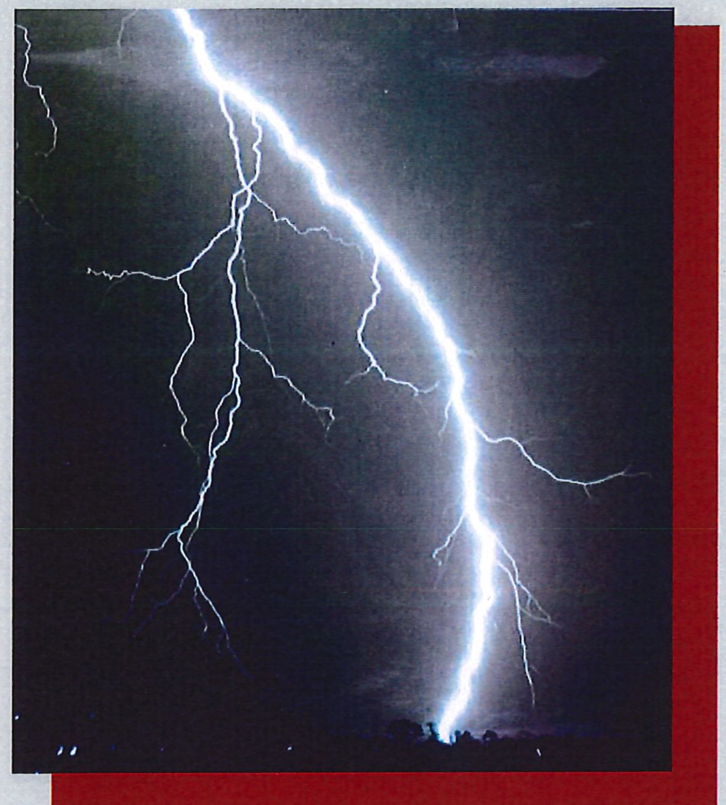
SCAMPS 2004

Annual Meeting
June 7, 2004



LIGHTNING:

IS YOUR COMMUNICATIONS FACILITY PROTECTED?

presented by

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INTRODUCTION

Rockingham County, NC has been experiencing communication equipment failures and personnel shock events at its 911 Center (C-Com) in Wentworth, North Carolina. These problems have been prevalent during times of electrical storms, but have also occurred on fair weather days.

Utility Technology Engineers-Consultants (UTEC) was retained by Rockingham County to determine the cause and determine how to mitigate the problems. UTEC has followed a systems engineering approach to investigate the problems and has determined the cause and identified the modifications required to mitigate the problems.

There are four systems within the 911 facility:

1. **Electric Power System**
2. **Telephone Communications System**
3. **Cable TV System**
4. **Radio System**

These four systems are interconnected and each is grounded. UTEC has determined the primary cause of the problems is ground potential rise (GPR) caused by three events:

1. **Direct Lightning Strokes**
2. **Indirect Lighting Strokes**
3. **Power system events**

We have also identified several issues that we will address to mitigate the effect of GPR:

1. **Single Point Ground**
2. **Surge Protection / Surge Dissipation**
3. **Direct Stroke Protection**
4. **Remote Ground Isolation**
5. **Equipment and Personnel Insulation**
6. **Tower Location**

GROUND POTENTIAL RISE (GPR)

GPR from Power System Events

To understand GPR, we would first like to review a simplified depiction of the electric utility facilities, the telephone company facilities, the cable company facilities, and the radio equipment serving the 911 building.

Figure 1 depicts the electric utility facilities in Rockingham County serving the 911 building. Duke Energy is the electric utility provider in the area. Duke owns a substation close to the County's Government Center. This substation includes a 20 MVA transformer which transforms transmission voltage (100,000 volts) to primary distribution voltage (12,500/7,200 volts or 12.5 kV). The substation includes an extensive below-grade grounding electrode. This substation electrode has a dc resistance to remote earth of 5.2 ohms. The transmission line shield wires, distribution line neutral conductors, fence, and all metal structures within the substation are connected to this below-grade ground electrode.

Two 12.5 kV distribution circuits are fed from the substation. One of these distribution circuits provides service to the 911 building. Along the electric distribution lines, the neutral conductors are periodically connected to below-grade pole grounds. These pole grounds usually include an 8' copper clad ground rod. The calculated resistance to remote earth of each pole ground is approximately 527 ohms.

The 911 facility is fed by a 25 kVA overhead distribution transformer that transforms the primary distribution voltage (7,200 volts) to a three-wire 240/120 volt 1-phase service. At the transformer pole, the neutral is connected to the pole ground, and then connected to the 911 building ground electrode at the service entrance to the building. The building electrical service entrance is on the south side near the east end of the building. The 911 building includes a below-grade grounding electrode that encircles the building. This electrode includes approximately 600 feet of bare copper conductor and several 8' ground rods. This 911 facility electrode has a calculated dc resistance to remote earth of approximately 31.6 ohms.

Figure 2 depicts the same information as Figure 1 with the addition of the other three systems: telephone, cable, and radio. The telephone service provider is BellSouth. The telephone system includes a 100 pair copper cable. The telephone cable service entrance is at the same general location as the electric service entrance. The telephone cable shields are connected with the 911 facility ground electrode at this point. The cable system provider is Time Warner. The cable system building entrance is also in the same general location as the electric service entrance and the cable shield is connected with the 911 facility ground electrode at this location. The communication tower is on the opposite side of the building from the electric, telephone, and cable service entrances. Thirty-one coaxial cables are attached to the tower and enter the building from the tower. The shields of the cables are connected to the building ground electrode at the tower approximately 7 feet above grade, and are again connected with the facility ground conductor inside the building.

Figure 3 depicts the four systems serving the 911 facility and a line-to-ground power system fault. A power system ground fault is an abnormal condition in which an energized conductor(s) touches a grounded object such as the neutral conductor. When this happens, the current flowing in the power system greatly exceeds normal current. For example, normal current in a distribution line might be 200-500 amperes, and fault current might be 2,000-8,000 amperes. A few examples of ground faults are:

- Energized line falling on the neutral conductor
- Energized line falling on the ground
- Energized line momentarily contacting the neutral due to wind
- Foreign objects touching an energized line and the neutral at the same time
- An animal, such as a bird, squirrel, or snake, getting itself between an energized line and neutral
- Lightning flashing-over the insulator of an energized line.

Power system faults can be permanent (i.e. a broken structure or conductor that must be repaired) or temporary (i.e. a tree limb touching an energized line momentarily, then the limb falling to the ground clearing the fault). Statistically, 90 percent of power system faults are temporary.

