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EFFECTS OF STRAY CAPACITANCE ON HIGH VOLTAGE TESTING OF VEHICLE-MOUNTED ELEVATING AND ROTATING AERIAL DEVICES IN ACCORDANCE WITH ANSI/SIA A92.2-2009

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Abstract

The capacitive effects of a ground plane on an aerial bucket truck undergoing periodic testing can have a significant impact on the measured test results. The capacitive coupling of a building can reduce the leakage current through the boom resulting in a lower reading from the return point of the truck. Since the coupling is not as prevalent outdoors, more current flows through the boom resulting in larger leakage readings. The capacitive effects of a large ground plane (such as a building) are proven both mathematically and with small scale tests.

I. Introduction

During periodic dielectric leakage testing on Class C Aerial Bucket Trucks an unusual phenomenon occurred in which the leakage current measured was significantly higher in an outdoor testing environment when compared to an indoor environment.

The tests conducted on the boom trucks are held to ANSI/SIA Standard A92.2-2009, which sets forth all testing aspects for Vehicle-Mounted Elevating and Rotating Aerial Devices. The test setup used is outlined in the standard and is illustrated below in Figure 1.

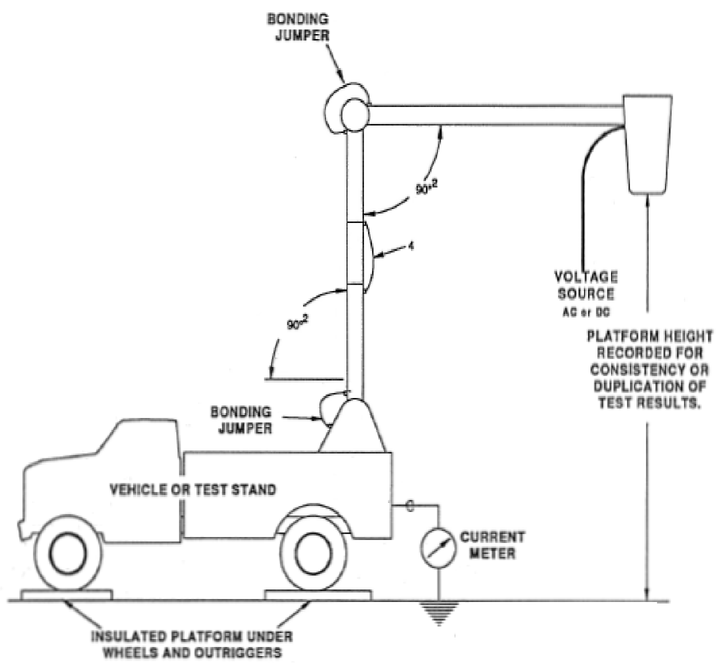

Figure 1. Dielectric Test Configuration for Category C Aerial Devices [1]

Bonding jumpers are connected across the elbow, across the lower arm (#4 on the above drawing) and from the boom to the truck. High Voltage is then applied to the boom directly behind the bucket connection. Current measurement is taken from the return, located on the rear bumper. In addition to the insulation of the tires, the truck is also on insulated platforms both under the wheels and outriggers.

Trucks are passed under the following conditions:

Unit Rating	60 Hertz Voltage	Maximum Allowable Current	Test Duration
46 KV & below	100 KV (rms)	1 milliAmpere (RMS)	3 minutes

Table I. Acceptance Requirements [1]

II. Theory

Due to the nature of high voltage AC testing and the inevitable appearance of stray capacitances, it is important to understand the effects of the testing environment on the measured data. In this case, the test circuit of an insulating boom consists of a resistance in parallel with many small capacitances due to the high voltage lead, the effects of corona, and grounded planes in close proximity to the equipment under voltage. To simplify this circuit a single parallel RC circuit is formed by combining all the small capacitances into one equivalent capacitance shown below in Figure 2.

