Lightning Protection for Modern Signal Systems

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ABSTRACT

In this paper we present our approach for lightning protection of modern signal systems. The approach is driven by the need to have highly reliable signal systems in order to greatly reduce system downtime and corollary economic losses.

The approach relies on the fundamental concepts of stress and strength, and the basic principle of keeping lightning away from the signal system electronics. Implementation of the approach to both new and existing installations is described.

1.0 Introduction

Lightning protection of signal systems is necessary in order to increase their reliability and availability. Experience has shown that signal system lightning outages can cause significant train delays with resulting losses in revenues.

The need for lightning protection has increased with the transition from relay based technology to microprocessor based signal systems. Because of this, it is necessary to implement corresponding protection methods which take into account the physical processes of transient damage to low-level solid state electronics.

The methods we present here are not new, in that they have been successfully implemented in other industries. We do believe, however, that the application of these methods to railroad signal systems is new.

In this paper we present the following:

- The rationale for lightning protection
- Overview of lightning problems in existing systems
- The CSXT approach
- Implementation methods
2.0 **Rationale for Lightning Protection Requirements**

The basic requirement for lightning protection is economic. Lightning has proven to be a significant cost factor in that loss of signal systems with resulting train delays can cause losses of millions of dollars of revenue in a year.

For example, in 1994, CSXT experienced 1414 documented lightning incidents of various degrees of significance. In addition, many events result in damage which is repaired and not documented. These events occur over the entire CSXT system, which occupies nearly all of the eastern half of the United States.

The lightning exposure can be illustrated with the map shown in Figure 2.1, which is an overlay of CSXT trackage and lightning flash density for the year 1998. The map clearly shows that CSXT assets are located in the highest flash density areas of the United States.

Before implementation of microprocessor-based signal systems, the relay-based systems were fairly robust in a lightning environment. As the solid state systems came into use, it became apparent that the existing lightning protection methods were inadequate.

There is therefore a need for lightning protection methods which result in highly reliable signal systems.

3.0 **Overview of Lightning Issues**

3.1 Typical Wayside Wiring and Installation Practices (Former CSXT Standard)

Wayside signal systems usually are inside a metal bungalow or signal case, although other structural materials are possible. For purposes here, we will consider only the metallic bungalows. Typical configurations are shown in Figures 3.1 and 3.2.

Buried signal cables (black) penetrate the bungalow floor through a cable chute, and are attached to AAR connectors on a wooden terminal board (TB). These black wires can be called “dirty”, because they can have the full external lightning environment on them.

Usually only the AC cables and the track wires have arresters. The track wires penetrate the TB, attach to an arrester and a blue case wire which penetrates the TB again. The blue wire is mixed with the dirty wires, and is routed on to the electronics. The blue case wires can be called “clean”, because they have been cleaned up by the arrester.

The arrester itself is a standard air gap, and is attached to the local ground reference by a “ground bus” or a cable which can be several inches or feet long.

The above wiring and installation practices reveal the following lightning protection issues:
-Lightning is brought directly into the electronic volume where the electronic signal systems are located.

-The mixture of clean and dirty wires greatly reduces the benefits of the arresters.

-The long “ground busses” for the arresters creates a large inductive voltage drop which may be larger than that of the arrester itself.

-The arrester let-through voltage is too large for solid state electronics

We now discuss each of these issues in more depth.

3.2 Direct Lightning Penetration into the Signal Equipment Volume

The basic rule of lightning protection is to keep lightning out the area in which the signal system electronics are located.

With this in mind, an aluminum bungalow has a very desirable property, in that the skin material provides an excellent electromagnetic shield, which has the capability of isolating the internal volume from the external lightning environment. However, the shield is violated by the direct injection of the lightning currents, via the signal and power cables, into the volume of space which houses the electronics.

Violation of this rule frequently occurs with other aspects of wiring and cabling practices as well. For example, there are some instances in which the ground wire from an external ground rod is allowed to penetrate into the bungalow interior through a hole in the bungalow skin. This practice allows lightning currents on the ground wire to get directly into the bungalow interior.

In addition, sometimes RF coaxial cables are allowed to penetrate the bungalow skin without having their shields circumferentially bonded to the skin with a bulkhead RF connector, as shown in Figures 3.3 and 3.4. Because the cable goes to the top of a tall antenna mast which can be struck directly by lightning, this practice allows 10’s of kA of lightning current to penetrate directly into the bungalow, coupling or arcing to nearby signal or power cables.