When a line-to-ground fault happens, the line current must return to the substation transformer neutral. The return fault current flows through all available ground paths to return to the transformer neutral. Figure 3 depicts this current flow in all of the pole grounds, neutrals, and the 911 facility ground electrode. At the 911 building, because the ground electrode is connected with the power system neutral, current flows from the ground electrode into the earth. This flow of current through the ground impedance of the building electrode causes a voltage drop, or "potential", between the electrode and points on the earth remote for the building. This condition is called "Ground Potential Rise", or GPR.

What this means is that all objects within the building that are connected to the ground electrode are energized at an elevated voltage relative to remote objects away from the building. **Figure 4** is a graph that depicts typical voltage at the earth surface versus distance from the 911 buildings during a line-to-ground fault. The figure indicates that inside the building, the voltage is relatively constant, but as one traverse away from the building, the voltage between the earth and the ground electrode increases. At a point far enough away, the voltage between the 911 building electrode and the earth at that point is the full GPR.

The problem with this situation is that the telephone lines and the cable lines enter the building from remote locations. The telephone line shields and cable shields are grounded along their routes to the building, and may also be grounded at the building. These grounded shields bring the remote ground points into the building where the ground electrode is now at an elevated voltage. The telephone lines and cable conductors have very low insulating capability. These conductors are protected by surge suppressors which are designed to operate, or short circuit, when an excessive voltage is impressed across the conductors. These surge protectors operate at around 200 volts. When the surge suppressors operate, the conductors, along with the cable shields, provide a path to remote earth. The voltage difference between the telephone conductors or cable conductors, and building ground electrode is causing some of the damage to communication equipment, and is causing nuisance blowing of low current fuses in the telephone system.

UTEC has calculated the GPR at the 911 facility for line-to-ground faults at various locations along the distribution line as shown in the following table.

FAULT LOCATION	E 911 Center GPR (volts)
911 Building Primary Line	1,400
Primary Line Fault Beyond 911 Building	1,463
Primary Line Fault at 1-Ph Tap to 911 Building	1,400
Primary Line Fault at 3-Ph Tap to Main Line	862

Figure 5 is a plot of the actual earth potential profile for a line-to-ground fault at the primary line serving the building distribution transformer.

GPR from Lightning Strikes

A more serious situation occurs during lightning storms. Before we review lightning problems, consider **Figure 6** which depicts lightning surge current. Lightning is a very fast movement of electrical charge, or "wave" of electrical charge. Unlike power line current where the electrical charge oscillates in a line at a relatively slow steady rate of 60 times per second, lightning is a wave of electrical charge moving at about 10 percent the speed of light. When lightning strikes an object such as a power line or the 911 communication tower, the lightning surge moves through that object attempting to reach the opposite electrical charge in the ground. The current of a lightning stroke can range from just a few thousand amperes to 200,000 amperes or more, depending on the severity of the stroke. Statistically, the average lightning strike reaches a peak of about 31,000 amperes. The lightning wave typically reaches its peak in just a few microseconds, and then tails off at a much slower rate of change. The wave shown in Figure 6 is a typical representation of a lightning strike adopted as a standard by the power industry. In this case, the current reaches its peak of 31,000 amperes in 1.2 microseconds, and falls to 50 percent of its peak in 50 microseconds. Because lightning is a fast movement of charge, the inductance of objects, including ground electrodes, becomes a major contributor to voltage drop as the surge flows through the object. The voltage produced across an object that lightning is flowing through is approximately equal to the inductance of the object times the rate of change in the current. As can be seen from Figure 6, the rate of change of the current in the first 1.2 microseconds is much greater than the rate of change after the current peaks.

Figure 7 depicts the four systems and the 911 facility during a lightning strike to the communication tower. As in the case for power system faults, the ground electrode experiences a GPR. However, the thing that is significantly different about this condition compared to the power system fault is that the lightning surge is flowing from the strike point through different components of the ground electrode and the connected power system neutral to reach the opposite charge in the earth. This moving wave produces different voltage magnitudes along the ground electrode as the wave moves through the conductor and into the earth. This is a major problem at the 911 facility because the radio equipment will be at one voltage while everything else, telephone equipment, computers, power system, and the operators themselves, are at a different voltage. This is a condition that will not only cause major equipment damage, but personnel injuries as well.

It is much more difficult to precisely calculate the voltages associated with lightning current flow than for power system faults because the magnitude of a lightning strike and the wave shape varies according to Mother Nature. However, to give an idea of the magnitude of the problem, if we assume the inductance of the ground grid is conservatively 0.5 micro-henries (0.5 X 10^{-6} H), and a 31,000 ampere lightning strike with a 1.2 microsecond time to peak, the GPR would be approximately:

$$GPR = L\,(di/dt) = (0.5 \times 10^{-6}) \times (31{,}000/1.2 \times 10^{-6}) = 12{,}917 \text{ volts.}$$

GROUND POTENTIAL RISE MITIGATION

Single Point Grounding

A major concern we discovered at the 911 facility is that the four systems (electric power, telephone, cable, and radio) are not grounded at a single point. All of the systems are connected to the buried ground electrode, but not at a single point. Single point grounding is important for protection of equipment and personnel during a lightning strike condition for reasons as follows:

When a lightning surge enters the 911 facility, the wave moves along all ground paths to reach the opposite charge in the earth. As the wave moves, an instantaneous voltage relative to earth is produced at the locations of the wave. Other equipment connected to the ground electrode will not necessarily be at the same voltage. This voltage difference across equipment can cause equipment damage as well as electrical shocks to personnel.

The way to mitigate this problem is to provide a single point where all of the systems' grounds are connected together and then connect this common point to the ground electrode. We have also identified some installation and application problems with the radio cable shield grounds. Our proposal will be to correct the problems with the radio cable shield grounds along with developing a single ground point for all four systems.

Surge Protection / Surge Dissipation

Direct lightning strokes to a 195 foot communications tower are inevitable. Therefore, it is critical to direct the stroke energy away from personnel and equipment. Lightning acts as a high frequency current source. This means that any strategy to divert lightning surge energy must consider inductive impedance in the design criteria. A properly designed tower system can divert up to 90 percent of the energy of a lightning stroke to ground before it reaches the building. This involves the proper grounding of the tower and the communication cable shields. UTEC noted that in Rockingham County the cable shields are grounded with wire cables that include sharp bends and loops. These bends and loops introduce inductive impedance into the path to ground and cause more of the energy to flow along the cable toward the equipment. Shield grounds should be straight, free of loops, and go directly to a large surface-area ground bus. The ground bus should have multiple large surface-area flat straps connecting the bus to the below-grade ground grid.

