

Understanding Design, Installation, and Testing Methods That Promote Substation IED Resiliency for High-Altitude Electromagnetic Pulse Events

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Understanding Design, Installation, and Testing Methods That Promote Substation IED Resiliency for High-Altitude Electromagnetic Pulse Events

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Abstract—Recently, governments and concerned private entities have given considerable attention to high-altitude electromagnetic pulse (HEMP) events. Both groups are concerned that a HEMP event would have a serious social and economic impact on our society. However, to date, a limited amount of literature exists that focuses on HEMP events as they relate to substation intelligent electronic devices (IEDs). This paper demonstrates IED resiliency to HEMP events through analysis and test results. It presents substation grounding and wiring practices that are HEMP resilient and also highlights available HEMP standards as they relate to IEDs and substation control houses. This information will help utilities prevent unnecessary mitigation efforts and address the concerns regarding the effects of HEMP on substations and substation IEDs.

I. INTRODUCTION

When a nuclear weapon detonates at an altitude greater than 30 km above the earth's surface, radiation (gamma rays) from the nuclear explosion interacts with air molecules and the earth's magnetic field producing a high-altitude electromagnetic pulse (HEMP) [1]. We can analytically separate a HEMP event into a series of three waveforms of different durations. Each has naturally occurring counterparts with proven design and test methods that ensure a level of immunity [1].

The waveform of longest duration is similar in effect to an aurora, which can produce geomagnetically induced currents (GIC) [2]. GIC does not adversely impact the functionality of substation intelligent electronic devices (IEDs) [3].

The intermediate-duration waveform is similar to lightning, but with much less energy than lightning [4]. Substations and substation equipment have a proven lightning resiliency, and therefore, the intermediate-duration event is of no concern. HEMP experts in the International Electrotechnical Commission (IEC) state, "HEMP protection principles in civil applications shall take advantage of already installed lightning protection. The designers of the HEMP protection shall estimate, if by admitting a certain risk, the lightning protection can also be considered to be sufficient against HEMP..." [5].

The short-duration waveform resembles substation arcing, electrostatic discharge (ESD), and AM/FM radio wave pulses, albeit with higher field strengths [6] [7]. These short-duration waveforms have the potential to damage electrical systems.

The HEMP event that followed the high-altitude test explosion, conducted in the Johnston Island area of the Pacific Ocean in 1962, affected some civilian electrical and electronic equipment on the Hawaiian island of Oahu. The nuclear test caused no serious damage, and the power grid remained operational [1].

However, HEMP events are of concern to policy makers, grid operators, and others, because of society's increased reliance on electricity for nearly every aspect of life and the limited explicit information regarding HEMP effects on present-day electrical systems. This paper addresses this concern with regard to substation IEDs that comply with internationally recognized IEC requirements, by demonstrating their resiliency to HEMP events.

Section II provides an overview of the three HEMP waveforms, highlights the short-duration waveform as the concern for substation IEDs, and provides further detail about the short-duration waveform.

Section III analyzes and demonstrates the HEMP resiliency of IEDs in substations. We show by analysis, testing, and statistical evaluation that robust IEDs, designed for the harsh substation environment, are HEMP resilient in existing substations.

Section IV describes design techniques for HEMP resiliency in new substations. IEDs in these substations are (by design and test) HEMP resilient. Section V discusses possible HEMP resiliency improvements to legacy substations and implementing chosen improvements with other planned upgrades.

Appendix A presents various aspects of the HEMP standards related to substations, substation signal wiring, and substation IEDs. Appendix B highlights the coupling of the short-duration HEMP waveform to signal and control wires within the substation.

II. OVERVIEW OF HEMP WAVEFORMS

When a HEMP event occurs, gamma rays interact with air molecules to create Compton electrons; the earth's magnetic field deflects the electrons, creating electron currents. These electron currents are the source of electromagnetic (EM) waveforms, which interact with systems on the earth [8].

HEMP literature labels the short-duration, intermediate-duration, and long-duration HEMP waveforms as E_1 , E_2 , and E_3 respectively [8]. These three stages of EM waveforms are shown in the electric field versus time log-log plot of Fig. 1 [9]. E_1 has a duration of tens of nanoseconds. E_2 has a duration of tens of milliseconds, while E_3 has a duration of hundreds of seconds.

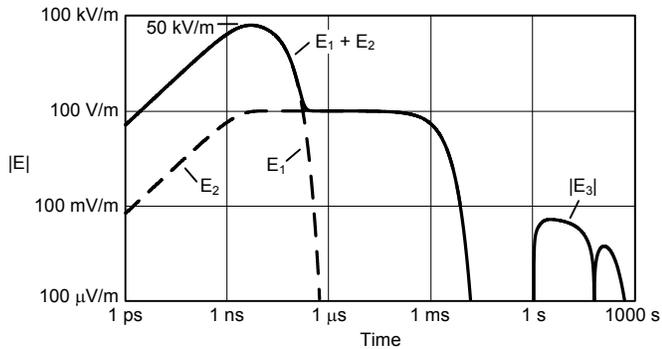


Fig. 1. Three stages of EM waveforms from a HEMP event: E_1 , E_2 , and E_3

As noted earlier, the three stages of EM waveforms have various impacts on electric power substation equipment. Only the E_1 waveform has the potential to affect substation IEDs, as Table I indicates. The impact of the E_1 waveform on substation IEDs is the primary focus of this paper.

TABLE I
THREE STAGES OF EM WAVEFORMS FROM A HEMP EVENT

EM Waveform (HEMP)	Duration Similarity to Natural Phenomena	Concern for Substation IEDs
E_1 : short-duration	Electrostatic Discharge	Yes
E_2 : intermediate-duration	Lightning	No
E_3 : long-duration	Geomagnetic Disturbance	No

The E_2 waveform has lower electric field levels and frequency content compared to lightning-related events [10]. The electromagnetic compatibility (EMC) requirements of IEC 60255-26 include surge immunity type-test levels for demonstrating IED lightning resiliency. These EMC surge levels are above and beyond the E_2 surge immunity levels for demonstrating HEMP resiliency. The IEC EMC standards adequately cover the impact of the E_2 waveform on substation IEDs; thus, we do not address it further in this paper.

The E_3 waveform is of no concern for IEDs, but it is important for long external conductors, such as power and communications lines. The effects are similar to geomagnetic disturbances related to solar activity, causing quasi-dc current to flow on power distribution and transmission lines via grounded transformers [11]. The quasi-dc current may cause harmonics from half-cycle transformer saturation creating a large inductive load and transformer losses and heating [2]. The impact of the E_3 waveform on transformers and the power system is outside the realm of this paper.