The practice of shield penetration by unprotected conductors is so notorious that the High Power Electromagnetics Community (mostly military) has a tongue in cheek but real award for persons who find this practice in a protected installation. The award is presented at every international High Power Electromagnetics Conference, which is held every two years. The name of the award is AZED (German: Abshirmungszerstorungserdungsdraht, meaning ”shield destroying wire”). The purpose of the award is to create awareness of so-called protection practices which in fact make matters worse.
Therefore, the first and fundamental function of the lightning protection approach must keep lightning away from the signal system electronics.

3.3 Mixing of Clean and Dirty Wiring

The mixing of clean and dirty wiring is a serious issue. The clean wires, downstream from the arresters and in close proximity to the dirty wires, can be significantly contaminated again by the the lightning currents flowing on the dirty wires. The process occurs mainly because of magnetic field coupling from one wire to the other.

This issue has been quantified by experiment and numerical analysis. Results are shown in Table 3.1. These results are for two wires 12 inches above a perfectly conducting plane, and the wires are various distances from each other. The results are for wires which are shorted to the ground plane on each end, and therefore the results are independent of wire length.

The results show that for two wires which are separated only by their insulation, the clean wire can have as much as 70% of the current on the dirty wire. Even when separated by 12 inches, 13% can be induced.

It is therefore necessary that the lightning protection approach must not allow clean and dirty wires to interact with each other.

Table 3.1 Induction of Dirty Wire Current on Clean Wires. Dirty Wire Current is 10kA.

<table>
<thead>
<tr>
<th>Distance between Wires (inches)</th>
<th>close</th>
<th>3</th>
<th>6</th>
<th>9</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Induced on Clean Wire (kA)</td>
<td>7</td>
<td>4</td>
<td>2.5</td>
<td>1.9</td>
<td>1.3</td>
</tr>
</tbody>
</table>

3.4 Long Ground Busses

The terminology “ground busses” is misleading. It seems to imply that this conducting metal strip or cable is able to somehow provide a sink for undesirable current, such as from a lightning event.

However, any metal conductor has inductance which impedes the flow of current, therefore creating a voltage. The situation is illustrated in Figure 3.5. The resultant inductive voltage drop is larger than that of the arrester.

It any lightning protection approach, therefore, it is necessary to minimize this inductive voltage drop.
3.5 Air Gap Arresters

Air gap arresters have been used for a long time in the railroad industry, and have worked well with relay based systems.

We have measured their let-through under simulated lightning conditions (Figures 5.3 and 5.4), and have found that the let-through of the arrester mounted on an aluminum ground plane is on the order of 2200 V, and lasts a fairly long time. This is the voltage at the arrester itself. At the equipment end of the cable connected to the arrester, the voltage can be much larger, (more than 3000 V has been measured), because of transmission line or circuit loading effects.

We believe that this voltage is too large for electronic equipment and should be reduced. This is because of the statistical and cumulative nature of lightning damage to electronic systems, resulting in reduced reliability, as described in Section 4.2. These voltages are also large enough to induce transients on “buried circuits”, circuits which are not directly at the interface of the electronic system to the external cables.

In particular, it is possible to reduce the let-through to about 100 V, which should result in increased reliability. In addition, this approach eliminates the need for an equalizer, so arresters never have to be placed directly across a track circuit. This is discussed in Section 5.0.

4. The CSXT Approach

4.1 Background

The general approach has been developed and implemented over a period of about 30 years, beginning first in the nuclear electromagnetic pulse (EMP, an environment similar to lightning in many respects, and which poses a substantial threat to critical military command and control, and weapons delivery systems) community. The approach has been formalized into MIL-STD-188-125. In the 1980s and 1990s, the approach has also been formalized in documentation describing the lightning and HIRF (High Intensity Radiated Fields, a plane wave electromagnetic environment originating from broadcast, radar, and other RF emitters) certification processes for civil aircraft. The approach therefore has a substantial history and has been validated by a considerable amount of military, civilian, and commercial research, as well as by operational experience of hardened systems.