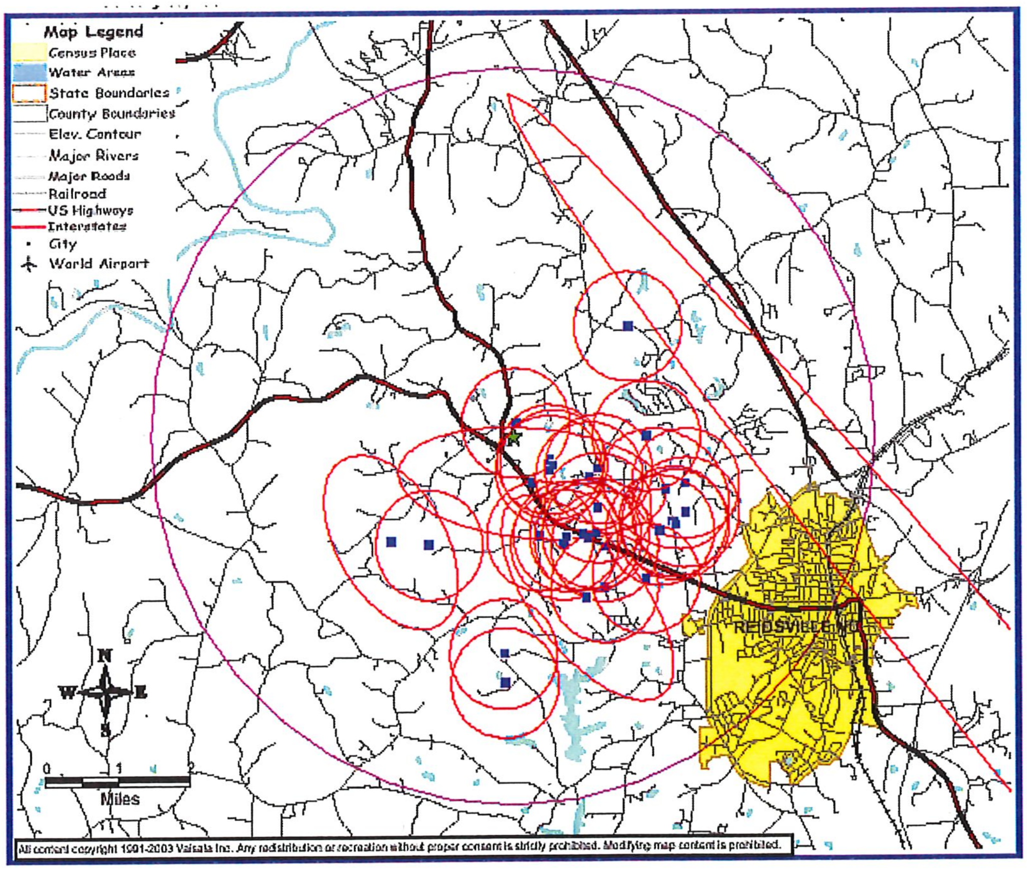
A second layer of protection against surge energy on the communications cables are surge protectors installed at the building cable entrance. Again, because of the high frequency nature of lightning surges, the surge protector ground connections should have the lowest inductive impedance possible. The surge protectors should be mounted to a flat copper bulkhead that has large surface-area straps connecting the bulkhead to the single point ground. UTEC noted at Rockingham County that only six of the 30 tower communication cables have surge protectors. None of the six are mounted to a bulkhead and all six had long wire ground leads that include sweeping loops.

Direct Stroke Protection

The National Fire Protection Standard NFPA 780, *Standard for the Installation of Lightning Protection Systems*, provides data for the expected lightning activity in Rockingham County. This standard indicates that the average lightning flash density in the area should be 3-flashes/km^2/yr. We have obtained actual lightning strike data within a five-mile radius of the 911 facility for 1999 through 2003. **Figure 8** show this data for this four year period. The actual stroke density at the location of the 911 building was 14 or greater strokes/km^2/yr. This stroke density is almost five times the expected levels shown in NFPA 780.

We obtained lightning strike data for each date that major problems have occurred at the 911 facility. As an example, lightning strike information within a 5-mile radius of the 911 facility is in the following table and plotted on the following map for August 29, 2003.

DATE	TIME	Amplitude in kA	DATE	TIME	Amplitude in kA
8/29/2003	16:52:06	-10.32	8/29/2003	16:57:33	-13.84
8/29/2003	16:52:42	-10.49	8/29/2003	16:57:34	-15.67
8/29/2003	16:52:58	-9.75	8/29/2003	16:58:28	-22.98
8/29/2003	16:53:55	-10.01	8/29/2003	16:58:28	-14.43
8/29/2003	16:53:55	-9.58	8/29/2003	16:58:28	-9.16
8/29/2003	16:54:14	-17.45	8/29/2003	16:58:28	-17.3
8/29/2003	16:54:36	-12.71	8/29/2003	16:58:28	-15.82
8/29/2003	16:54:46	5.37	8/29/2003	16:59:19	-15.17
8/29/2003	16:55:23	-18.44	8/29/2003	16:59:19	-19.33
8/29/2003	16:55:23	-11.99	8/29/2003	16:59:19	-7.55
8/29/2003	16:56:16	-13.95	8/29/2003	16:59:19	-7.14
8/29/2003	16:56:16	-7.44	8/29/2003	17:00:22	-15.6
8/29/2003	16:56:16	-35.35	8/29/2003	17:00:22	-11.53
8/29/2003	16:56:59	-34.37	8/29/2003	17:00:22	-20.02
8/29/2003	16:56:59	-8.08	8/29/2003	17:57:02	5.79 3
8/29/2003	16:56:59	-13.69			



The table shows that 31 strikes occurred on this date. The table also shows the magnitude of each lightning strike.

We do not know why the stroke density is so great in Rockingham County. However, the more important issue is to properly protect facilities so they can sustain such lightning strikes without damage.

"Direct Stroke Protection" is protection of the building from direct lightning strikes. In actuality, the communication tower provides direct stroke protection of the building. It is very unlikely that a lightning strike would hit the building because the building is within the "zone of protection" provided by the tall tower. However, lightning will occasionally "jump" from a struck object to other nearby objects. In this case, the nearby object is the 911 building. Rockingham County 911 employees have witnessed this happening inside the facility a couple of times. The reason lightning can jump from one object to another is because the air insulating capability breaks down and the lightning wave finds a lower impedance path to ground through the other object. Unfortunately, there is no practical way to prevent this from occasionally happening at the 911 facility. What is needed is the ability for the structure to properly handle a lightning surge when it does jump from the tower to the building. To accomplish this, we are recommending the installation of several lightning rods and interconnecting conductor along the ridge of the building and the chimney, and the installation of down conductors to connect directly with the below-grade ground electrode. The direct stroke protection system will be kept isolated for the other building ground conductors except for the connection to the below-grade ground conductor. The installation will be laid-out to provide **halo-ground** shield for the building. The idea of a halo-ground is to provide a low impedance metallic path to ground should lighting flash-over from the tower to the building.