The E_1 waveform is a composite curve based on waveforms from various regions on the earth's surface underneath the event. The frequency spectrum between

100 kHz and 100 MHz contains nearly all (96 percent) of the E_1 waveform energy content [9]. The lower frequency spectrum corresponds to the AM broadcast band (535 to 1700 kHz) and the upper frequency spectrum corresponds to the FM broadcast band (87.5 to 108 MHz). However, the field strength of the E_1 spectrum is thousands of times larger than radio waves. The radio frequency (RF) E_1 composite waveform has an amplitude of 50 kV/m, a rise time of 2.5 ns (10 to 90 percent), and a pulse width of 23 ns (at 50-percent level) as Fig. 2 shows.

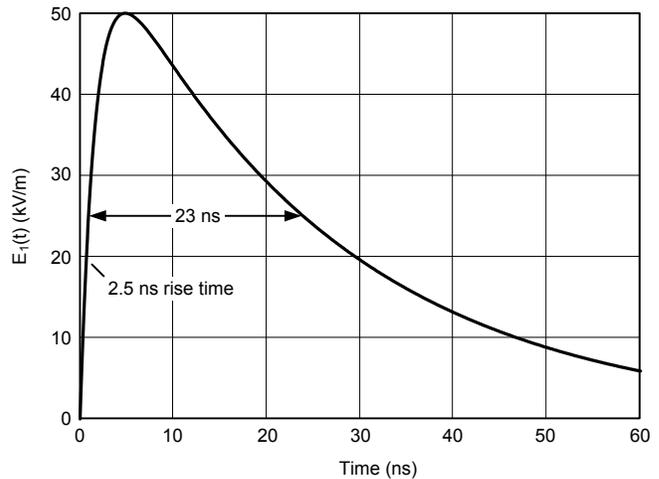


Fig. 2. Composite RF E_1 waveform

The burst height of a nuclear weapon determines the affected area of the earth's surface. For example, Fig. 3 shows the HEMP impact to a region of the earth's surface for a given burst height [12]. Only a small portion of this region has an RF E_1 waveform level that is at the maximum peak amplitude of 50 kV/m. The vast majority of the region has RF E_1 waveform levels that are less than 75 percent of this maximum.

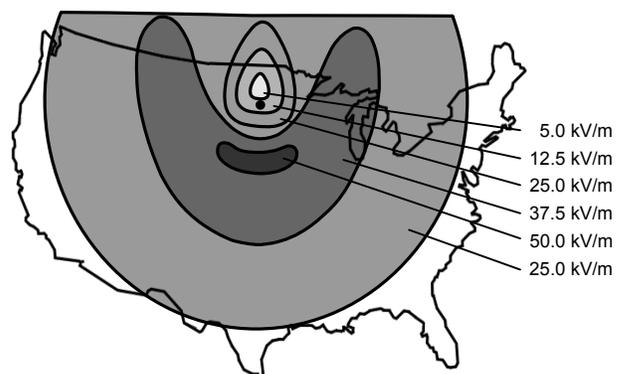


Fig. 3. RF E_1 waveform peak amplitude levels from a HEMP event

The RF E_1 waveform directly impinges on substation outdoor equipment and structures. After attenuation by a control house, a fraction of the RF E_1 waveform also impinges on the IEDs and wiring in the control house. The RF E_1 waveform also couples into aerial and buried cables.

A HEMP-related generic standard, IEC 61000-6-6, specifies the immunity requirements for HEMP resiliency of

substation IEDs [13]. When designers use EMC principles and design techniques in substation and IED designs, they effectively eliminate any effects of the RF E_1 waveform.

III. HEMP RESILIENCY OF IEDS IN LEGACY SUBSTATIONS

Schweitzer Engineering Laboratories (SEL) protective relays are substation-hardened IEDs and are HEMP resilient in legacy substations. This conclusion is based on 1) IED design, analysis, and testing, 2) legacy substation design practices, 3) assessment of IED resiliency by comparing lightning and HEMP events, and 4) the statistical nature of the RF E_1 waveform coupling to signal wires.

We define the legacy substation as a typical substation that incorporates standard design practices for lightning, RF, and electrical transient resiliency. A power utility's design criteria or standards contain established guidelines for these legacy substation designs.

HEMP resiliency of IEDs in a legacy substation control house is a function of both the substation and the IED designs. Substation and IED design techniques for HEMP resiliency are similar to RF resiliency and electrical transient resiliency design techniques. Substation and IED designers have implemented these techniques for decades, which incorporate elementary EMC design principles.

Recall that elementary EMC design principles fall into three categories: 1) eliminate or reduce the EM disturbance source, 2) shield the susceptible device from the disturbance source (attenuate the EM disturbance, reducing the impact to the susceptible device), and 3) harden or reduce the vulnerability of the susceptible device. For HEMP, eliminating or reducing the source is outside the control of the substation and IED designers. Therefore, providing IED HEMP resiliency focuses on attenuating the disturbance and designing robust IEDs.

The next two subsections highlight legacy substation designs and substation-hardened IED designs respectively. The third subsection summarizes immunity type tests for HEMP resiliency, performed on a representative robust IED design. The last subsection evaluates the HEMP resiliency of IEDs designed for the harsh substation environment.

A. Legacy Substation Design

Many IEEE standards are the basis for legacy substation design practices, including:

- IEEE Std 80: IEEE Guide for Safety in AC Substation Grounding
- IEEE Std 142: IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems
- IEEE Std 525: IEEE Guide for the Design and Installation of Cable Systems in Substations
- IEEE Std 1100: IEEE Recommended Practice for Powering and Grounding Electronic Equipment
- IEEE Std 1143: IEEE Guide on Shielding Practice for Low Voltage Cables

The definition and refinement of substation design practices stems from decades of experience with electrical

transients from switching arcs, capacitor bank switching, lightning, and power system faults. These design practices also support IED HEMP resiliency. Fig. 4 depicts a typical legacy substation design in the presence of the RF E_1 waveform.

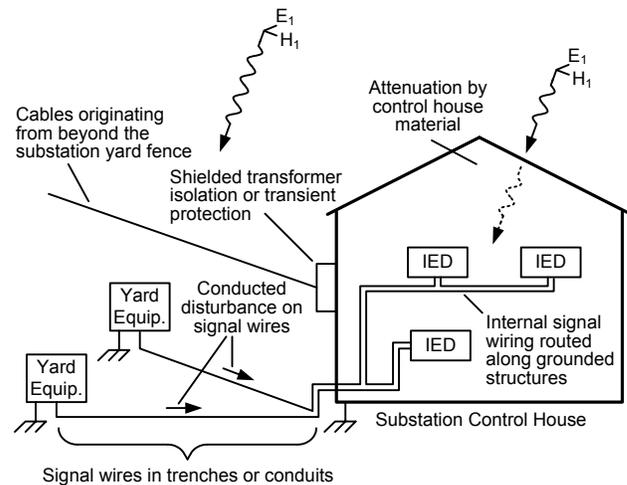


Fig. 4. Legacy substation design

Legacy substation design practices support IED HEMP resiliency in numerous ways including:

