Calculating Electromagnetic Field (EMF) Distortion to Maintain and Secure Electric Transmission Lines

John Puryear
ABS Consulting, San Antonio, TX

David Rodriguez
ABS Consulting, San Antonio, TX

Iñaki Çaldichoury
Livermore Software Technology Corporation

Abstract

Critical to the electric power grid are the high voltage transmission lines. These assets are geographically dispersed and typically transverse large distances across remote areas. Those attributes make them challenging to maintain and physically secure. Electrical power system operators are continually improving data acquisition and interpretation to draw new inferences about system performance. These advances raise the possibility of monitoring the power lines' electromagnetic fields (EMFs) and using them as "sensors" with a range of potential applications.

One possible application is ballistic detection. A common problem for utilities is ballistic damage to insulators. Were reliable ballistic detection available, inspection could be triggered by actual gunshots and restricted to where gunshots occurred. With growing concern of attacks to the power grid, being able to detect gunshots is additionally attractive. A bullet passing near a power line is a conductor passing through a large EMF. This physical condition raises the possibility that a change in the line signal could be detected when a bullet passes near the cable. LS-DYNA®'s electromagnetic (EM) solver was used to calculate the change in line signal due to a bullet passing nearby.

Another potential application of power lines as sensors is structural health monitoring. Transmission lines themselves are conductors within a baseline EMF. Displacements caused in service conditions (galloping conductors or damaged insulators) or by extreme events (seismic damage or high winds), change the mutual inductance between the cables. This scenario served as a second case study for calculating the effect of an external event (kinematic motion of cables) on the cable signal.

Finally, metal theft or willful damage is a persistent threat to utility assets, and the capability of sensing and identifying the location of an intruder anywhere along the line would assist in apprehending the intruder and deter future intrusions. In principle, the power line can function like existing electromagnetic devices that sense intrusion. This possibility was investigated using the EM solver. Specifically, a finite element model including an energized transmission cable and intruding truck has been used to calculate any change in cable current density due to the presence of the truck.

In this paper, the motivation for analyzing these case studies, the details of the studies themselves and results from the calculations are presented. In addition, recommendations for future work are discussed.

Introduction

Electrical transmission and distribution lines span large distances across remote areas. The large scale of these assets makes them costly to maintain and secure. The Brattle Group projects $120-

160 billion of investments over the next decade to maintain transmission line reliability.[1] Physically securing lines is similarly costly. For example, the annual cost of copper theft to utilities is estimated to be $1 billion.[2]

Line maintenance is scheduled based on continuous, visual inspection of the condition of the line. Line inspectors travel the length of the line, visually examining conductors and supporting structures. Line components requiring attention are noted, and repair is accordingly scheduled. Under normal service conditions, this inspection process is labor-intensive; after an extreme event, the process is overwhelmed. However, if structures supporting the electrical conductors are continuously monitored, utilities could optimize inspection labor during normal service conditions and more rapidly identify damaged locations along the line after an extreme event.

Currently, the best practice for securing electrical right of ways entails installing security technology: security lighting, intrusion detection and surveillance, personnel and vehicle barriers and anti-tamper devices (e.g. locks and anti-tamper fasteners). The length of transmission right of ways generally precludes installation of these protective devices to provide a reasonable coverage. For example, analytic video surveillance combined with infrared illuminators might be installed along a short segment of a transmission line but are simply too expensive for surveilling the entire line.

A parallel development is that utility operators are continually improving data acquisition and interpretation to draw new inferences about system performance. The installation of Phasor Measurement Units (PMUs), which allow GPS-synchronized data acquisition at reduced sampling intervals, is one example. These advances raise the possibility of monitoring the power lines' electromagnetic fields and using them as "sensors" with a range of potential applications. This approach would use data gathered from the line to monitor the health of structures supporting the line, particularly after extreme weather events, and potentially detect intruders within its right of way (ROW). Using electrical lines as sensors has the potential to significantly reduce both maintenance and security costs.