Remote Ground Isolation

The telephone conductors, cables, and radio systems are provided with surge suppressors. These devices are designed to operate, or short circuit, when the voltage impressed on them exceeds the rating of equipment being protected. While these devices are necessary and do a good job protecting the equipment from some induced surges, these devices do not protect the equipment or personnel from GPR. In fact, when these devices operate, the conductors are parallel with the shields and current flows from the elevated 911 building ground electrode in the reverse direction to the remote locations. The only solution is to install devices to "isolate" the incoming communication circuits. Isolation is accomplished using either optical isolators or isolation transformers. These devices isolate the incoming lines and thus prevent current flow. With no path for outgoing current to flow, there will be no harm to equipment or associated operating personnel.

Equipment and Personnel Insulation

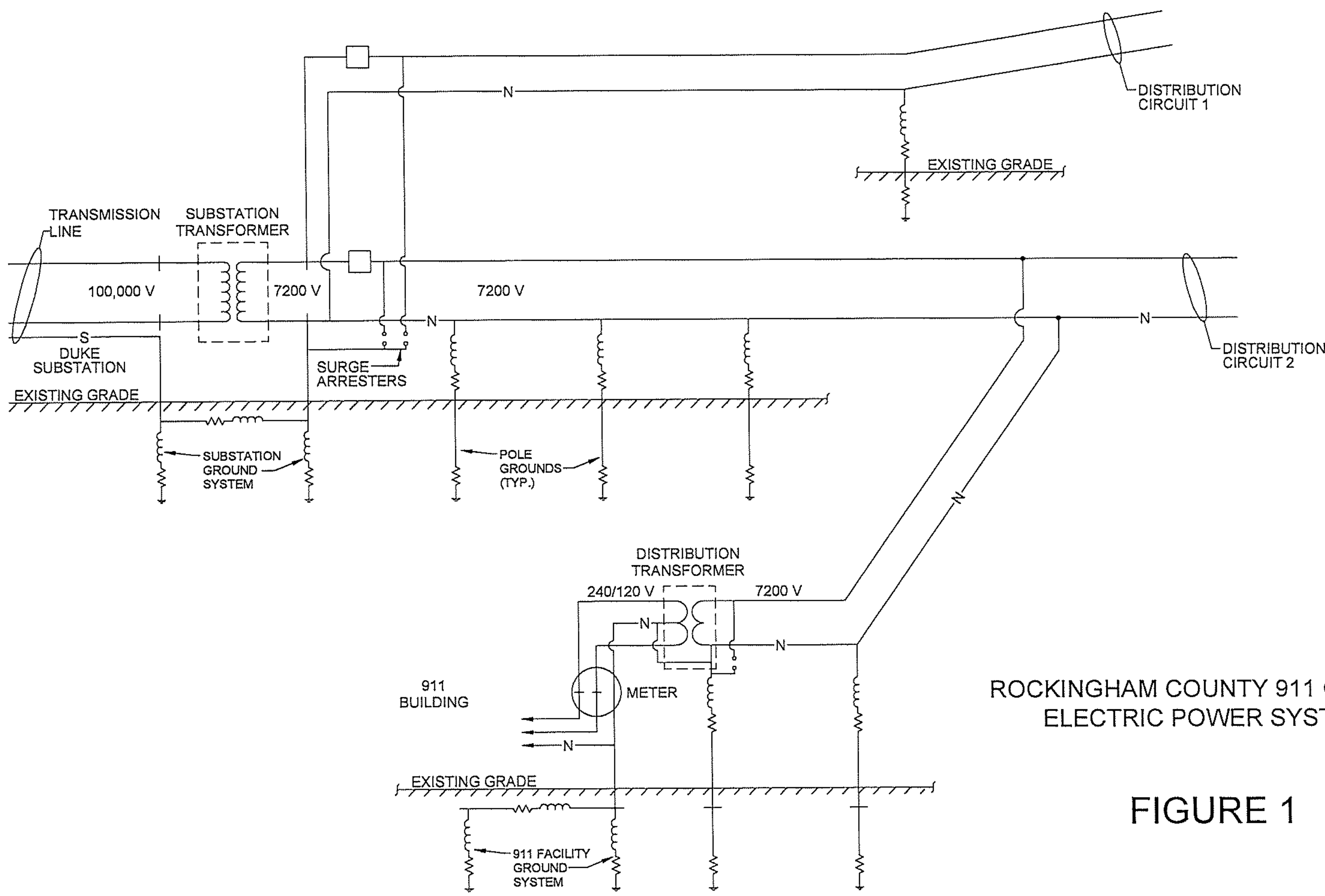
With the installation of single point grounding and telephone cable insulation, all equipment will be of the same potential. However, one problem still exists. During lightning strikes and fault conditions, the concrete building floor may be at a different potential than the single point ground. Personnel standing on the concrete floor, will be at the floor potential. To insulate personnel and equipment from the floor, we recommend the installation of rubber or phonellic insulating plates for equipment to sit on. We also recommend the installation of ¼" rubber flooring throughout the entire building floor.

Tower Location

Tower location at the Rockingham Country 911 center is purely an academic issue since neither the tower or the building can be moved. However, in the design of a new facility, the tower location relative to the building is important. Issues include the distance of the tower to the building (flash-over distance) and the elevation and angle of cable entrances into the building.