1. Attenuation of the RF E_1 waveform by the control house material. This reduces the impact on the IEDs and the coupling to wiring inside the control house.
2. Routing of internal wires along grounded chassis, panels, cable trays, or trenches containing a ground conductor. This reduces the area between the wire and ground, thus minimizing the RF E_1 waveform coupling. In turn, this minimizes the voltage transients on the signal wires with respect to ground.
3. Routing of signal wires that leave the control house and connect to substation yard equipment in trenches or conduits. This provides some attenuation for the coupling of the RF E_1 waveform, minimizing conducted disturbance on the signal wires.
4. Construction of the substation ground grid beneath the substation yard. This reduces the area between the yard signal wires and ground, in turn minimizing the RF E_1 waveform coupling and transients on the signal wires with respect to ground.
5. Additional shielded transformer isolation or transient protection of ac station power feeds and telecommunications cables. These cables include pilot wires, telephone lines, and other wide-area network (WAN) connections that originate from beyond the substation yard fence.

Legacy substation control houses may provide between 0 to 20 dB attenuation to the RF E_1 waveform. The HEMP standard, IEC 61000-2-11, categorizes above ground concrete structures with rebar, buried brick or concrete structures, shielded enclosures with minimal shielding effectiveness, and typical equipment boxes with small apertures as providing 20 dB attenuation to the RF E_1 waveform [14].

Within the substation control house, the system consisting of the grounded panels, cabinets, chassis, trays, raceways, and ground conductors forms an interconnected metallic skeleton framework. The grounded metal within the control house further shields many IEDs and control house wires from the RF E_1 waveform, reducing coupling to these IEDs and wires.

Designers route signal (and control) wires along the metallic framework to minimize the loop area that the signal wires make with ground. Recall that the loop area of a signal wire is the area bounded by the signal wire and the ground return path. IED signal wires include current transformer (CT) inputs, potential transformer (PT) inputs, and binary (or contact) inputs and outputs.

Internal IED components and circuitry isolate the connection terminals from the IED chassis or safety ground connection. IED isolation components include transformers, electromechanical relays, optical isolators, and digital isolators.

Electrical transients couple to IED signal wires and cause a voltage transient across isolation components. IEDs that are designed for the harsh substation environment use isolation components that withstand multiple kilovolts of transients ranging from power system frequencies through RF frequencies and beyond.

Within the substation yard, design for lightning resiliency is important because of the high currents in a lightning stroke and the high energy transients in signal wires as a result of lightning. Recall that lightning impacts substation yard wiring in three different ways:

1. Current flowing through the earth, substation ground grid, and ground conductors from a nearby lightning strike produces a ground potential rise between different grounded points [15]. Signal wires that are grounded at substation yard equipment encounter a common mode voltage transient at the IED wire terminal end with respect to the ground of the substation control house. The common mode voltage transient is a result of the ground resistance voltage drop from the lightning current flowing between the substation yard equipment and the control house grounds.
2. Current transients flowing on ground conductors from lightning strikes may also inductively couple to signal wires, running parallel to these ground currents.
3. Lightning produces an electromagnetic pulse (EMP), which is highest for the larger magnitude of the first lightning return stroke (lightning current as high as tens of kiloamperes) [16].

Because of the similarities between lightning EMP and the RF E_1 waveform, substation yard wiring that provides lightning resiliency also provides HEMP resiliency. Table II gives a comparison between the lightning EMP (first return stroke) and the RF E_1 waveform [17] [18] [19] [20].

The electric field strength for the RF E_1 waveform is similar in magnitude to the EMP from a lightning strike 50 meters away. However, the available energy from a lightning EMP that is 50 meters away is hundreds of times greater. If

we presume that legacy substation design techniques provide IED resiliency for lightning 50 meters away, then they also provide IED resiliency for HEMP. As such, substation wiring designs that are lightning resilient are also HEMP resilient [5].

TABLE II
COMPARISON OF LIGHTNING EMP AND THE RF E_1 WAVEFORM

	Lightning EMP (first return stroke)	RF E_1 Waveform (HEMP)
Frequency spectrum	300 Hz to 2 MHz	100 kHz to 100 MHz
Electric field (peak)	100 kV/m (50 m) ¹	50 kV/m
Rise time/pulse width	10/350 μ s	2.5/23 ns
Energy ²	250 mJ (50 m) ¹	0.7 mJ
Energy fluence	0.15 J/m ² (600 m) ¹	0.114 J/m ²

¹Distance away from lightning return stroke

²Dissipated in a gas discharge tube from a conducted disturbance induced into a transmission line 1 km in length and 10 m in height

B. Substation-Hardened IED Design

Engineers design IEDs that are intended for installation in a control house or yard cabinet for the harsh EMI environment of a substation. Robust IED designs employ many of the same techniques as substation designs.

Similar to the control house in Fig. 4 that attenuates the RF E_1 waveform, reducing its impact on IEDs and internal wiring, the chassis and internal shields of an IED attenuate the RF E_1 waveform, reducing its impact on internal integrated circuits, sensitive circuitry, and components.

Similar to substation designers routing signal wiring in the control house along grounded structures, the IED designer routes traces on the IED internal printed circuit boards (PCBs) over electrically continuous PCB ground planes. IED designers typically connect these planes to chassis metal or shields that tie to the IED chassis or safety ground connection. Routing PCB traces over ground planes reduces the loop area of the traces and thus reduces the coupling of any RF energy to electronic circuits.

Similar to keeping large transient currents out of the control house (from cables originating beyond the substation yard fence), robust IED designs prevent transient currents from flowing inside the IED (from the signal wires connected to the IED terminals). IED designers typically achieve this with isolation components that are capable of withstanding the transient voltages that couple to the signal wire terminals.

Nonisolated interface circuitry (e.g., serial communications) typically contains transient suppressors to protect internal circuitry. IED designers place these filters or transient suppressors near the IED wire terminals, reducing the loop area of transient currents flowing back to the chassis ground. This design minimizes any reradiation of RF energy inside the IED from the transient currents flowing through the filters or suppressors.

Self-diagnostics of IED functionality and health by the IED firmware is an important component of robust IED designs. If a detected functionality degradation is temporary, the IED

restarts to restore availability of all functions. If the degradation is permanent, the IED issues an alarm that is monitored through supervisory control and data acquisition (SCADA), and personnel take actions to repair or replace the IED [21].

Another important aspect of designing IEDs for the harsh substation environment is complying with the EMC and low-voltage European Union (EU) directives. IEDs that pass the immunity and withstand type tests demonstrate their compliance to these directives. For measuring relays and protection equipment, the EMC and safety (low-voltage) requirements are IEC 60255-26 and IEC 60255-27 respectively. Table III shows the EMC immunity level requirements for substation IEDs per IEC 60255-26 [22].