It is important to note the words “highly reliable”. Application of this approach is to systems which must have extraordinary reliability. These types of systems perform mission critical and/or safety critical functions, such as command, control, and delivery of nuclear weapons; the safe flight of a commercial aircraft which costs $100M and transports 300 people; and the movement of trains, in which delays can create significant revenue losses.
The approach is based on two fundamental factors which require careful consideration:

- Stress
- Strength

Stress refers to the lightning environment incident on an electronic system. Strength refers to the ability of the system to withstand the stress. The protection approach is based upon a comparison of stress to strength. If the stress is greater than the strength, protection is necessary.

In addition, in the real world we do not know everything we would like to know about either the stress or the strength, and the cost of determining this information is often prohibitive. It is therefore necessary to create a margin (the difference between stress and strength, assuming that strength is greater than stress) sufficiently large in order to accommodate this uncertainty. The value of this margin therefore depends upon the confidence one has in his knowledge of the stress and strength.

4.2 Lightning Stress on Signal Systems

The lightning environment consists of current waveforms which would appear on cables entering the bungalow. The lightning environment for any wire into a bungalow is assumed to be represented by two worst case waveforms:

- Waveform A, 20 kA, 8x20 us; action integral=5900 joules/ohm; charge=.44 C
- Waveform B, 4 kA, 10x1000 us; action integral=11600 joules/ohm; charge=5.7 C

In terms of effects upon electronics, there are several attributes of these waveforms which are important insofar as they damage electronics:

- Peak Current
- Action Integral, a measure of energy
- Charge
- Peak Derivative

Each attribute may have its own peculiar effect upon a system; however, their effects are usually not isolated. There usually is a synergism among the attributes in their effects upon electronics.

The confidence one has in the overall protection design is directly related to the confidence one has in the knowledge of the environment. In our case, we know of only a few direct measurements of lightning currents on wires penetrating bungalows. The environments we are using are based on experience, observed damage on bungalow equipment, and environments previously determined for similar systems. We believe that direct measurements of lightning currents on bungalow signal wires are greatly needed.
4.2 Strength of Signal Systems

The effects of lightning on an electronic system can be classified as either upset or damage. Upset is defined as a temporal loss of function without any permanent damage. Recovery can occur by a reset operation of some kind, and the function restored. We have observed no significant problems related to upset, so we will focus on permanent component damage. Damage may include a gradual loss of performance, or a catastrophic loss of a component.

Damage of electronic components from transients is a complex scientific discipline in its own right, and has been under study for several decades. In signal equipment, the parts most likely to be damaged include semiconductors, resistors, and capacitors. Semiconductors are usually thought to be the most sensitive, but in fact the other components have sometimes been found to be damaged at levels similar to that of semiconductors. There are complex failure modes which are related to the stress attributes and/or their interaction.

In general, failures of all components have the following properties:

- The larger the stress, the larger probability there is of failure.
- The failure threshold for any device obeys a statistical probability distribution.
- Failures can result from single transient events, and also from cumulative effects of repeated events.
- Failure from transients can also be affected by other environments over the component life cycle, such as temperature, vibration, and humidity.
- There are often stress thresholds, below which damage to a device would never occur.

Serious interest in transient component failure began in the late 1960s when the US military (and others) began to develop the technology for hardening critical military systems to nuclear EMP. Since that time up to the conclusion of the cold war, the military funded millions of dollars of research in this area to determine failure physics and characterize individual specific components. The results of this research can be found in numerous technical reports, public papers, and conference proceedings. An extensive data base was also developed and maintained for many years, and it contained failure levels for tens of thousands of specific components.

We now summarize some of the important aspects of component damage.

**Semiconductors**

Semiconductors include discrete transistors and diodes, and integrated circuits. The first model for transient failure was presented in 1968 [1]. This and other studies [2,3] have shown several failure modes:

- Junction damage by thermal effects related to the transient power/energy deposited
in the junction
-Metallization damage to conductor traces on the chips. Melting occurs by virtue of
the heat generated in the trace by the transient current. The melting tends to occur
at discontinuities in the trace such as at corners or interfaces with other
components on the chip.
-Voltage punch-through of oxide layers
-Burnout of resistors deposited on the chip

A startling feature of semiconductor damage is the large variation in the required amount
of transient power deposited in the device, even with parts from the same manufacturing
lot. An example from Reference 4 shows the measured variation in failure power for a
2N1613 transistor. The variation for devices made by a single manufacturer is more than
two orders of magnitude, and from manufacturer to manufacturer is more than three
orders of magnitude. By measuring a significant number of devices, one can determine a
probability distribution for device failure power.

