THE LINE VOLTAGE ANOMALY PROBLEM

The Destructive Phenomena

Table 1 subdivides destructive anomalous voltage events into natural and man-made causes and lists the most common potential sources. Lightning is a primary source of natural destructive anomalies. The lightning risk factor is related to the isokeraunic number for the area of concern, the character and location of the facility to be protected (the exposure factor) and the probability factors related to the lightning stroke itself.

POTENTIAL ANOMALY	NATURAL CAUSES			MAN-MADE CAUSES			
	CLOUD-TO-GROUND LIGHTNING	CLOUD-TO-CLOUD LIGHTNING	TORNADOS	PUBLIC UTILITY	OTHER CUSTOMERS	OWN PLANT	ACCIDENTS AND EXPLOSIONS
OVER-VOLTAGES				X			X
UNDER-VOLTAGES				X			X
SURGES	X				X		X
TRANSIENTS	X	X	X		X	X	X
EMP	X	X					X
SINGLE PHASING	X			X			X

Table 1. Potentially Destructive Power Mains Anomalies.

The isokeraunic number (number of lightning days per year) can vary from a low of near zero for the arctic regions to a high of over 265 for some equatorial regions. While the maximum for the U.S.A. is 100 (for central Florida), the average is about 35. Specific values for a given area can be obtained from a World Meteorological Society publication[1].

The isokeraunic number can be used to estimate the probability of lightning for a given day (if seasons are disregarded) and the number of strikes that may be expected to terminate in any given area for that year. In applying these data two factors must be considered in concert. First, the number is an estimator only, and the actual value can vary considerably. More significantly, only one strike can cause irreparable damage to electronic systems.

In general, lightning results in three specific, but different, forms of hazard: direct strikes producing power or energy surges, induced transients from nearby strikes, and the EMP from the strike's magnetic field.

A direct strike to any or all phase conductors near or at some distance from the facility will create a power surge. The character of this surge is therefore directly related to the character of the lightning strike, the line it strikes and the distance to the point of concern. To define the character we must look at specific cases or quantify the character relationships. The significant factors include stroke rise time, stroke peak current, distance between strokes and the facility or the resulting line impedance and the grounding resistances at significant points in between. One significant factor is shown by Figure 1, where the surge voltage is estimated for an average lightning strike for various distances from the station of concern. These numbers must be greatly increased for higher energy strokes. Some measurements indicate that these voltages could achieve levels in excess of 100 Kv if the wire insulation would support that potential without arcing, and if the measurement point were near the stroke. The higher voltages seem to be the norm rather than the exception for communications sites and FM and TV transmitters at remote mountain-top sites.

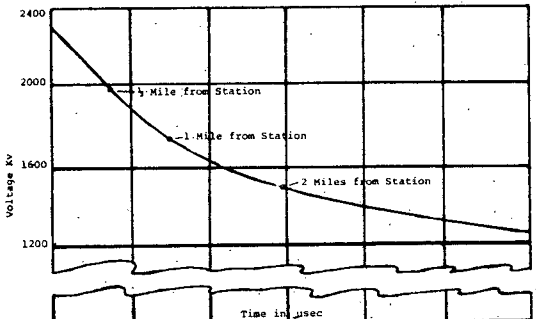

Figure 1. Sample Surge Voltage as a Function of Distance from Stroke to Line.

Table 2 presents a summary of the range of pertinent parameters which were taken from many sources and represent a compilation of many works [2-6]. The shape of a typical lightning stroke current is such that it rises rapidly to its peak and then tapers off relatively slowly, following a log-normal shaped curve. There are two classes of lightning strokes: the impulsive stroke and the non-impulsive, or "hot," stroke. This characteristic determines the damage caused. The impulsive stroke is the one that creates most of the damage to electronic systems since it embodies a large percentage of high frequency energy. The rate of rise exceeds 10,000 amperes per microsecond and can achieve rates of over 100,000 amperes per microsecond. An impulsive stroke usually lasts for no more than 100 microseconds.