Certified testing lab reports for the individual basic standards listed in Table III demonstrate the EMC immunity of an IED that complies with these requirements.

TABLE III
EMC IMMUNITY LEVELS FOR SUBSTATION IEDS
(IEC 60255-26 REQUIREMENTS)

Immunity Requirement	Basic Standard	Immunity Level
Radiated RF electromagnetic field ¹	IEC 61000-4-3	10 V/m 80 MHz – 1 GHz 1.4 GHz – 2.7 GHz
ESD ^{1,2}	IEC 61000-4-2	Contact: 6 kV Air: 8 kV
Power frequency magnetic field ¹	IEC 61000-4-8	Continuous: 30 A/m 1 s to 3 s: 300 A/m
Conducted RF disturbance	IEC 61000-4-6	10 V 150 kHz – 80 MHz
Electrical fast transient/burst ³	IEC 61000-4-4	4 kV
Slow damped oscillatory wave ³	IEC 61000-4-18	Differential Mode: 1 kV Common Mode: 2.5 kV
Surge ³	IEC 61000-4-5	Line to Line: 4 kV Line to Earth: 2 kV
Power frequency	IEC 61000-4-16	Inputs/Outputs: 150 V _{rms}

¹Enclosure immunity tests

²Immunity levels for SEL IEDs are 8 kV contact and 15 kV air

³Power supply and input/output port immunity tests; communications port immunity level requirements are lower

Table IV shows the impulse and dielectric voltage withstand level requirements for substation IEDs per IEC 60255-27. Impulse voltage withstand testing verifies the clearance requirements of the isolation components that are integral to IEDs. Both impulse and dielectric voltage withstand testing demonstrate the electrical insulation of the IED isolation components. See Appendix A (Section D) for further detail on the creepage distance and clearance requirements of IEDs.

IEDs designed to IEC 60255-27 have additional clearance for the protective impedance or solid insulation of the IED isolation components. We validate the clearance of the isolation components by performing impulse and dielectric voltage withstand testing at higher levels (see Table IV) [23].

TABLE IV
ELECTRICAL INSULATION WITHSTAND LEVELS FOR SUBSTATION IEDS
(IEC 60255-27 REQUIREMENTS)

Withstand Requirement	IED Withstand Level	Isolation Component Withstand Level
Impulse (1.2/50 μ s) (Clause 10.6.4.2)	5.0 kV	7.0 kV
Dielectric (60 Hz or dc) (Clause 10.6.4.3)	ac: 2.5 kV _{rms} dc: 3.6 kV	ac: 3.7 kV _{rms} dc: 5.2 kV

In summary, for the harsh substation environment, IED designers:

- Provide a chassis (or internal RF shields) for shielding sensitive integrated circuits, sensitive circuitry, and components
- Create a metallic framework of PCB ground planes, shields, and chassis-connected metal
- Route PCB traces over electrically continuous ground planes, minimizing loop areas
- Design isolation circuitry or isolation components to withstand the transient voltages that appear on signal wire terminals
- Place filters or transient suppressors at the IED interface

In addition, such IEDs:

- Perform self-diagnostics of functionality and health: restart for temporary functional degradation and alarm for permanent degradation
- Comply with the IEC 60255-26 EMC RF and voltage transient immunity requirements (as tested by a certified testing lab)
- Comply with the IEC 60255-27 creepage distance, clearance, and impulse and dielectric voltage withstand requirements (as tested by a certified testing lab)

C. Immunity Tests Demonstrating HEMP Resiliency of IEDs

Demonstration of IED HEMP resiliency includes two additional immunity type tests: radiated pulse and fast damped oscillatory wave.

For an IED in a substation control house that provides 20 dB attenuation of the RF E₁ waveform, the radiated pulse immunity level is 5 kV/m (see Appendix A, Section C for details). At a certified testing lab, we tested an SEL protective relay that is representative of a typical substation-hardened IED. The testing result demonstrates immunity at a 50 kV/m level [24]. Therefore, if a control house provided little to no attenuation, such an IED would still be resilient to the RF E₁ waveform.

In addition, testing of the same SEL protective relay PCBs, without any chassis or metallic PCB trays or supports, demonstrates IED integrated circuits, components, and circuitry are resilient to the RF E₁ waveform at 25 kV/m [25]. Given the phenomenal testing outcome of a representative IED, the authors question the value of performing radiated pulse type testing of similar IEDs designed for the harsh substation environment. HEMP resiliency to the non-

attenuated RF E_1 waveform is inherent in substation-hardened IEDs designed for EMC immunity.

For an IED in a substation design that provides 20 dB attenuation of the RF E_1 waveform for both the control house and yard signal wiring, the fast damped oscillatory wave immunity level is 2 kV for signal wire terminals and 1 kV for capacitive coupling to serial communications cables (see Appendix A, Section D for details).

At SEL's certified testing lab, we tested an SEL protective relay that is representative of a typical substation-hardened IED. The testing result demonstrates immunity at the margin levels of 4 kV for signal wire terminals and 2 kV for capacitive coupling to serial communications cables [26]. This substantiates the resiliency of such IEDs to the RF E_1 waveform that couples to control house and substation yard signal wires.

D. HEMP Resiliency of IEDs in Legacy Substation Designs

Although legacy substation designs may not include the HEMP resiliency techniques described in Section IV, they use similar lightning resiliency and other electrical transient resiliency design techniques. These techniques are sufficient such that IEDs designed for the harsh substation environment still offer significant HEMP resiliency in legacy substations.

Since substation-hardened IEDs are immune to the non-attenuated 50 kV/m RF E_1 waveform, the only concern regarding IED resiliency to HEMP is the RF E_1 waveform coupling to the IED signal wires. Assuming no attenuation for substation yard signal wiring, a suitable upper limit of the coupled transient voltage from the RF E_1 waveform is 20 kV [27] (see also Table XI in Appendix A).

Determining IED vulnerability in legacy substations is a combination of 1) identifying the transient withstand voltage limit of an IED and 2) determining the probability that this voltage exists from a HEMP event. We analyze these aspects in the following two subsections.

1) Withstand Voltage Limit of IED Signal Wire Terminals

IEDs that comply with the low-voltage EU directive requirements of IEC 60255-27, withstand an impulse voltage of 7.0 kV for isolation components (see Table IV). The impulse wave shape is similar to a lightning impulse with a rise time of 1.2 μ s and a pulse width of 50 μ s. However, the conducted disturbance from the RF E_1 waveform coupling to signal wires is a faster event, similar to ESD.

Conducted disturbances from the coupling of the RF E_1 waveform may have a rise time/pulse width from 10/100 ns to 25/500 ns (see Table XI in Appendix A). For comparison, a discharge to IED terminals from a typical ESD gun used for type testing may have a rise time/pulse width ranging from 0.7/30 ns for contact discharge to 30/60 ns for air discharge [28] [29].