Models for component failure have been developed and validated, and are generally of
the form

\[ P_f = At^{-B} \]  

(4.1)

Where \( P_f \) is the power required for device failure, deposited in the device by a
rectangular pulse transient waveform of length \( t \); and \( A \) and \( B \) are constants which are
usually empirically determined, and are statistical in nature.

Another feature of semiconductor damage is that there are cumulative effects [5,6,7]. A
study from Reference 6 summarizes the number of failures of three different integrated
circuits in terms of multiple pulsing at various fractions of a damage threshold level (This
is the level for which one would expect the device to be damaged by a single pulse). The
data shows clearly that the cumulative effect of multiple pulses even at 25% of the the
threshold value can cause damage.

Semiconductors can also have latent failures; that is, application of a stress at a point in
time may result in a failure at a later time. Latencies [5,8] are subtle, and may be a form
of cumulative effects. They may also arise from an initial stress creating a partial failure
which may still allow the device to function, and then be degraded at a later time by
either its normal signal environment or by other environmental factors such as
temperature and vibration.

Resistors

Transient failure of resistors has also been characterized [9,10]. Failure modes are
primarily thermal and obey the same semiconductor model provided in Equation 4.1. Failure powers significantly depend upon the resistor construction.
Capacitors

Transient failure of capacitors has also been evaluated [11,12]. Observed failure modes are complex and depend upon the capacitor construction, and include the following:

- voltage breakdown
- repetitive breakdown
- series resistance/zener action
- series resistance/slow voltage breakdown

Voltage breakdown is a simple dielectric breakdown which occurs when the voltage becomes large enough. The repetitive breakdown is associated with the “clearing action” of the capacitor dielectric. The series resistance/zener effect is associated with tantalum and aluminum foil capacitors in which the oxide forming voltage provides a zener-like effect. The slow breakdown effect is associated with solid tantalum capacitors pulsed to voltage levels slightly larger than the oxide forming voltage.

The basic failure is an increase in the capacitor leakage current. The value of capacitance is not greatly affected unless there is a catastrophic breakdown event. Tantalum capacitors, in particular, have been observed to sometimes having failure levels as low as some low power semiconductor devices.

A large statistical variation in capacitor failure levels has also been observed, as in the case for semiconductors.

4.3 Elements of an Ideal Protection Approach

In this section we present the main elements of a well established protection approach which has resulted in highly reliable systems. The approach is based on the stress/strength concept which is summarized in Figure 4.1, and is borrowed from the aircraft industry [13]. The figure defines the important concepts related to stress (TCL, ATL), strength (ETSL, ETDL) and margin.

The TCL are design levels which the designer selects, and he designs the protection so that the lightning environment incident on the electronics will not be larger than the TCL. The ATL is the real, actual lightning environment, and is less than the TCL. The ATL is usually determined by a combination of field measurements and analysis.

The ETSL is the real, actual transient susceptibility level of the equipment. The ETSL is usually not known, and has a statistical distribution. The ETDL is a known safe level for the equipment, and is lower than the ETSL by an unknown amount. The ETDL is almost always verified by testing the equipment on the bench, and is a known quantity. In some industries, there exist prescribed test methods, waveforms, and levels for these tests, and electronic equipment can be stamped/certified to these levels.
There can be large uncertainties in the overall process of determining both the stress and the strength levels.

The stress is usually determined by a combination of testing and analysis. Neither the testing nor analysis is perfect, because both have technical limitations. For example, even if one were to perform a measurement of induced cable current on one system sample, this does not give information on system to system variation. On the analysis side, the analyst is confronted with similar problems, because he probably doesn’t know where all the system cables are precisely located, and how they vary from system to system.

The strength side is not known precisely, either, because of the variabilities described in Section 3. In addition to those factors, there is the problem of testing complex systems and making sure that all electronic states of the system are adequately covered by the testing.

Another factor in the overall process relates to changes of the system configuration over its life cycle. The possibility exists for events such as shield degradation, functional part replacement but with parts having different damage parameters, etc.

The way in which uncertainties are dealt with is to employ the concept of margin. From Figure 4.1, margin is the difference between ETDL and TCL. The amount of margin used depends upon the confidence one has in his values of stress and strength.

