than Line B. However this error will be in a conservative direction, effectively under-reporting clearance. This direction of error is favorable considering the goal is to verify conductor clearances are not violated. However, it is most important to note that as the 138kV and 25kV conductors are not linked, their swinging in relation to each other is random. As such, this random motion causes them to occasionally cross underneath each other. At this point they again lay in the same plane and their vertical separation will be a minimum, equal to Line A, which is again derived by simple subtraction of the two line-to-ground distance measurements. Therefore even when wind is present, the method will return either the actual conductor-to-conductor clearance, or some value slightly smaller than actual. In no case will the system be reporting greater clearance than is occurring.

Based on the above, it was determined that there was no need to compensate for any such measurement error due to lateral conductor movement.

6.1.3. Miscellaneous Observations

- During windy conditions, significant conductor cooling will result, which will tend to increase clearance compared to the critical case. Therefore even in the case of notable lateral conductor movement, the clearance of concern will not become critical.
- Both line designs are such that there is effectively no insulator movement contribution; the 25kV circuit is on rigid pin insulators, and the 138kV line uses a brace post design.

7. FUTURE PLANS

For the future, ENMAX intends on installing additional monitor pairs along the path where the lines are co-located. Because the conductor monitors also provide (+/-1%) line current measurements, conductor temperature, ground temperature and conductor vibration measurements, ENMAX is considering plans to take advantage of this data and implement a pilot dynamic line rating system based on their output.

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