For power lines to be used as sensors, utility operators need to know what signal features (e.g. amplitude change or frequency shift) are associated with the events of interest. More specifically, operators need a library or suite of signal features that can be algorithmically identified in the operational data. When the signal feature is identified, appropriate action can be taken, whether it is recording conductor response to an extreme wind event or dispatching security in response to unauthorized activity in the ROW.

Toward the end of identifying these signal features, three case studies have been performed using LS-DYNA's electromagnetic (EM) solver:

- Ballistic detection near the conductors
- Conductor motion in high winds
- Truck intrusion detection into ROW

[1] Pfeifenberger, Johannes et al. The Brattle Group, "Contrasting Competitively-Bid Transmission Investment in the U.S. and Abroad." 13 May 2014. http://www.brattle.com/system/news

[2] http://www.cnbc.com/id/100946683

This paper describes the methodology used in the case studies, the geometric and kinematic initial conditions for the case studies, results from the calculations and finally recommendations for future work.

EM Solver Methodology

The LS-DYNA EM solver was used to perform the calculations for the case studies. The EM solver was invoked using *EM_CONTROL and supporting control cards. The baseline model was a transmission cable composed of five strands, each 50mm in diameter. *SECTION_SOLID elform=1 was used for the strand elements. The strands were arranged as shown in Figure 1.

*EM_MAT_001 with mtype=2 was used as the material for the cable strands. The conductivity of the material was 3.7E7 S/m, a typical value for aluminum wires used to fabricate transmission cables. A sinusoidal signal with amplitude 345 kV and frequency 50 Hz was imposed on the cable strands using *EM_CIRCUIT. Current densities were interrogated from the model at midspan, as shown for element 78179 in Figure 1. The baseline signal in the cable is shown in Figure 2.