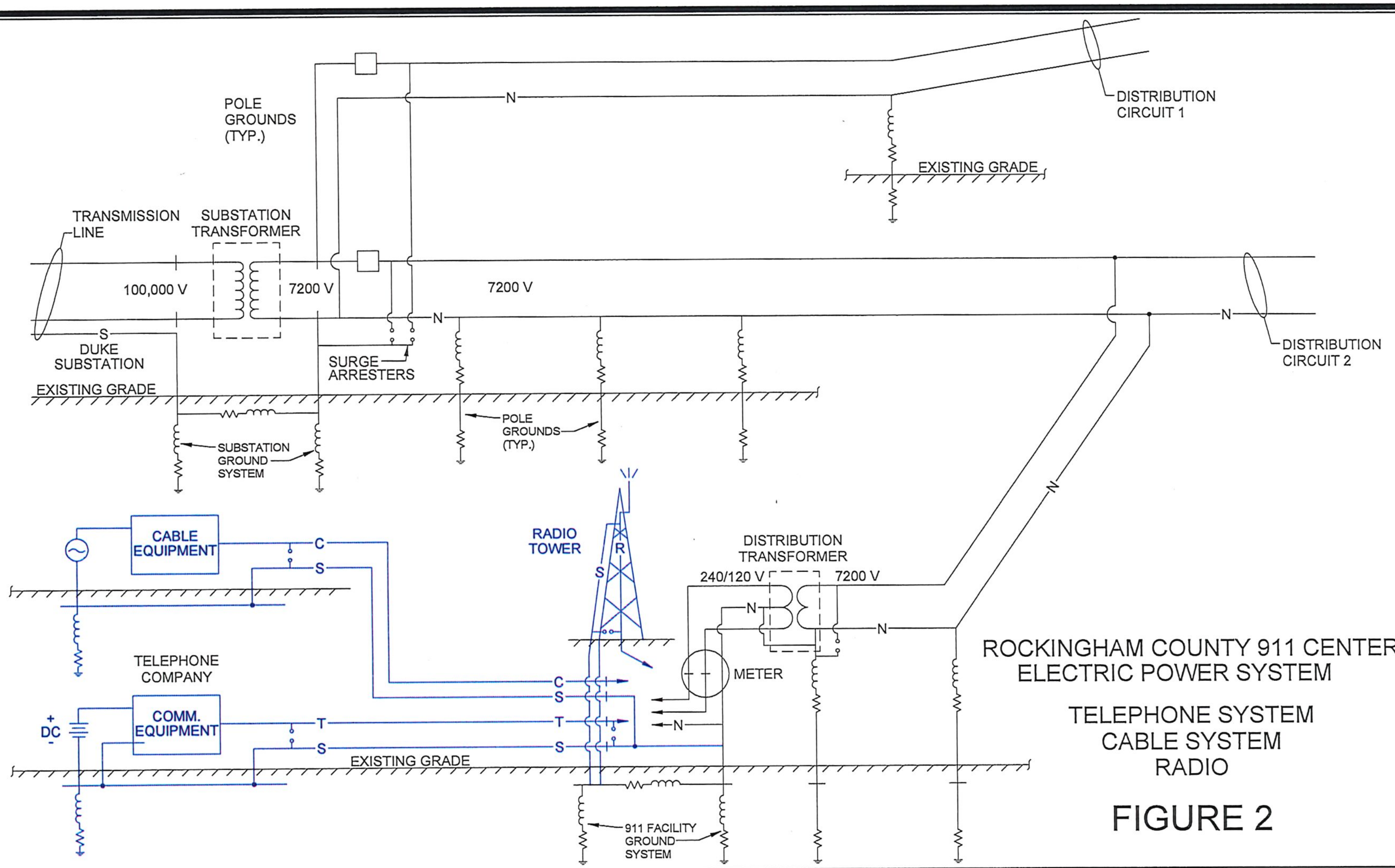
Summary

- The equipment failure and shock problems are occurring because of GPR caused by power system faults and lightning strikes to or near the communication tower.
- The power system, telephone lines, and cable TV lines bring connections to remote earth into the 911 building.
- Modifications to mitigate the problem are:
  - ♦ Provide a "single point" for connecting all systems' grounds, then connect that single point to the below-grade ground electrode.
  - ♦ Improve the surge protection system.
  - ♦ Insulate the incoming telephone lines so GPR can not be transferred away from the 911 site.
  - ♦ Install lightning rods and a halo ground system to intercept any strikes that jump from the tower to the 911 building structure.
  - ♦ Insulate all equipment from the concrete floor.
  - ♦ Install rubber insulated flooring in the building.