A general property of insulation material is the ability to withstand a higher voltage for transients having a faster rise time and shorter duration [13] [30]. Therefore, the expectation of the IED terminal transient withstand voltage for the faster transient pulses related to the RF E_1 waveform is significantly higher than the 7.0 kV of the 1.2/50 μ s impulse.

Testing with an ESD gun, used for enclosure immunity ESD type testing, provides supporting evidence that IEDs can withstand a higher transient voltage with a shorter pulse width. SEL conducts margin type testing on new product designs by applying 12 kV contact ESD to all signal wire terminals while using standard type test setups and relay settings.

In addition, setting an ESD gun to a fast repetition rate with maximum air discharge level is a common exploratory test that SEL design engineers apply to signal wire terminals [31]. Because of IED self-diagnostics, such exploratory ESD testing results in an occasional system restart with full functionality at the conclusion of the test.

At SEL's certified testing lab, we applied 30 kV ESD air margin type testing to the signal terminals of an SEL protective relay that is representative of a typical substation-hardened IED. The testing results demonstrate the capability of IED isolation circuitry and isolation components to withstand high-voltage transient levels [32]. Impulse voltage withstand testing (IEC 60255-27), performed at the completion of the ESD margin test, validates the insulation system integrity.

We presume similar IEDs that comply with the 7.0 kV impulse voltage withstand level of IEC 60255-27 (see Table IV) will also be immune to the 30 kV ESD air margin type testing (with an occasional system restart). We assume the withstand voltage level is inversely proportional to the logarithm of the pulse width. Using linear interpolation of the impulse voltage and ESD levels and pulse widths, the IED withstand voltage is nearly 23 kV for the conducted disturbance pulse width of 500 ns. This is above the upper limit of 20 kV conducted transient from a HEMP event; thus, IEDs that comply with the 7.0 kV impulse voltage withstand level of IEC 60255-27 are HEMP resilient.

We infer that SEL protective relay designs and other substation-hardened IEDs that are impulse voltage type tested to 5 kV, withstand 16 kV for the conducted disturbance pulse width of 500 ns. We derive the 16 kV withstand level by applying a proportional relationship between the impulse voltage levels and the conducted disturbance withstand voltage level. The contact ESD margin testing of 12 kV for these IEDs further validates this inference [33].

2) IED Signal Wire Terminal Voltage Level Probability From a HEMP Event

For a monopole antenna, the largest transient voltage coupled from the non-attenuated RF E_1 waveform occurs when the antenna aligns with the electric field. For instance, coupling to a monopole antenna with a height of 0.4 m produces a 20 kV transient waveform at the open-circuit antenna terminals. An antenna of this height is unlikely within the signal wiring of the control house, substation yard, or yard equipment structures.

It is also unlikely to have signal wiring exposed to the non-attenuated RF E_1 waveform. Signal wiring is either within the control house, yard equipment metallic structure, or substation yard cable trench that is covered with a concrete cover or metal grate sections.

The coupling of a transient voltage to a signal wire that is terminated on a particular IED is statistical. The statistics involve 1) the location of the substation within the various electric field strength zones beneath the HEMP event [34], 2) the alignment of the signal wire with the electric and magnetic fields, 3) the height of the monopole antenna and transmission line within the signal wire, and 4) the amount of signal wire shielding inherent in cabinets, structures, cables, and trenches.

Table V shows the random variables we define to statistically analyze the transient voltage level on IED signal wires. Each random variable is its own attenuation factor, except that the alignment angle attenuation factor is $\cos \theta$.

The random variable for the fraction of the RF E_1 waveform (based on location) corresponds to a burst height of 500 km [34]. This burst height covers an area roughly equivalent to the continental U.S. (see Fig. 3). A little over 96 percent of this area has a level that is less than 75 percent of the RF E_1 waveform peak of 50 kV/m.

TABLE V
STATISTICAL ANALYSIS OF A HEMP EVENT PRODUCING A TRANSIENT VOLTAGE ON IED SIGNAL WIRES

Random Variable	Distribution	Range
Fraction of the RF E_1 waveform (50 kV/m) based on location	see [34]	0 to 100%
Signal wire alignment angle with RF E_1 electric field	Uniform	θ : 0 to π
Normalized height of monopole antenna and transmission line	Uniform	20% to 100%
Signal wire shielding	Uniform	10% to 100% (i.e., 20 dB to 0 dB)

To obtain the probability density function for the transient voltage level on an IED signal wire terminal, we combine the four random variable distributions. The combined probability density function uses the product of the four attenuation factors and the upper transient voltage limit of 20 kV identified at the beginning of Section D. Fig. 5 shows the combined probability density function.

We use this probability density function to calculate the percentage of installed IED signal wire terminals that are exposed to a transient voltage level that exceeds the withstand voltage limit of the IED (see Table VI).

Statistically, SEL protective relays and other substation-hardened IEDs are HEMP resilient if they 1) comply with the 5.0 kV impulse voltage withstand level of IEC standards prior to IEC 60255-27 and 2) have an inferred withstand voltage limit of 16 kV. For every 10,000 of these IEDs in substations throughout the U.S. that have an assumed average of 20 signal wires, only 6 IEDs would statistically be exposed to a terminal voltage exceeding 16 kV from a HEMP event.

The statistical aspect of the signal wire voltage transient level from the HEMP event provides an additional HEMP resiliency margin if 1) the electric field is higher than 50 kV/m, 2) the insulation property of isolation components degrades with time, and 3) shielding properties degrade with time.

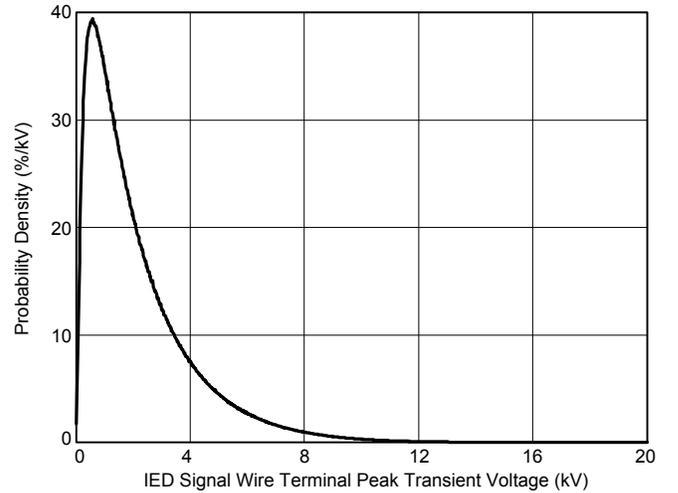


Fig. 5. Probability density function for the transient voltage level on an IED signal wire terminal

TABLE VI
PERCENTAGE OF INSTALLED IED SIGNAL WIRE TERMINALS EXPOSED TO A TRANSIENT VOLTAGE LEVEL FROM A HEMP EVENT THAT EXCEEDS THE WITHSTAND VOLTAGE LIMIT OF THE IED

IED Withstand Voltage Limit	Percentage of Installed IED Signal Wire Terminals Exposed to a Transient Voltage That Exceeds the IED Withstand Limit
16 kV	0.003%
12 kV	0.09%
8 kV	1.6%
6 kV	4.9%
4 kV	14.3%
2 kV	40.6%

In addition, the transient voltage on the signal wire is the impulse response of the wiring system to the RF E_1 waveform (approximately an impulse function). The rise time of the RF E_1 waveform does not appreciably change the magnitude of the impulse function. Therefore, the upper limit of 20 kV for the transient voltage is valid for any RF E_1 waveform with various rise times and a peak electric field of 50 kV/m.