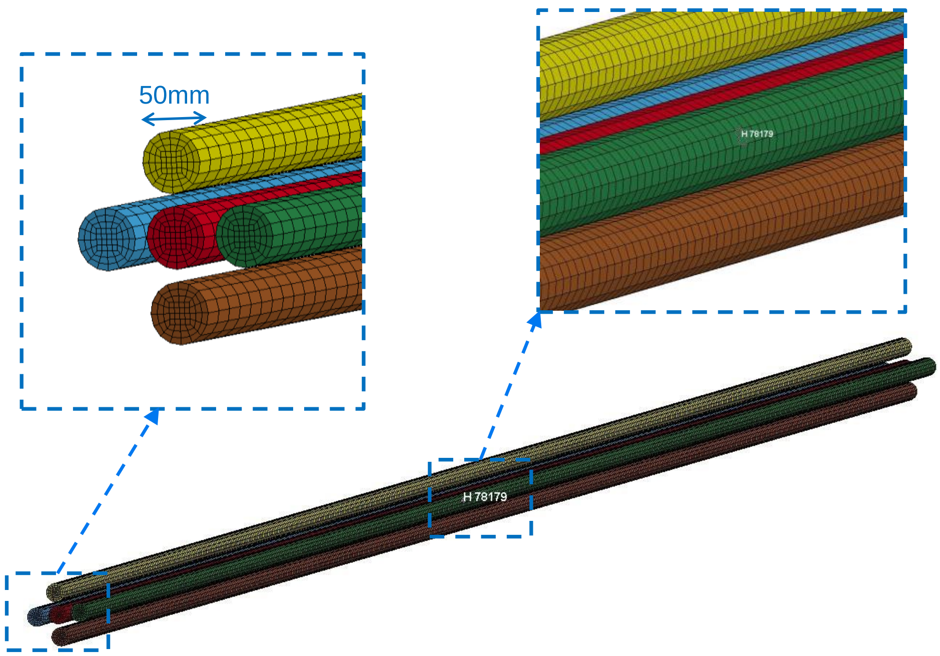

Figure 1. Baseline Cable Model

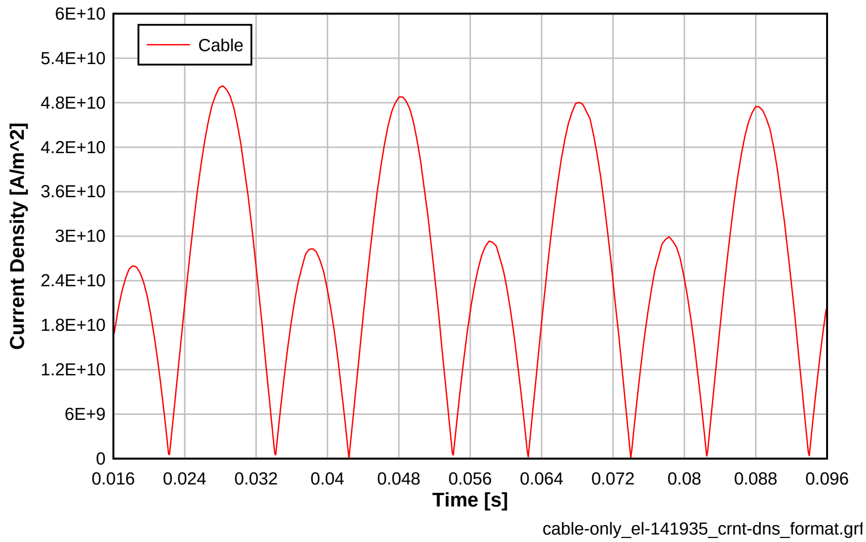

Figure 2. Baseline Signal for Cable Only

Ballistic Detection near Conductors

A common problem for utilities is ballistic damage to insulators. This can occur in rural areas where hunters see insulators as a handy target for target practice. Ballistic damage to insulators is easily identified only if the damage is severe, either the result of multiple shots to insulators or thermal cracking resulting from ballistic damage. Consequently, utilities are compelled to perform costly inspection of insulators for ballistic damage.

Were reliable ballistic detection available, inspection could be triggered by actual gunshots and restricted to where gunshots occurred. With growing concern of attacks to the power grid, being able to detect gunshots is additionally attractive.

Available gunshot detection systems are acoustic and distinct from the line itself. Obtaining them is a large added cost for utilities. To eliminate the need for a separate gunshot detection system, the problem becomes identifying that a bullet has passed near the line conductor. In theory, the effect on the line signal can be calculated because passage of the bullet near the line is motion of a conductor through a large EMF. Calculation of the effect of the bullet passing near the conductor on the line signal is discussed below.

The objective of the calculation is to determine the change in cable state (current density) due to a conductor (bullet) passing through line EMF. The surface area of the bullet is small, but its high speed and its being close to the line (the only case of real interest) where the magnetic field is large, suggest the possibility of the bullet having a measurable effect on the line signal. The dependence of the emf induced in the bullet on the magnetic field, speed of the bullet, and its geometry is shown in Equation 1.

Equation 1

$$\varepsilon = -Blv$$

$$B \propto \frac{1}{r}$$

ε – induced emf
B – magnetic field
L – length bullet
V – velocity bullet
r – distance from cable

The change in the signal of the line due to the bullet passing nearby was explored using LS-DYNA's EM solver. The arrangement of parts for the ballistic model is shown in Figure 3. The cable cross section is identical to the one shown in Figure 1. The velocity of the bullet was 720 m/s, a typical speed for a 7.62x39 bullet. A relatively coarse mesh was used for the bullet to manage run times, but a surface area approximately equal to a 7.62x39 bullet was maintained.