ROCKINGHAM COUNTY 911 CENTER
ELECTRIC POWER SYSTEM

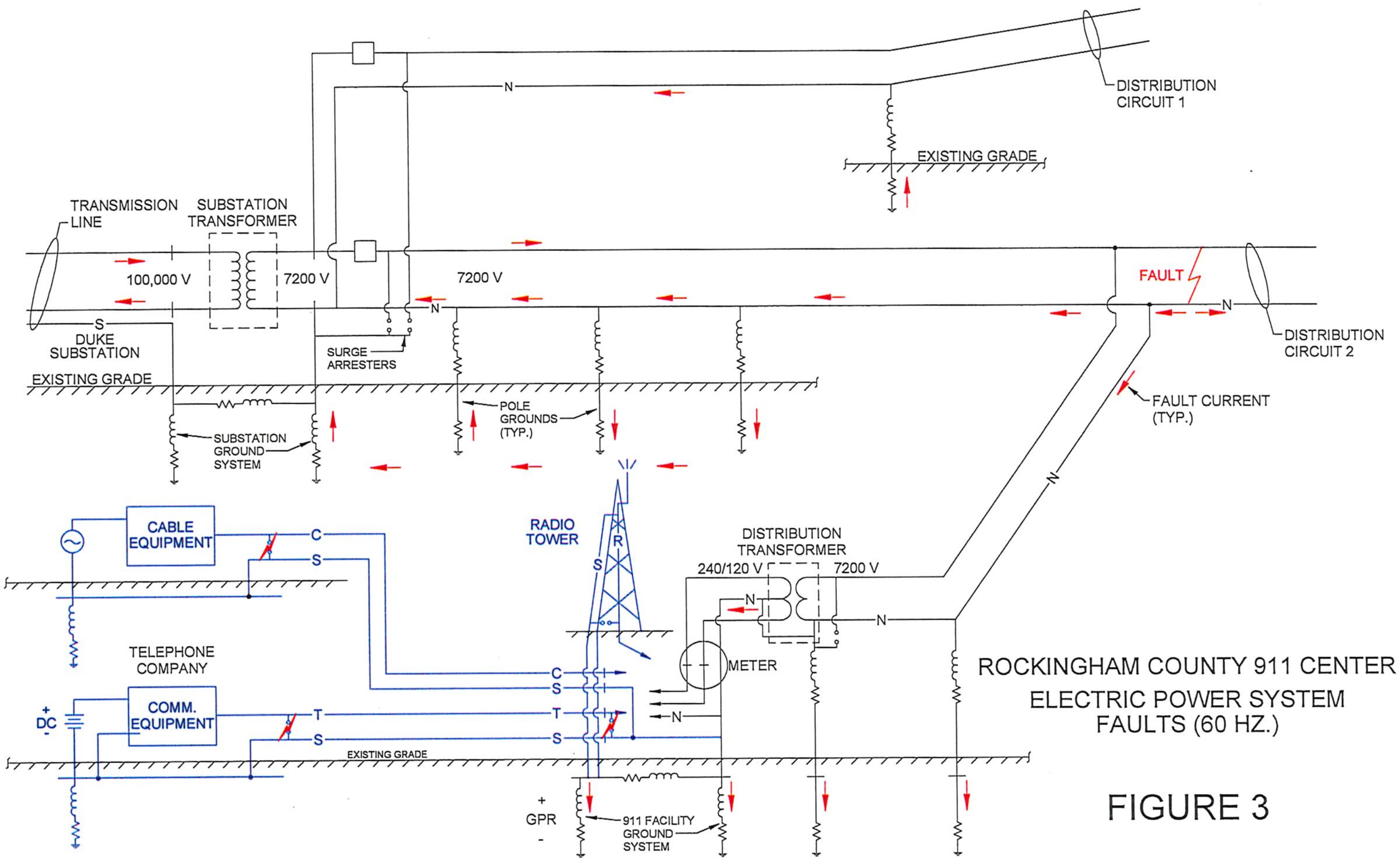
FIGURE 1



ROCKINGHAM COUNTY 911 CENTER
ELECTRIC POWER SYSTEM

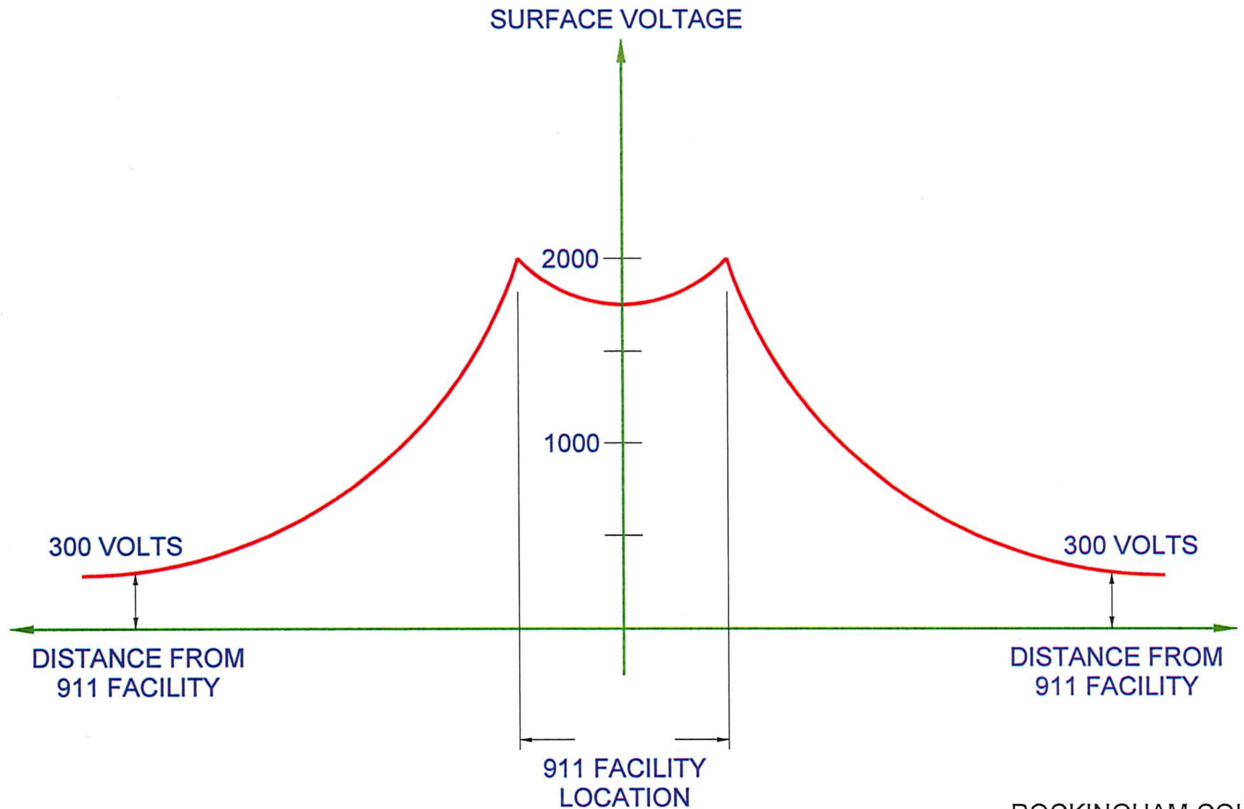
TELEPHONE SYSTEM
CABLE SYSTEM
RADIO

FIGURE 2



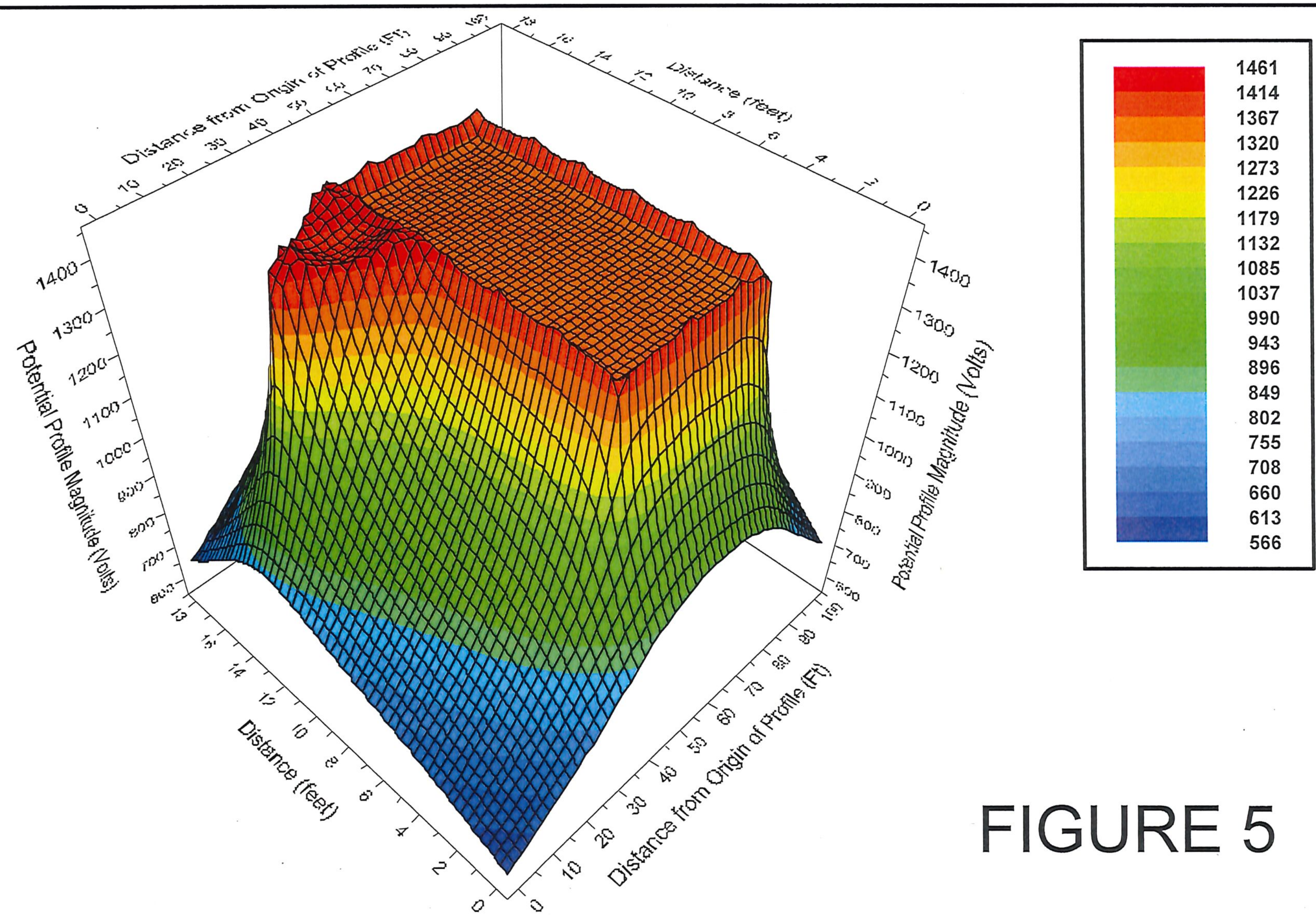
ROCKINGHAM COUNTY 911 CENTER
ELECTRIC POWER SYSTEM
FAULTS (60 HZ.)