IV. NEW SUBSTATION DESIGN TECHNIQUES FOR HEMP RESILIENCY

IEDs that comply with IEC 60255-26 for the EMC EU directive and IEC 60255-27 for the low-voltage EU directive are (by design and by type test demonstration) HEMP resilient when installed in a new substation implementing the design techniques of this section.

Design techniques for HEMP resiliency of new substations maximize immunity from RF sources, electrical transients, and the RF E_1 waveform. In addition to the design techniques for legacy substations, design techniques for new substations include:

1. 20 dB average attenuation of the RF E_1 waveform by the control house.

2. Use of shielded and properly grounded cable for the signal wires that leave the control house and connect to substation yard equipment. Shielded cable reduces the coupling of the RF E_1 waveform to the signal wires.
3. Additional shielded transformer isolation or transient protection of ac station power feeds and telecommunications cables are located before the cables enter the control house, preventing the RF energy from reradiating inside the control house.
4. Installation of only substation-hardened IEDs that comply with IEC 60255-26 for the EMC EU directive and IEC 60255-27 for the low-voltage EU directive in the control house or substation yard equipment and enclosures.

Fig. 6 depicts a new substation design that incorporates these additional techniques. With regard to HEMP, new substation designs provide a minimum attenuation of 1) the RF E_1 waveform by the control house, 2) the coupled E_1 conducted disturbance on signal wires in the substation yard, and 3) the coupled E_1 conducted disturbance on cables originating from beyond the substation yard fence. Table VII shows these minimum attenuation levels.

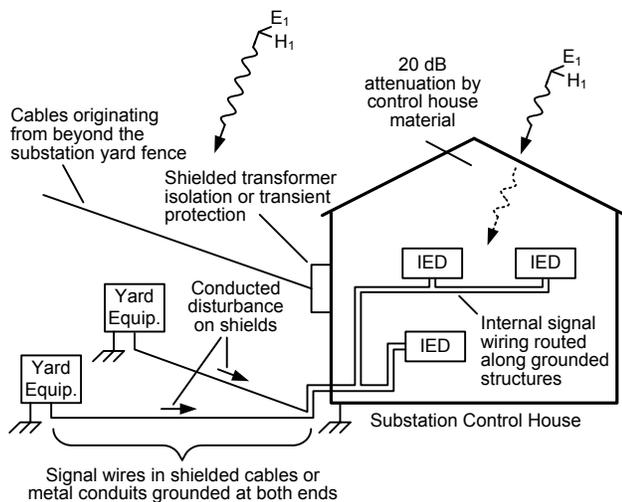


Fig. 6. Design techniques of new substations that minimize effects of RF E_1 waveform

TABLE VII
DESIGN TECHNIQUES OF NEW SUBSTATIONS PROVIDE ATTENUATION OF
RADIATED RF E_1 WAVEFORM AND E_1 CONDUCTED DISTURBANCE

	Radiated RF E_1 Minimum Attenuation	E_1 Conducted Disturbance Minimum Attenuation
Control house	20 dB (average)	---
Substation yard signal wires	---	20 dB
Cables originating beyond the substation yard fence	---	40 dB

The following subsections provide greater detail on the design techniques of new substations and how they minimize the effects of the RF E_1 waveform.

We acknowledge that these design techniques need not include hardening against the threat of intentional electromagnetic interference (IEMI) or other localized attack. Other than for substations that perform critical, time-urgent missions, the cost of hardening the typical substation against localized IEMI or even ballistic attacks does not justify the benefit. The risk is low that a localized attack would disrupt a large number of substations, since the police or military would intervene.

A. New Substation Control House Design

New substation control house designs provide a minimum average of 20 dB attenuation for the RF E_1 waveform. An above ground control house that is constructed from metalized panels or concrete panels with metal liners for the four walls, ceiling, and floor provides such attenuation.

The control house does not need to be over-designed as the perfect RF-shielded box, having riveted or welded seams between metal panels, flawless RF door gaskets, perfect waveguides below cutoff frequency for all wire entry points and openings, etc. An attenuation of 80 to 100 dB is easily achieved for a perfect RF-shielded box designed in this manner [35]. However, this would be 1,000 to 10,000 times what is needed for a control house to attenuate the RF E_1 waveform by just 20 dB.

An appropriate substation control house design incorporates metal or metal-lined panels with seam overlaps, door seam considerations, meshed air exchange openings, imbedded mesh windows, and a cable entry cabinet separating external shield terminations and signal wires from internal signal wires [36]. Research testing results of a representative control house support a minimum average attenuation of 20 dB for continuous RF waves [37].

Recall that continuous RF wave testing may produce minima and maxima field attenuation locations within a structure from standing waves or constructive and destructive interference from reflections. Since the 23 ns-wide RF E_1 waveform is a single pulse that has an electrical width of a little under 7 m, standing waves or constructive interference reflections are not possible. Therefore, averaging the continuous RF wave minima and maxima field attenuation locations in a control house appropriately represents the attenuation of the RF E_1 waveform.

The major contributing factor to attenuation of the RF E_1 waveform is the conductive material obstructing the electric field. The RF E_1 waveform is categorized as a transverse electromagnetic (TEM) wave; the direction of the electric field, E , is perpendicular to the magnetic field, H , and both are perpendicular to the direction of propagation. For TEM waves, attenuating either the electric field or the magnetic field attenuates both [38]. Therefore, continuous RF wave testing with lower frequency magnetic fields may incorrectly represent the attenuation of the RF E_1 waveform (low-frequency content) by the control house.

The 20 dB attenuation of a new substation control house reduces the peak of the RF E_1 waveform from 50 kV/m to

5 kV/m. This is an innocuous level for impacting typical IEDs that comply with IEC EMC requirements.