Charge Range	- 2 to 200 Coulombs
Peak Currents	- 2,000 to 400,000 Amperes
Rise Time to 90%	- 300 Nanoseconds to 10 Microseconds
Duration to 50%	- 100 Microseconds to 10 Milliseconds
Potential Energy at 99%	- 10^{10} Joules*

* Only a small portion is manifested in a surge, usually less than 10,000 Joules.

Table 2. Significant Lightning Stroke Characteristics.

The non-impulsive or hot stroke rises much slower than the impulsive stroke, as slowly as 500 amperes per microsecond. However, it usually lasts much longer, extending out to as long as 10 milliseconds to the 50 percentile. This type of stroke is responsible for many fires and explosions.

Induced transients are the second order effects of lightning activity in or near the area of concern. Their character is related to the lightning discharge and the system character into which the transient is induced. In general they are high voltage, low energy disturbances. Estimates of the potential for this phenomenon range up to 100 Kv (this value is more dependent on the system circuit parameters than lightning). Installation breakdown levels usually limit the peak voltages to much lower levels, except on primary feeders. Public utilities have found that this phenomenon accounts for most of the lightning faults on lines with a potential of 20 Kv and lower. Lines as short at 50 feet can pick up a significant transient, depending on their proximity to the stroke [7]. Induced transients tend to take a shape related to the first differential of the stroke itself: short, negative and/or positive having high voltage pulses of lower energy, but often destructive potential.

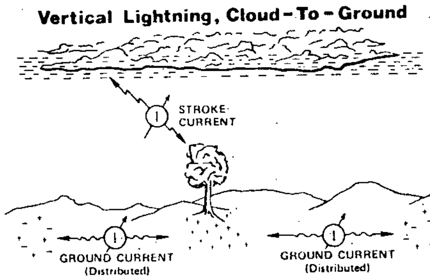

Figure 2.

Induced transients are created by one of three different, but related, phenomena. They are the result of the invisible, but highly potent, electrostatic field found between the charged clouds and the earth. This field moves and varies in strength with the charged cloud activity. Cloud-to-earth strikes create the situation shown in Figure 2; cloud-to-cloud strikes create the situation shown in Figure 3.

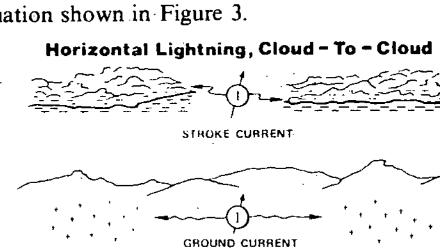

Figure 3.

Atmospherically induced transients are created by sudden variations in the electrostatic potential of the atmosphere. Where the clear air electrostatic field may be 150 volts per meter elevation above the earth, this field can achieve levels of up to 30,000 volts per meter of elevation during an electrical storm. A lightning discharge to the earth or another cloud will cause this field to collapse, leaving a bound charge on any conductor within its influence. The resulting charge seeks ground through any available path, even jumping large insulators in the way. This creates a voltage pulse that can exceed 100,000 volts. Transients resulting from electrostatic field changes are propagated over long distances. For example, an average energy, cloud-to-cloud discharge or a strike to earth one mile away will induce as much as 70 volts per meter of exposed wire into a thus connected system (see Figure 4).

Atmospheric Transients

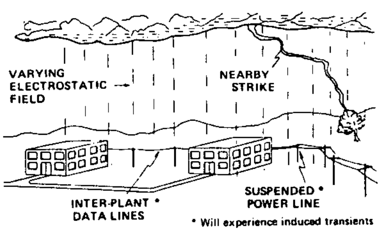

Figure 4.

Earth current induced transients are created by lightning strikes to the earth at or near the facility of concern. With the termination of a stroke to earth all the charge induced into the earth by that cloud must move from the point where it was induced to the point of impact of the stroke (see Figure 5), and thereby neutralize the charge. As a result of this motion of the induced charge, earth currents are set up within the earth's crust *near the surface*. Any good conductors buried in the earth within the charged area will provide a preferred path for these earth currents and thus be the recipient of these severe earth currents. The results are induced transients within the conductor directly related to the earth current character. Current along the sheath of wires will induce transients into the inner conductors through mutual induction or these currents will be superimposed on the conductors without sheaths.