FIGURE 3



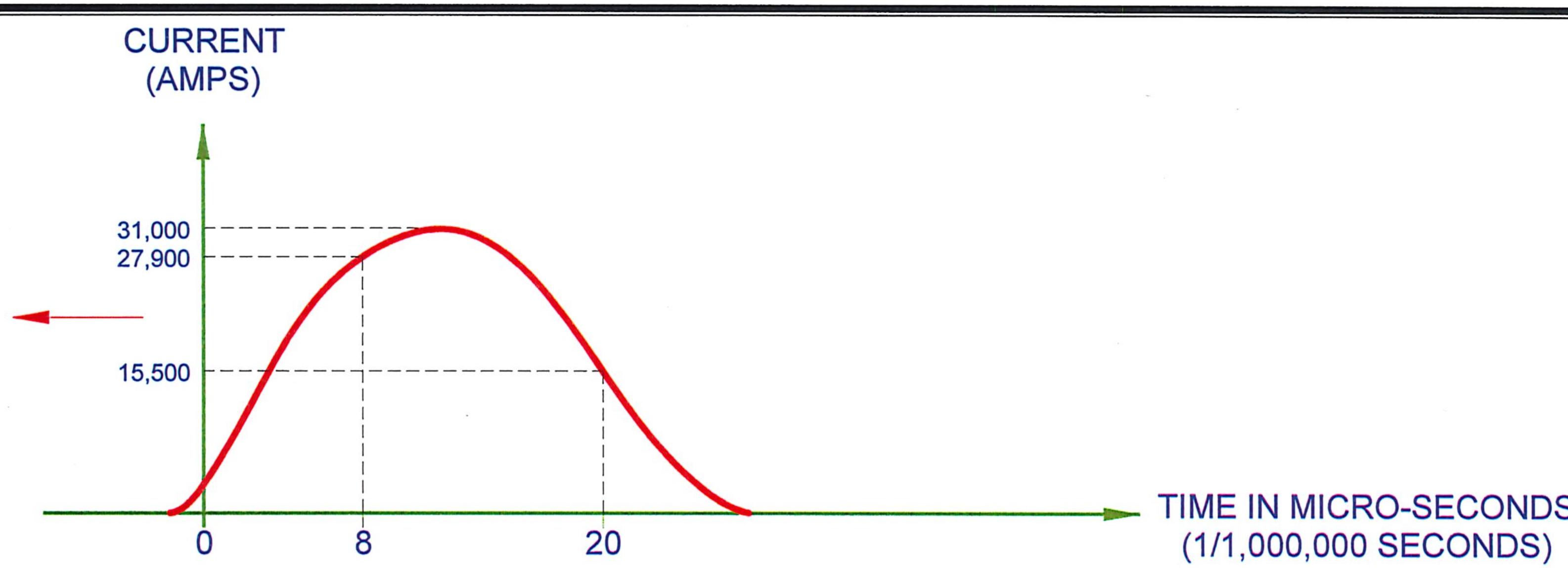
ROCKINGHAM COUNTY 911 CENTER
ELECTRIC POWER SYSTEM
GROUNDING POTENTIAL RISE
FAULTS (60 HZ)

FIGURE 4



Potential Profile Magnitude (Volts)
Distance (feet)
Distance from Origin of Profile (Ft)
1461
1414
1367
1320
1273
1226
1179
1132
1085
1037
990
943
896
849
802
755
708
660
613
566