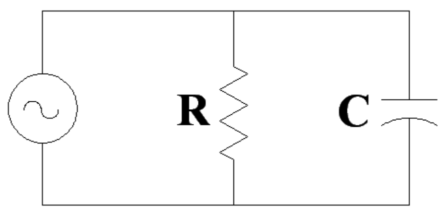

Figure 2. Model RC Circuit

For comparative analysis, the capacitor is expressed as an impedance or reactance which is displayed in Equation 1.

$$X_C = \frac{1}{j\omega C} \qquad \text{(Eq. 1)}$$

From there, the resistance R and reactance X_C are combined as two parallel impedances and result in the following "lumped impedance". The final version of Equation 2 has been broken down into its real and imaginary parts by using the complex conjugate.

$$Z = \frac{-jRX_C}{R - jX_C} \xrightarrow{\text{Complex Conjugate}} Z = \frac{RX_C^2}{R^2 + X_C^2} - j\frac{R^2 X_C}{R^2 + X_C^2} \qquad \text{(Eq. 2)}$$

Thinking in terms of real and imaginary components, the first element of the "lumped impedance" will draw current solely due to the resistive component of the circuit, or the boom of the truck. The imaginary element which contains the *j* term is an effect of the combined stray components of the RC circuit which are present due to the high voltage field. Applying Ohm's Law in Equation 3 yields a final useable equation for finding the leakage current through the insulating portion of the truck.

$$I = \frac{V}{\frac{RX_C^2}{R^2 + X_C^2} - j\frac{R^2 X_C}{R^2 + X_C^2}} \qquad \text{(Eq. 3)}$$

Using Equation 3 and varying the magnitude of the capacitance value C from Equation 1, the following two limits of current I can be stated:

$$\lim_{C \to 1} \quad I \to \frac{V}{\alpha - j\beta} \quad where\ \alpha << \beta \qquad \text{(Eq. 4)}$$

$$\lim_{C \to 0} \quad I \to \frac{V}{\alpha - j\beta} \quad where\ \alpha >> \beta \qquad \text{(Eq. 5)}$$

In Equations 4 and 5, the real portion of Equation 3 (the section modeling the truck's boom) has been replaced with the generic variable α, and the imaginary portion (the section modeling the coupling stray capacitances) with variable β. To illustrate the behavior of this test circuit represented by a mathematical equation we must look at both extremes of the capacitive element.

In Equation 4, as the capacitive term of X_C goes to 1, or the farad range, the real portion of the denominator goes to zero X_C times faster than the imaginary portion because of the squared reactance term. In this extreme case there is a purely imaginary term to divide Equation 3 forcing the angle between the voltage and current phasers to 90°. In this instance, current will flow back through the capacitor and subtract from the leakage current flowing through the boom resulting in a lower measured current due to the highly capacitive "lumped impedance".

Equation 5 eliminates the capacitive element because the real portion (α) of the denominator goes to infinity X_C times faster than the imaginary term β because of the squared reactance of Equation 3. By removing the $-j\beta$ term, the phase shift is also removed and in this case the angle between the current and voltage vectors is zero. Now the voltage is divided by a real number, and the majority of the current measured will be that which is due to the high resistance of the insulating material of the boom since there is no reverse current.

By minimizing the effects of the surrounding environment (ie. grounded walls/floor), and by using appropriate high voltage connections to reduce corona, a close-to-pure look at the leakage current of the boom can become possible. While it is nearly impossible to replicate either of the extreme cases in Equations 4 or 5, the real world displays some combination of each. Testing indoors in a grounded building will lead to a higher coupling environment and promote growth of the β term increasing the phase angle of the circuit and lowering the measured current at the high voltage source. Whereas reducing corona at the high voltage connections and distancing the test circuit from any grounded planes plays to a stronger α. Although each boom truck circuit will be slightly different, it is important to be mindful of the scenario in which data is recorded. Minor adjustments in the test setup and conductors used can change the value of the current measured on the order of tens of micro amps due to the magnitude of the R and C components.

III. Results

Analysis done on similar test objects, discussed above, concludes that the results of leakage current measurements are heavily dependent upon the physical testing environment and the material composition of objects in close proximity to the test circuit. Investigations were also conducted on the method and orientation of routing cable connections.