Earth Current Transients

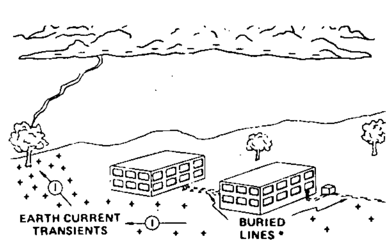

Figure 5.

Figure 6 illustrates two other forms of earth current transient effects. The results on the connected system are the same regardless of the cause.

Some Earth Current Transients

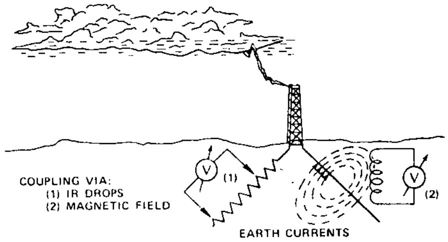

Figure 6.

Electromagnetic field induced transients are also created by lightning discharges. For this phenomenon, the lightning flash channel acts as a large vertical radiator or antenna. The large, rapid flow of current down the ionized lightning flash channel sets up a rapidly changing electromagnetic field propagating out from the stroke channel in much the same fashion as AM broadcasting stations. This flow of current is the cause of static in a radio receiver and reflected waves in the transmitters and transients in nearby conductors, as shown by Figure 7. Generally, cloud-to-cloud strokes produce predominantly horizontally polarized waves while the cloud-to-earth strokes produce vertically polarized waves. The di/dt's often exceed 100,000 amperes per microsecond.

Electromagnetic Field Induced Transients

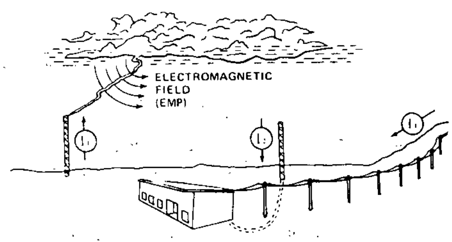

Figure 7.

Tornados create a cyclic variation in the atmospheric field; the induced transients are of a shape similar to a poor sawtooth generator. This phenomenon is the result of a charge separation within the eye of the twister and its rotary motion. As the twister rotates the induced voltage rises and falls with, and at the frequency of rotation of the twister. The induced potentials can be damaging to electronic systems if the twister passes near an area of concern.

To protect against all of these destructive forms of induced transients, regardless of their cause, the protective equipment must be designed to satisfy the worst case situation, i.e., at least 99 out of 100 possible events. The protective requirements include the following:

Transient Energy	- 500 Joules
Transient Peak Current	- 20,000 Amperes
Transient Peak Voltage	- 6,000 Volts
Transient Rise Time	- 50 Nanoseconds

IEEE Standard 587-1980 presents a summary of findings from several sources. Figure 8 presents a composite of pertinent transient data as recorded by different investigators.

Combined Transient Recording Data (IEEE)

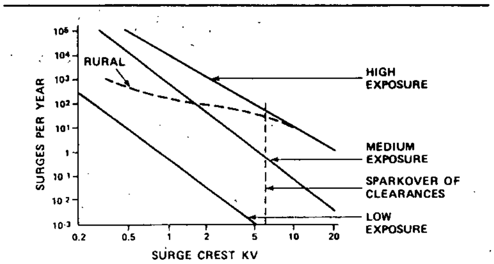

Figure 8.

Man-Made Disturbances or Hazards

Man-made disturbances come from the electrical system's environment as created by man. Again, these disturbances can be the result of a directly injected phenomenon or an externally induced phenomenon. It is futile to attempt to define all the potential causes, but the following identifies and deals with some of the more significant possibilities. Man-made disturbances may be subdivided into those caused by electromagnetic or electrostatic fields and those caused by some form of "accident."

Man-made electromagnetic field transients are usually created by poor installation practices or inflexibility in the plant layout. For example, the power lines for large motors and power lines for sensitive electronics are laid side-by-side in the same cable tray or raceway.