The validation process relies on a combination of several tests and analyses. The validation does not depend upon one verification test, for example, but instead consists of the sum total of information obtained from many activities. A typical example might be:

- An experiment, in which low level lightning-like currents are injected into the system, and various responses are measured
- Mathematically extrapolating the above results to the entire system and to threat level waveforms
- 3D numerical analysis of lightning coupling to the system
- Laboratory development tests of various protection methods
- Bench testing of the electronic systems
- A full system demonstration test

In summary, the development of a protected complex highly reliable system involves both science and art, and a variety of related activities.

5.0 Protection Implementation

5.1 Protection of New Installations

An approach like the one described in Section 4 would be desirable, if it were possible to implement. However, CSXT, and all railroads, find themselves in a situation in which high reliability to lightning is desired, but is difficult to achieve because of several
cultural factors:
- There are no specific strength levels (ETDLs) to which equipment suppliers are held.
- There are no lightning related reliability requirements.
- There are no measurements of the lightning environment (stress, ATLs) on wires penetrating bungalows.
- There are no railroad-oriented guidelines or approaches for achieving high reliability, such as exists for some other industries.

We therefore have to use an approach which embodies the main principles of that given in Section 4, and which also fits the railroad context. The approach we have taken minimizes risk by accounting for uncertainties in a cost effective manner. The approach has the following basic elements:

- Faraday Cage
- Hybrid Low Voltage Arresters

Faraday Cage

The Faraday Cage is shown in Figure 5.1. It is basically a metal box which is penetrated by the dirty wires which are cleaned up by arresters which are mounted on an internal metal surface of the cage, which also serves as the ground return for the arresters. This eliminates the long lead length problems described earlier. Clean wires route from the arrester through another hole in the cage, and go to the signal equipment. The exposure length of this clean wire inside the cage is very short, virtually eliminating the clean/dirty coupling issues. The cage in the figure has expanded metal doors which open to the bungalow interior, allowing visibility of the terminal board and maintenance access.

The dirty environment is completely contained within the cage, and the clean environment is the volume of the remainder of the bungalow, which contains the signal equipment. Experiments have shown that the cage reduces the environment within the bungalow by as much as a factor of 140, when compared to previous practices.

The cage provides a well controlled boundary which keeps lightning away from the signal electronics and reduces the following uncertainties in stress to negligible levels:

- Coupling from dirty to clean wires
- Degradation of arrester performance by its long leads
- Radiation coupling from a dirty environment to the electronic volume inside a bungalow

The Faraday Cage eliminates guess-work because its performance can be easily quantified by testing and analysis, and it can be simply maintained. It provides the only location where the lightning protection occurs. Its performance does not depend upon anything else in the bungalow or at the site, such as earth grounds.
The Faraday Cage simplifies the lightning protection in that the only significant part of the lightning environment which passes to the electronics is the arrester (which is also in the cage) let-through.

**Hybrid Low Voltage Arrester (HLVA)**

Once the Faraday Cage is in place, the only stress applied to the electronics is the let-through of the low voltage arresters. The present airgap arresters have a let-through of about 2200 volts, and we have developed a hybrid design (Figure 5.2) which has a let-through of 100 volts or less. Furthermore, the time duration of the stress is reduced considerably. A one-to-one comparison of the measured let-through voltages for each arrester mounted on the Faraday Cage ground plane is shown in Figures 5.3 and 5.4.

The advantages of the HLVA are as follows:

- The HLVA reduces the stress amplitude by a factor of 20.
- The HLVA reduces the stress time duration by more than a factor of 20.
- We never have to place an HLVA across a track circuit (no equalizers needed).

The implications of these advantages for reliability are huge:

- Electronic failure modes related to the peak amplitude have their stress reduced by at least a factor of 20. The reduction is probably even more, because there is usually a “threshold effect”, in which the peak amplitude has to be larger than a threshold in order for damage to occur at all. 100 v is probably less than the threshold.

- Electronic failure modes related to the charge have their stress reduced by a factor of at least 400. Threshold effects are also at work here.

- Electronic failure modes related to the energy have their stress reduced by an even much larger number, perhaps 20x400=8000.

- The damage to buried circuits should be eliminated, because the voltage incident on the track circuit inputs is very small.

- Because no equalizers are needed, two failed short arresters on a track circuit are required to create a safety problem. This improvement factor can be shown to be more than 1000.