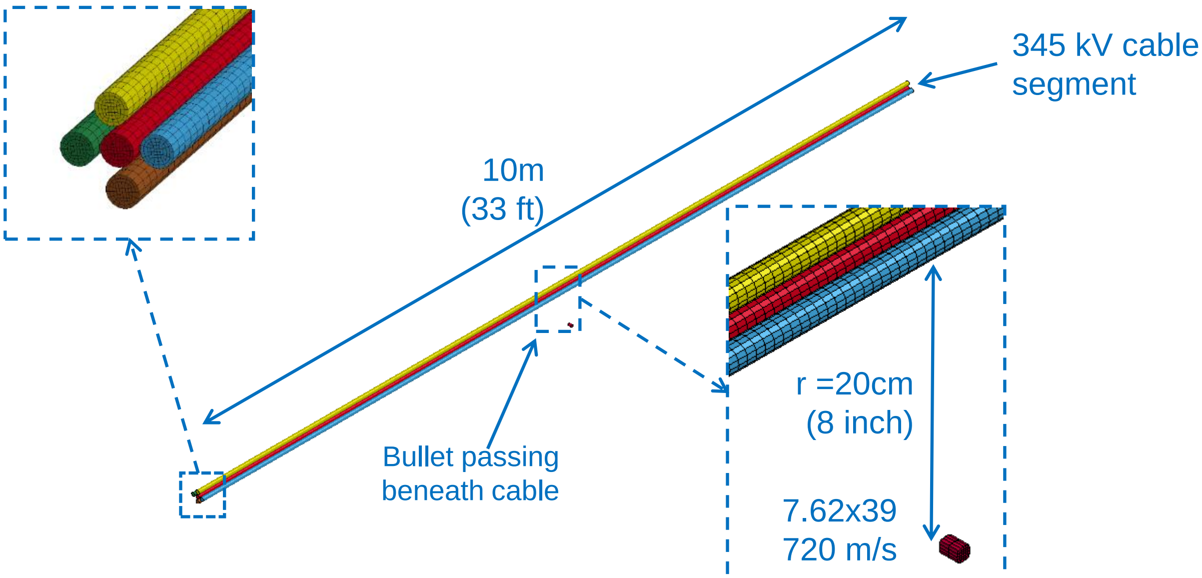

Figure 3. Parts Ballistic Model

A detail of the comparison of the line signal with and without the bullet passing near the conductor is shown in Figure 4. The detail depicts the time when the bullet is closest to the cable. A clear change in signal is observed, and the predominate feature of the change is a shift in the signal.