Extensive testing was performed on various types of cylindrical electrical insulators. Intentions were to simulate the test object, setup, and environment in order to obtain the most comparable results. Data points were taken from 20KV – 100KV, in 20KV steps, thus providing a substantial pool of data for analysis. Figure 3, below, shows a plot of normalized "lumped impedance" versus applied test voltage taken in both indoor and outdoor environments. This data was extrapolated from measurements of leakage currents measured at the return of the AC source. The trend of the lines individually is not particularly as important as the displacement between them. The findings prove that performing test procedures in an indoor environment give rise to error in leakage current readings as a result of increased capacitive coupling. In this case, the effects of stray capacitance cause the coupling of charge to points elsewhere in the environment, thus reducing the real component of the return current to the AC source. Viewing the graph, a 7.5% average decrease in impedance is measured when testing outdoors versus indoors.

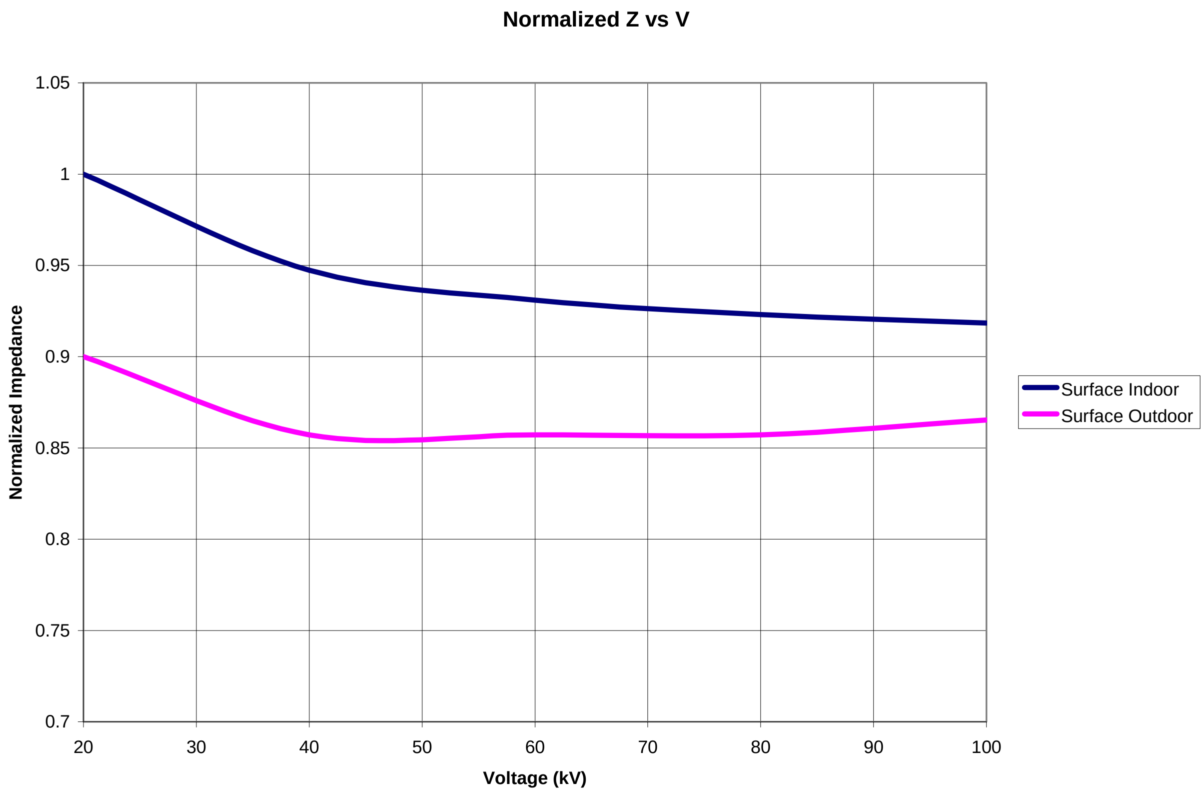

Figure 3. Plotted trends of Normalized Impedance vs. Applied Test Voltage

A second set of data showed that there can be cabling discrepancies. Data collected shows that the leakage current level measured by the AC supply is dependent upon the location of the high voltage supply return cable. Several orientations of cable routing were attempted in order to reduce effects of stray capacitance, the most effect of which was the suspension of the return wire from the grounded steel-reinforced-concrete flooring in the indoor environment. Measurements taken conclude that suspending the return cable, in air, reduces capacitive coupling of the return signal to the ground plane. This allows for a more accurate reading at the current meter of the AC source. Figure 4 displays plots of the experimental data. Two qualities of these line plots are of interest; the overall impedance measurements are reduce by approximately 10% and the average displacement between the indoor and outdoor readings is reduced by approximately 40%.