The role of the HLVA is therefore reduce the stress to negligible levels. Although we know very little about the equipment strength, we account for this fact by reducing the stress to such a small level, that damage to equipment of any kind is extremely unlikely. This also is a futuristic approach, because it allows CSXT to deploy new equipment with little risk.

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5.2 Protection of Existing Systems

Protection of existing systems is a significant problem because:

- There are ten’s of thousands of them in the field
- They cannot be taken off-line while they are retrofit

These factors preclude the complete rewiring of a bungalow and the installation of a Faraday Cage. We therefore have to live with the idea of lightning penetration directly into the bungalow. Nevertheless, there is much that can be done to statistically improve the survivability of these systems.

Our approach has two elements:

- A CSXT Train Control Regulation (TCR)
- A Retrofit Kit

The TCR is an internally enforcable set of retrofit procedures, which includes the following:

- Physical separation of clean and dirty wires as much as is possible
- Isolation of clean and dirty wires by flexible cable shielding
- Installation of low inductance ground planes to reduce inductance in the arrester ground path.
- Installation of improved AC protection devices
- Bonding of spare cables to the bungalow skin
- Bonding of cable shields to the bungalow skin
- Bonding cable shields together at a splice

The Retrofit Kit provides the means for TCR implementation. It contains various hardware, as follows:

- Cable ties
- Velcro flexible shielding material
- Ground plane material
- Miscellaneous hardware for bonding, etc.

A picture of the Retrofit Kit is shown in Figure 5.5.

6.0 Conclusion

It is important to point out some of the differences between this approach and other approaches which have been put forth.
An important point is that this approach does not depend upon and does not need an earth grounding system. This is because all of the protection takes place at the Faraday Cage boundary, and the voltage seen by the electronics is a function only of the arrester performance. Nothing else matters. In fact, it can be shown that creating a lower impedance earth ground system can actually increase the lightning threat to a system (whether the system is of the conventional design already out in the field, or of our new design).

We hasten to say, however, that the earth ground system is needed for personnel safety, and must be implemented and maintained. But there is no point in improving the earth ground system for lightning protection purposes.

When we compare our approach to that used for other highly reliable systems, there are some aspects we have not implemented. First, we have not really made the bungalow into a true RF shielded enclosure. This would require RF gasketing at the doors, which is extremely expensive to implement and maintain. We also believe this is not required for lightning, whose energy is mostly in the low frequency regime.

Second, in some systems, filters are used at the point of penetration of the wire from the arrester through the Faraday Cage into the main electronic volume. We also do not believe this is necessary, given the small let-through of the HLVA.

Finally, we believe that our approach is based on sound, well proven technology, and will result in an overall enhancement of the reliability and availability of our signal systems.
REFERENCES

Figure 2.1 Overlay of CSXT Trackage and Lightning Flash Density for 1998
Figure 3.1 Back Door of a Bungalow Showing Black Dirty Wires and Blue Clean Wipes Intermingled

Figure 3.2 Front of Terminal Board Showing Long Lead Lenghts on AC and Track Wire Arresters
Figure 3.3 Direct Penetration of RF Cable Shields through Bungalow Skin to Interior

Figure 3.4 Direct Penetration of RF Cables into Bungalow and in Close Proximity to Signal Cables
Example: Assume

\[ V_{\text{arrester}} = 500V \]
\[ L = 2\mu h \text{ for 2m bus length} \]
\[ I = 10kA, \text{ peaks in 8\mu s} \]
\[ V_{\text{bus}} = (2 \times 10^{-6}h) \frac{10^4}{8 \times 10^{-6}s} = 2500V \]
\[ V_{\text{electronics}} = 500V + 2500V \]

Figure 3.5 Degradation of Arrester Effectiveness by Long Leads

Figure 4.1 Relationships Among Transient Levels [13]
Figure 5.1  CSXT Faraday Cage Installed in a Bungalow

Figure 5.2  Basic Hybrid Arrester Configurations

- Buried cable input
- Gas tub
- L ~ 25 µH
- MOV
- ≤ 100V
- To electronics
Figure 5.3 Comparison of Arrester Responses mounted on a Ground Plane in a Bungalow (Fast Time Scale)

Figure 5.4 Comparison of Arrester Responses mounted on a Ground Plane in a Bungalow (Slow Time Scale)
Figure 5.5  CSXT Retrofit Kit