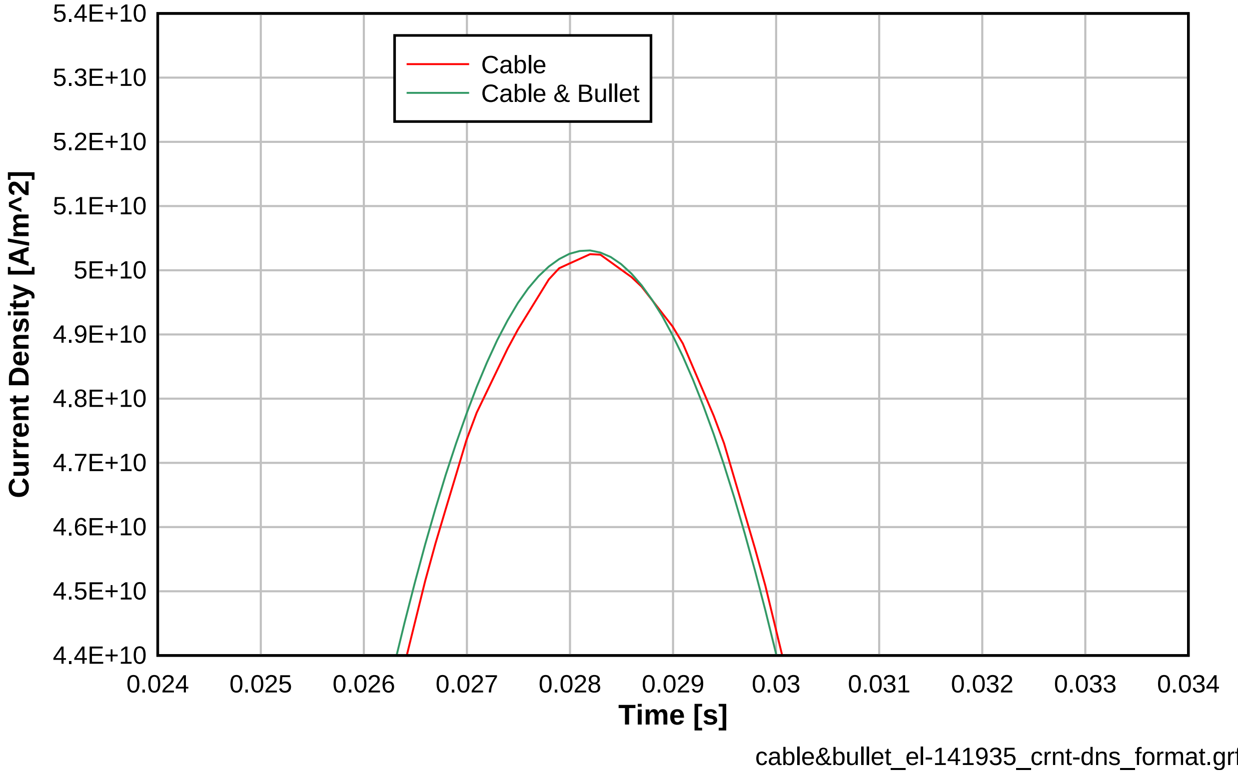

Figure 4. Current Density – Cable vs. Cable + Bullet

Conductor Motion in High Winds

Transmission lines themselves are conductors within a baseline EMF. Displacements caused in service conditions (galloping conductors or damaged insulators) or by extreme events (seismic damage or high winds), change the mutual inductance between the conductors. Just as will be discussed below, the truck can be identified by this change in mutual induction, so the wind displacement can potentially be inferred from line operational data. Identification of these signals can then trigger focused inspection.

An example of distortion of the service EMF by high wind is illustrated in Figure 5. This type of event was modeled using two cables, each cable like the one shown in Figure 1. Relative motion between the two cables was prescribed by holding one cable stationary and moving the other at a speed indicative of a galloping cable (10m/s). The part arrangement for this scenario is shown in Figure 6; the change in the signal of the stationary line is shown in Figure 7 and Figure 8. The primary feature caused by relative motion between the two cables is change in amplitude of the signal.