In summary, the design of a new substation control house includes the following:

- Metal or metal-lined panels
- Metal overlap of panel seams
- Door seam consideration
- Meshed air openings
- Imbedded mesh windows
- Cable entry cabinet

B. New Substation Control House Wiring Design

New substation control house wiring designs limit transient voltage from the RF E_1 waveform to IEDs by minimizing the loop area of internal wiring. Placing wires in metalized cable trays, along metal cabinets and panels, or in trenches containing a ground conductor reduces the area of the loop that the wire makes with ground.

The cable tray and wire raceway sections are electrically continuous and solidly grounded. The designer places a ground conductor in nonmetallic wire raceways and control house floor trenches and bonds it to ground at both ends (IEEE Std 525) [39].

Recall that electrical transients couple to signal wires in two ways. Capacitive coupling occurs when voltage transients are present on adjacent parallel wires (coupling proportional to the parallel length). Inductive coupling occurs when current transients are present on adjacent parallel wires (coupling proportional to the loop area of the signal wire). Crosstalk is the term given for coupling between adjacent parallel wires [40].

Crosstalk does not affect most control house signal wires. We presume that electrical transients, including those coupled from the RF E_1 waveform, have similar levels on any of the signal wires. Therefore, any crosstalk from electrical transients on adjacent signal wires is not appreciable compared to the transient level possible on a given wire.

Crosstalk that causes a differential voltage transient on signal wires is either small compared to the nominal voltage on the signal wire (i.e., 125 V_{dc} battery, 115 V_{rms} PT, etc.) or adequately filtered by the IED. Crosstalk that causes a common mode transient voltage on the signal wire with respect to ground is small compared to the transient withstand voltage of IED isolation components.

However, crosstalk may affect low-level signals including wired serial communications (Ethernet, USB, EIA-232, EIA-485, IRIG-B, etc.), resistance temperature detector (RTD) inputs, low energy analog (LEA) inputs, and analog inputs and outputs (4–20 mA, ± 10 V, etc.). To address these crosstalk effects, designers use fiber-optic cables or route low-level signals in shielded cables away from the other substation signal wires (IEEE Std 525) [41].

Grounding shielded cables on either or both ends is effective for quenching capacitive coupling crosstalk (IEEE Std 142) [42]. Grounding shielded cables at both ends is effective for reducing inductive coupling crosstalk (IEEE Std 1143) [43]. An example of a shielded cable that is grounded

on both ends is the Ethernet CAT-7 cable [44]. This cable contains individually shielded twisted pairs inside an outer shield.

For RF coupling analysis purposes, we view the control house signal wires as a combination of monopole antennas and transmission lines. An IED signal wire acts as an electrically short monopole antenna as it extends out before being bent to run parallel to the IED chassis (see Fig. 7).

Recall that a distance is electrically short if it is less than 1/10 of the wavelength [45]. For the RF E_1 waveform, the shortest wavelength is approximately 3 m, corresponding to the upper frequency of 100 MHz. Therefore, any distance less than 0.3 m is electrically short.

Once the wire is bent and runs parallel to the IED chassis (or panel, cabinet, raceway, cable tray, etc.), it becomes a transmission line above a ground plane. The signal wire transmission line length is not electrically short.

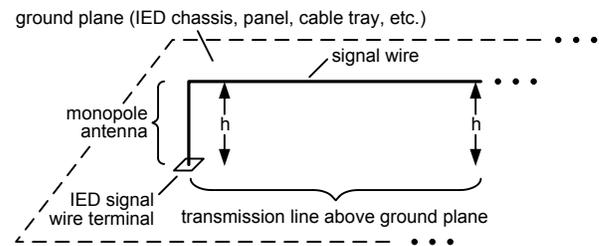


Fig. 7. Monopole antenna and transmission line of a signal wire connected to an IED terminal

Connecting the monopole antenna wire stub to the IED terminal without the additional transmission line would cause the open circuit voltage of the antenna to appear across the IED isolation component. For an electrically short wire stub height of 0.1 m that is aligned with the 5 kV/m peak electric field (inside the control house), the peak voltage across the isolation component is 500 V [46].

Simulations for the coupling of the RF E_1 waveform (having a peak of 5 kV/m inside the control house) into a monopole antenna height of 0.1 m and signal wire transmission line length up to 30 m, result in a transient peak voltage that is up to 1 kV across the IED isolation components (see Appendix B).

In summary, the wiring design for a new substation control house limits the transient voltage across the IED isolation components from an RF E_1 waveform. This transient voltage level is a fraction of the multiple kilovolt withstand capability of IED isolation components that are designed for the harsh substation environment. Designers of new substation control houses:

- Specify a metallic framework of grounded panels, cabinets, chassis, trays, raceways, and ground conductors that are electrically continuous and solidly grounded
- Route signal wires along the metallic framework, minimizing loop area
- Place additional ground conductors in nonmetallic wire raceways and control house floor trenches

- Use fiber-optic cables or route low-level signals in shielded cables away from other signal wires, with the shield grounded on at least one end

C. New Substation Yard Wiring Design

New substation yard wiring designs shield the signal wires that leave the substation control house and go to the electric power equipment in the substation yard. The signal wire shielding provides a minimum of 20 dB attenuation for a conducted disturbance resulting from the RF E_1 waveform. Designers achieve this by grounding metallic conduits or shielded cables at both ends.

For substation yard wiring, grounding shielded cables at both ends reduces the common mode transients that couple to the signal wires from electromagnetic interference (EMI). These transients are from switching arcs, capacitor bank switching, and lightning (IEEE Std 525) [47]. Shielded cables also attenuate the RF E_1 waveform, reducing conducted disturbances.

When the RF E_1 waveform impinges on a shielded cable, it causes a current transient on the shield, similar to the way a TEM wave that propagates to and reflects from a conductive plane causes a surface current to flow [48]. The distribution of these current transients on the shield and the attenuation of the impinging RF E_1 waveform both contribute to the shielding effectiveness of the cable. For single-layer braided cables, a shielding effectiveness of 40 to 60 dB is typical up to 100 MHz, with an increase of 20 dB for each additional braided layer [49]. Shielded cables that provide a minimum attenuation of 20 dB reduce the common mode transients on signal wires from the 20 kV open-circuit voltage value for buried conductors (see Table XI) to less than 2 kV.

Designers ground the substation yard cable shields at both ends in a way that eliminates or minimizes pigtail lengths [50], because RF E_1 transients may couple to the signal wires for the length of the pigtail. In addition, when transient currents flow in the pigtail, the currents may inductively couple to the signal wires.

Ideally, shields are circumferentially grounded on the exterior metal surface as the cables enter the control house or yard equipment cabinet [51]. This grounding method is effective for maintaining the shielding effectiveness of the cables for the upper frequencies of RF waves. It also minimizes the signal wire transients from ground potential rise. Although this grounding method is sufficient, we challenge whether circumferentially grounding the shield is necessary for achieving the minimum attenuation of 20 dB.