During the planning stages for a plant, it should be understood that power lines carrying any large loads will also carry and/or create transients on those lines as well as lines nearby. Electric motors with poor commutators will radiate transients into nearby lines and cause malfunctions in any electronic equipment sharing the common source of power; SCR switches, switching power supplies and the like are common offenders.

Directly injected hazards are usually the result of Murphy's Law at work. The possibilities are as diverse as the industry itself. Some common examples, that have happened include:

1. High voltage wires dropping onto the lower voltage lines, arcing over them, or striking them in high winds or accidents.
2. Failure of insulation or isolation devices which inject a high voltage onto the lines. This happened three times in one year at three similar facilities separated by thousands of miles. In all three cases a related computer was destroyed.

The electromagnetic pulse (EMP) resulting from a large atmospheric explosion, usually nuclear, will also create this phenomenon. The character of the EMP is usually considered similar to lightning, but with much faster rise times (nanoseconds) and much shorter duration (only a few microseconds). The energy induced into a facility can be very high if it is located near the center of the explosion, in excess of 100,000 joules.

Disruptive Transients

A disruptive transient is some form of voltage anomaly of less than a half cycle duration that is superimposed on the power line (mains) at a potential below the destructive level of the equipment it feeds, yet high enough to impair proper operation or significantly reduce the data or equipment reliability (mean time before failure).

The causes of disruptive transients are similar to those classified as destructive, but at lower voltage levels. Specifically, they include atmospherically induced transients, earth current induced transients, EMP induced transients and all of the man-made anomalies. In addition, disruptive transients can be caused by radio frequency interference (RFI) which is created by:

1. Cross coupling between cables in the same cable tray or raceway,
2. Nearby radio, AM, FM or TV stations, radar, or
3. Other types of equipment, such as motors or welders, any varying high current load using the same feeder, or radiated energy from nearby equipment which is manifested in the form of electromagnetic or electrostatic fields.

The potentials and forms of disruptive transients are related to the lines on which they are induced. The parameters of concern are:

1. Peak noise or transient voltage, found to vary from insignificant to values approaching the destruct level, i.e., nearly 400 volts peak-to-peak on a 120 volt RMS line and over 800 volts peak-to-peak on higher voltage lines. All are usually of very short duration, a few microseconds.
2. Radio frequency interference usually takes the form of a damped sine wave with peak voltages as in (1) above for the first cycle and frequencies extending from harmonics of the primary power source to the very high frequency band.

Disruptive Primary Power

The primary power source itself can be disruptive, even if it is clean of surges and transients. The four forms of disruption include:

1. loss of power;
2. loss of a phase;
3. under voltage; and
4. over voltage.

Loss of power may not need defining, but the related risk is important to facilities planners. To that end, public utilities data indicate that the risk of cumulative power loss is less than one hour per year for most locations in the well-developed countries; i.e., the power source reliability is about 0.9999 or there is less than one chance in 10,000 of losing the power for a cumulative total of one hour in a year.

Loss of One or More Phases (Momentary and Extended)

Single phase loss is a more frequent anomaly than complete loss of power, but there is no good statistical data as to the frequency of occurence. Data obtained by polling public utilities seem to indicate that the single phasing incidents are predominantly related to the lightning activity, and the frequency of occurrence is related to system exposure. It therefore follows that long overhead runs through high isokeraunic areas will experience more single phasing actions than systems buried or in urban areas.

Momentary Outages

Momentary power outages are by far the most predominant anomaly. They are caused by lightning arrestor actions on the transmission or distribution lines, substation relay tripout and reclosure, or insulator flashover often followed by tripout. These actions usually clear in a few cycles, but sometimes can take up to ten. As an estimate the average is three and the upper 99.9 percentile is about ten.

Extended Outages

Extended outages are usually the result of a system component failure or failure of an arc or insulator flashover to clear after several relay actions. Again, no reliable data on the length of these extended outages are available, but as previously stated the probability of such an event is extremely low, less than one chance in 10,000 for an extended outage in the well-developed countries.

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Please refer to Lightning Symposium on page 260.