Figure 5. Structural Motion through EMF Distortion

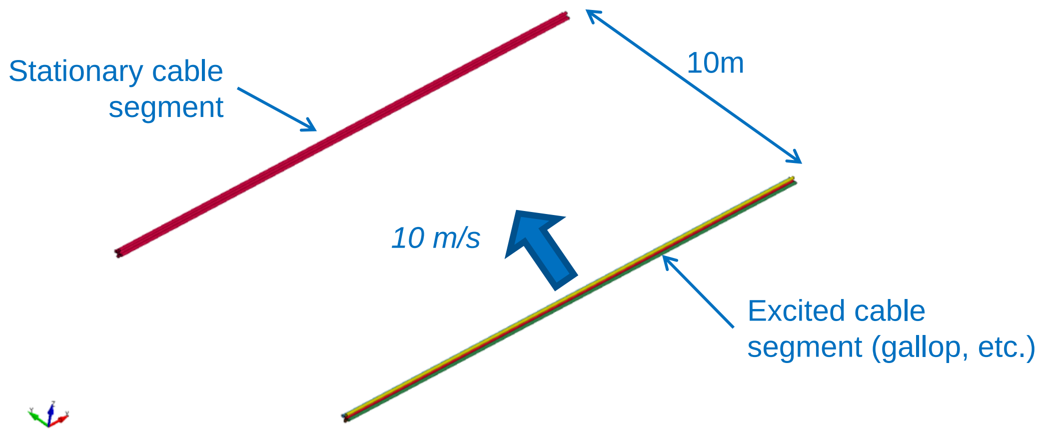

Figure 6. Parts for Relative Conductor Motion

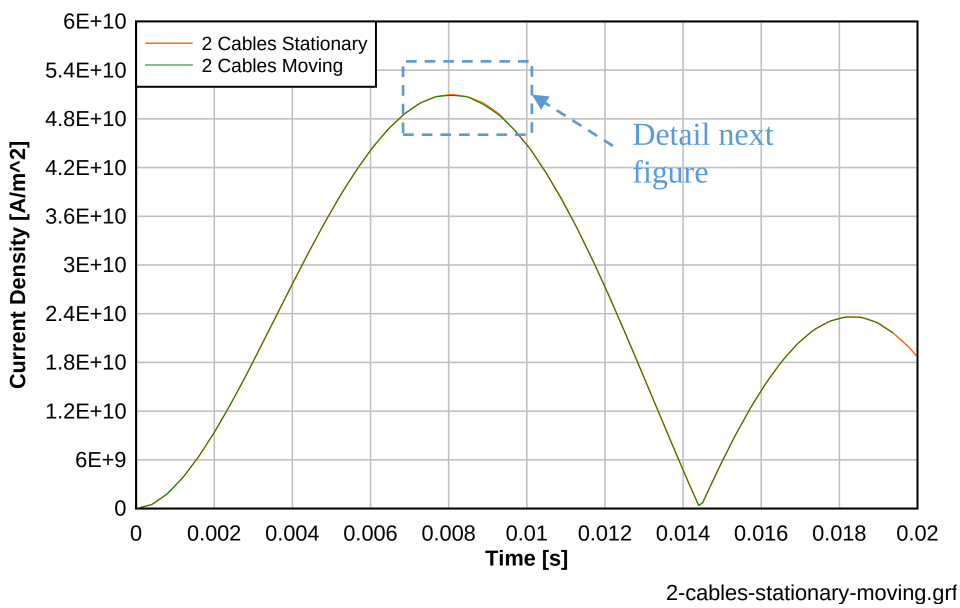

Figure 7. Current Density – Stationary Cables vs. Cables in Relative Motion

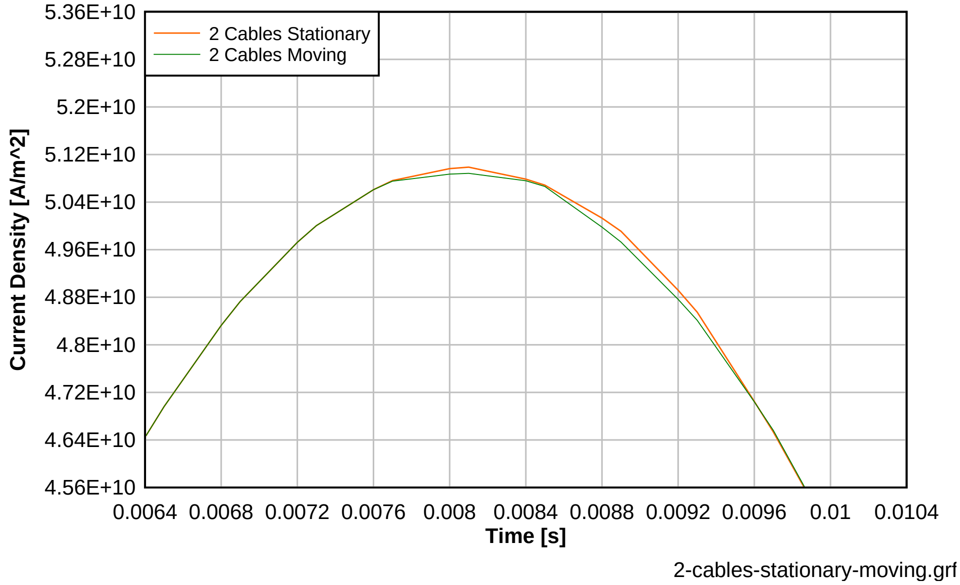

Figure 8. Current Density – Stationary Cables vs. Cables in Relative Motion (Details)

Truck Intrusion Detection in ROW

Metal theft and vandalism are persistent threats to power lines. They inflict costly damage to power infrastructure for a small income to the thief. Beyond repair costs, there are outages resulting from the damage. In most cases, the installation of intrusion detection for an entire transmission line is cost-prohibitive. The proposal here is to use EMF from the line for intrusion detection.

To detect intrusion, the operator may be able to take advantage of the power lines electromagnetic properties. For example, some EMF devices for intrusion detection feature a pair of buried leaky coax cables connected to a processing unit. Intrusion into the EMF induced by the cables is identified by the processing unit, which signals an alarm. The same approach can be considered to identify an unauthorized truck's intrusion into a transmission ROW (Figure 9). Improved data acquisition would take the role of the processing unit in the case of power lines.