FIGURE 5



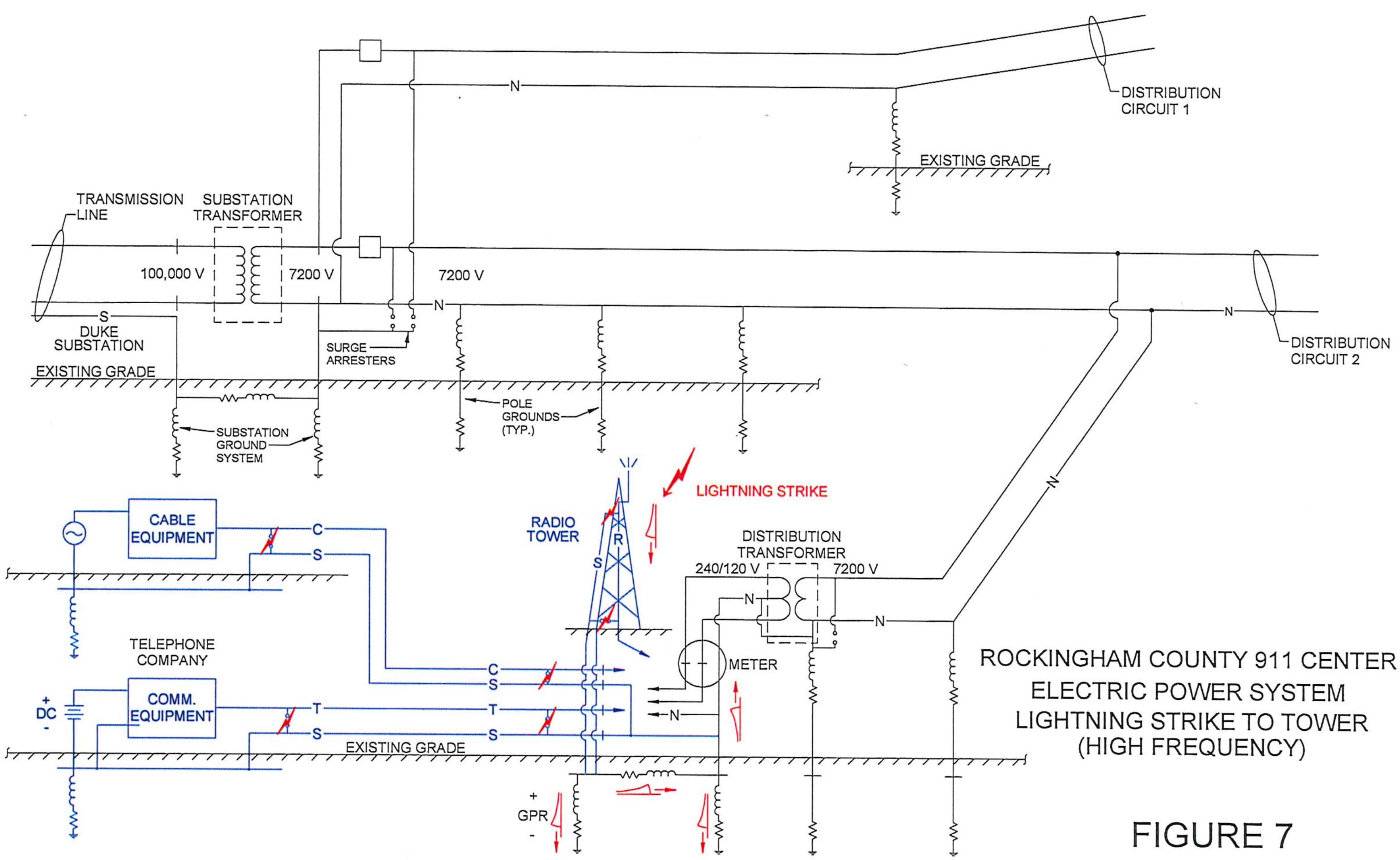
VOLTAGE PRODUCED BETWEEN OBJECT CONDUCTING LIGHTNING AND EARTH = $L\left(\frac{di}{dt}\right)$

WHERE
L = OBJECT INDUCTANCE
di = CHANGE IN CURRENT
dt = CHANGE IN TIME

ROCKINGHAM COUNTY 911 CENTER
ELECTRIC POWER SYSTEM

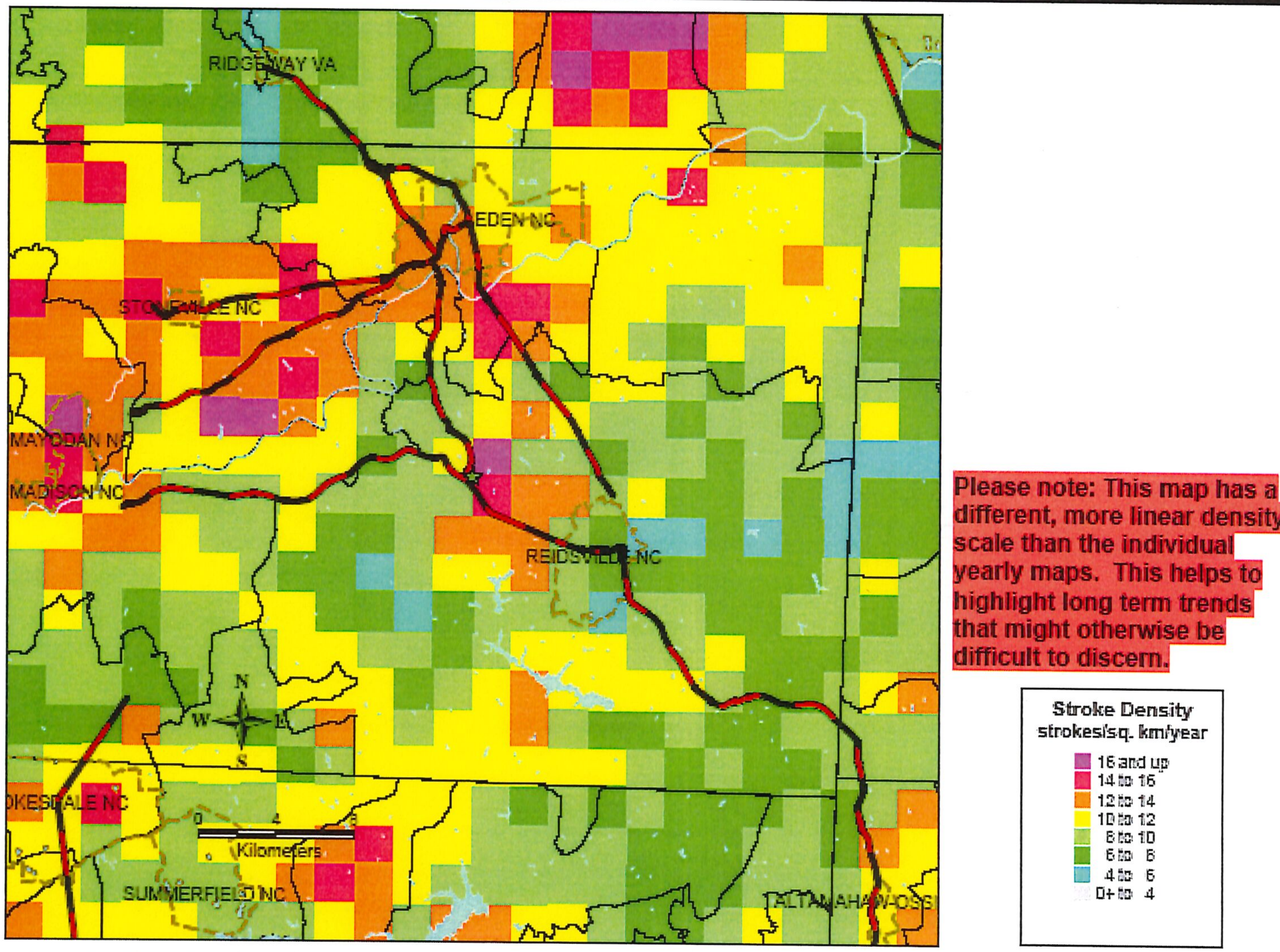
REPRESENTATION OF
LIGHTNING CURRENT

FIGURE 6



ROCKINGHAM COUNTY 911 CENTER
ELECTRIC POWER SYSTEM
LIGHTNING STRIKE TO TOWER
(HIGH FREQUENCY)

FIGURE 7



VAISALA

Utility Technology, Engineers - Consultants

Facility Site Analysis

1999 - 2003 Average Stroke Density Map

Jan 1, 1999 00:00:00 EST
To
Dec 31, 2003 23:59:59 EST

FIGURE 8