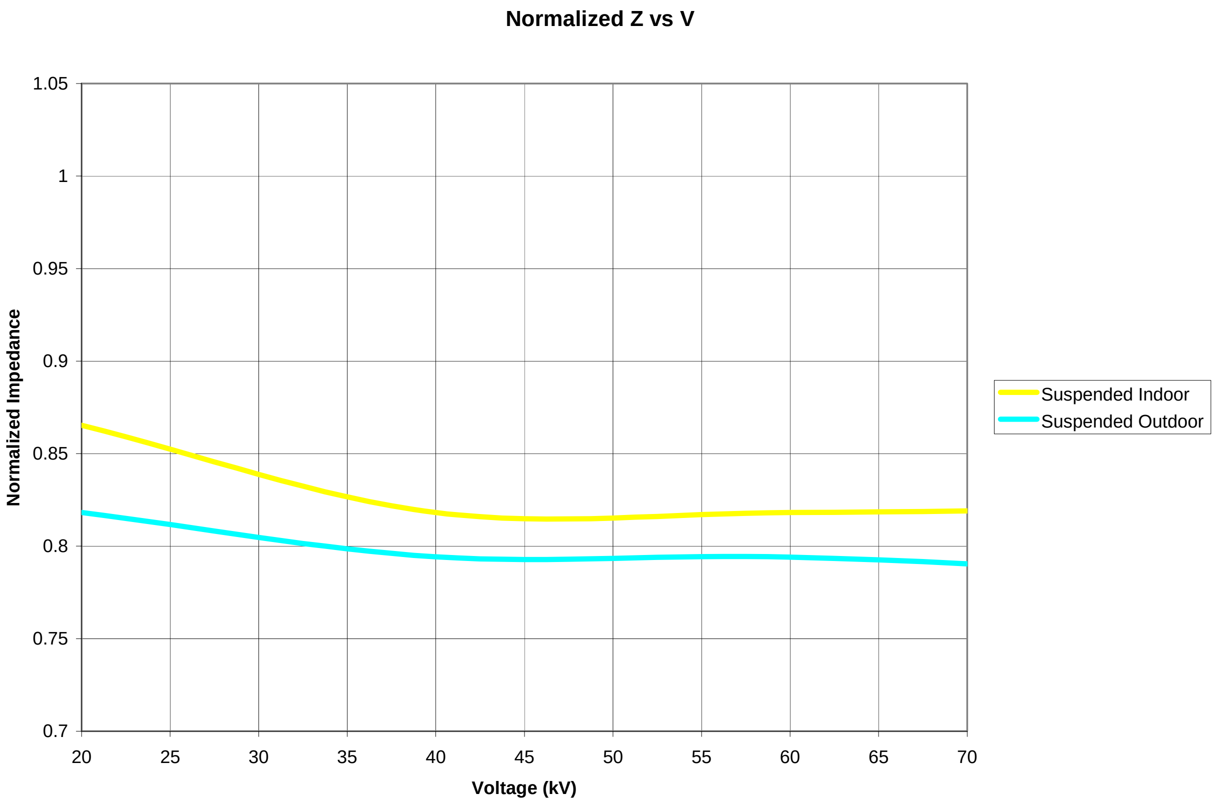

Figure 4. Effects of rerouting metering cables on impedance measurements

It was observed that, with orientations favoring a reduced value of stray capacitance, the testing would produce higher leakage current readings at the AC source.

IV. Conclusion

Our findings suggest that high voltage testing of bucket trucks require a higher degree of attention to both the routing of cable connections and determining appropriate test environments. The results above clearly show that testing aerial lift devices indoors versus outdoors can lead to variances in leakage current. This is because indoor testing allows for a higher coupling environment thus reducing leakage current measured at the high voltage source.

References

[1] ANSI Subcommittee A92.2, "American National Standard Vehicle-Mounted Elevating and Rotating Aerial Devices", ANSI/SIA A92.2-2009.