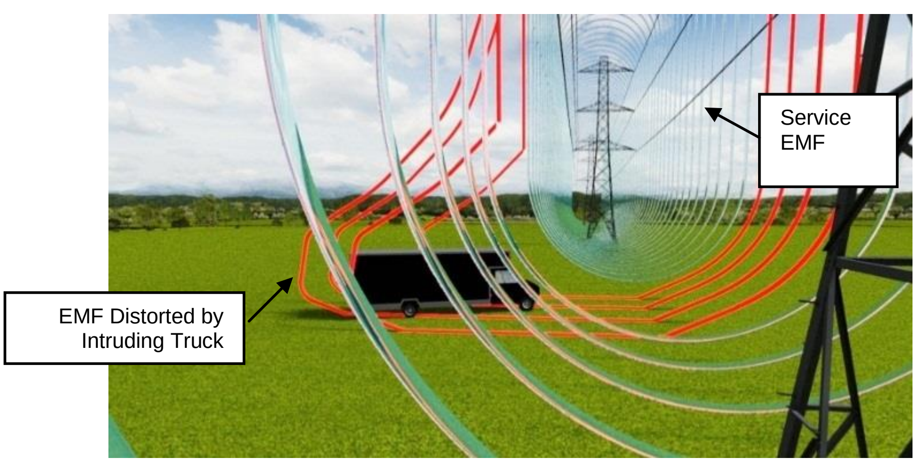

Figure 9. Intruding Truck Distorting Transmission Conductor EMF

The possibility of using transmission lines EMF for intrusion detection was explored using the EM solver. Specifically, a finite element model including an energized transmission cable and intruding truck has been used to calculate any change in cable current density due to the presence of the truck (Figure 10).

First, the model is run with only the cable present. Then, the model is run with the truck approaching the cable at 18m/s (40mph). The overall dimensions of the cable + truck model are provided in Figure 10. The current induced in the truck as it approach the energized cable is shown in Figure 11.

The presence of the truck near the cable did cause a change in amplitude, but the magnitude of the change would likely not be detectable by line data acquisition. In other words, whether the truck was present or not, the signal in the line was that shown in Figure 1. It was noted that if the speed of the truck was increased, a detectable change in amplitude was observed (up to 0.2% of the baseline amplitude), but the required speed of the truck (>100mph) for the change in the signal to be observable was physically unrealistic. The observation here is that what makes the truck undetectable is its slow speed relative to the bullet and its large distance from the line. In contrast, the bullet has a much higher speed and can pass close to the cable.

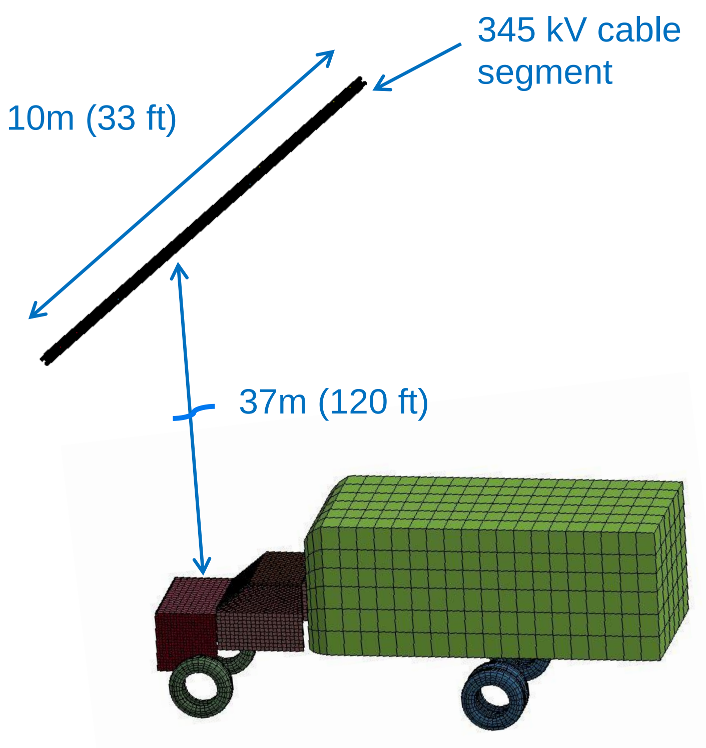

Figure 10. Cable + Truck

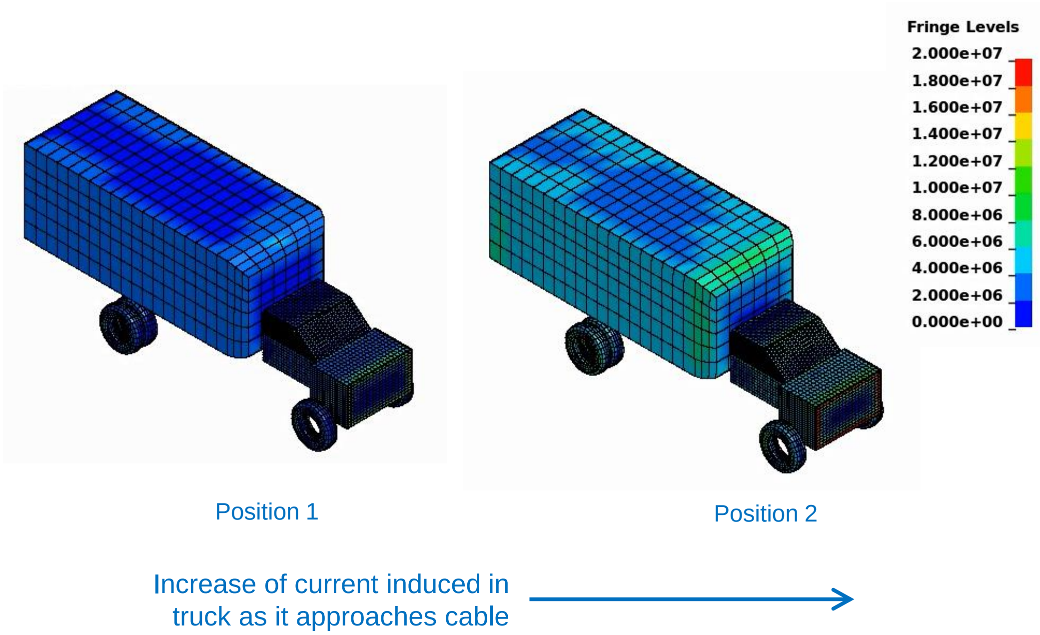

Figure 11. Current Induced in Truck

Conclusions and Recommendations

In conclusion, securing and maintaining power lines is critical to contemporary society. Current maintenance costs are high due to labor-intensive maintenance, and existing intrusion detection technologies are cost-prohibitive for the entire line. An alternative is applying improving data acquisition to security and maintenance challenges. This approach would use the lines themselves as sensors for security applications (intrusion and ballistic detection) and structural health monitoring.

LS-DYNA's EM solver has been used to investigate these proposals numerically. Specifically, the solver has been used to calculate a bullet passing near the conductors, two cables moving relative to each other due to high winds or galloping, and the change in line signal due to the presence of a truck below the conductors. The bullet and moving cables cases are potentially detectable in the signal of the transmission line. The presence of the truck below the conductor was not detectable.

The long-term goal of these calculations is to correlate kinematic/mechanical events of interest to signals in the line operational data. The result would be a library of physical events correlated to signal changes in the line. These could then be identified using algorithms applied to the line operational data to direct security and maintenance responses to line performance.

Future work would include increasing the fidelity of the models, such as adding a supporting tower to the two cable case. Also of interest is applying measured transmission signal to the cable strands in place of the idealized sinusoidal signal. Finally, increasing the length of the cables in order to determine how the change in signal for the bullet and cable case attenuates with distance could be investigated. Some utilities use traveling wave approaches to detect perturbations in a signal at a distance. These approaches may be applicable to detection a signal perturbation caused by a bullet passing near the conductor or relative motion of the conductors.