The RF E_1 waveform is not the same as a continuous RF wave impinging on a shielded cable, because standing waves do not occur with the RF E_1 waveform. In addition, the transient shield currents from the reflection of the RF E_1 waveform do not return through ground via the grounded shields. On the contrary, any surface currents in the ground from the impinging RF E_1 waveform are in the same direction as the shield currents. We model the return path of these shield and ground currents through the parasitic capacitance of the

shorted dipoles within the shield or ground sections (see Appendix B, Section C).

As such, the authors question the validity of using results from 1) injection tests that apply current or voltage transients to cable shields or 2) continuous RF wave tests, for evaluating the coupling of the RF E_1 waveform to signal wires in shielded cables with pigtails. If pigtails exist, placing them inside the yard equipment cabinet or substation house cable entry cabinet minimizes their impact. These cabinets attenuate the RF E_1 waveform, thus reducing the coupling to the unprotected signal wires for the length of the pigtails. In addition, attenuating the RF E_1 waveform reduces the surface currents on the portion of the shields and pigtails inside the cabinets.

Designers of new substations also route the shielded cables to yard equipment, either radially or in a tree branch fashion. This avoids large loops from signal wires going to one piece of yard equipment, then to another, and back to the control house via a different route (IEEE Std 525) [52].

For shielded cables in a cable trench, the designer routes one or more 2/0 or 4/0 ground conductors in the trench (usually along the top) and bonds them to the substation yard ground grid at both ends and at periodic points along the way (IEEE Std 525) [53]. Ground conductors allow current to flow when ground potential rise occurs from system faults or lightning. The ground conductor current induces a voltage on the cable shields, which tends to reduce the current flow on the shield.

Designers do not route low-level signals, including wired serial communications (Ethernet, USB, EIA-232, EIA-485, IRIG-B, etc.), RTD inputs, LEA inputs, and analog inputs and outputs (4–20 mA, ± 10 V, etc.) outside the substation control house. Fiber-optic cables provide serial communications from control house IEDs to IEDs in cabinets within the substation yard.

In summary, designers of new substation yard wiring:

- Place signal wires in shielded cables between the substation control house and yard equipment
- Ground cable shields at both ends
- Eliminate or minimize pigtail lengths and contain them within yard cabinets and the control house cable entry cabinet
- Route 2/0 or 4/0 ground conductors in the trench with the shielded signal wire cables
- Route shielded signal wire cables radially or in a tree branch fashion to yard equipment (to avoid large yard loops)
- Install fiber-optic cables for serial communications between control house and substation yard IEDs

D. Cables Originating Beyond the Substation Yard Fence

Designers of new substations do not bring cables that originate from beyond the substation yard fence directly into the substation control house. For these cables, the designer ensures a minimum of 40 dB attenuation of the E_1 conducted disturbance. These cables include ac station power feeds and

telecommunications cables (pilot wires, telephone lines, and other WAN lines).

New substation designs use a transformer in the substation yard for the ac station power feed. Typically, a cable raceway that is separate from all other substation wires brings this ac feed to the battery charger in the substation control house. In addition, designers typically wire any ac lighting and outlet feeds in metallic conduits, away from other substation wiring [36].

Designers install transient protection and transformer isolation for WAN wired telecommunications in a termination cabinet, mounted to an external wall of the substation control house. The external WAN wires enter the cabinet from outside the control house. This prevents transients on long remote lines from reradiating inside the control house. The transient protection and transformer isolation provide attenuation for the conducted disturbance resulting from the RF E_1 waveform [54] [55] [56].

V. IMPROVEMENTS TO LEGACY SUBSTATIONS

The decision to upgrade legacy substations to improve HEMP resiliency of IEDs is based on a risk-cost-benefit analysis. We consider substation-hardened IEDs HEMP resilient if they comply with the IEC EMC and safety standards, even when in legacy substations. We recommend reviewing IED specifications to ensure compliance with the IEC EMC and safety standards as demonstrated by the immunity and withstand type tests and levels of Table III and Table IV.

Improvements to grounding and IED signal wiring may be combined with lightning resiliency and switching transient resiliency improvements. The cost of rewiring a substation yard to use shielded cables that are grounded at both ends may not justify the benefit solely from a HEMP resiliency standpoint.

The following are lower-cost improvements (compared to rewiring) for HEMP resiliency that have benefits of lightning and electrical transient resiliency as well.

1. Ensure the ground bonding integrity of the panels, cabinets, chassis, trays, raceways, and ground conductors inside the control house. Place ground bonds between metallic items near signal wires. Reduce the loop area of signal wires with respect to ground to minimize the coupling of RF transients.
2. Add ground conductors to any nonmetallic control house cable trenches or raceways. Ground the conductors on both ends and at locations where signal wires leave the trench or raceway.
3. Replace unshielded, low-level signal wires inside the control house with fiber or shielded cables (at least, grounded at one end). Route low-level signal shielded cables away from other signal wires.
4. Install a cabinet (around existing terminals) at the control house cable entry location, separating external signal wires and shield terminations from internal control house signal wires.

5. Ground any shielded cables between the control house and yard equipment at both ends. Eliminate or minimize the length of the pigtailed to minimize the coupling of shield currents to signal wires. Confine pigtailed within the yard equipment cabinet and substation control house wire entry cabinet.
6. Install ground conductors with the signal wiring between the control house and yard equipment, even if using shielded cables. This reduces the loop area of signal wires with respect to ground. It also reduces the inductive coupling on signal wires and shields and thus the resulting shield current (IEEE Std 525 and IEEE Std 80) [53] [57].
7. Replace wired serial communications and other low-level signal wires between the control house and yard equipment with fiber.
8. Install a shielded isolation transformer outside the control house for any ac station power feeds that are originating beyond the substation yard fence. A shielded ac transformer may provide 40 dB of attenuation for the common mode electrical transients between primary and secondary windings [58].
9. Install transient protection and transformer isolation for wired telecommunications lines originating from outside the substation yard. Locate protection devices and transformers in a termination cabinet that is mounted to an external wall of the substation control house.
10. Replace IEDs that are not intended for the substation environment or not compliant with the IEC EMC and safety standards.

VI. CONCLUSIONS

SEL protective relays and other IEDs that comply with IEC 60255-26 for the EMC EU directive and IEC 60255-27 for the low-voltage EU directive are (by design and by type-test results) HEMP resilient when in legacy or new substations. In addition, substation-hardened IEDs that comply with the 5.0 kV impulse voltage withstand level [33] are (by analysis and statistical evaluation) HEMP resilient.

Legacy substation design techniques for resiliency to lightning and other electrical transients and IED design techniques for the harsh substation environment provide statistical HEMP resiliency for existing IED installations. IEDs not intended for the substation environment or not compliant to the IEC EMC and safety standards are at risk of isolation component damage and malfunction from voltage transients as a result of the RF E_1 waveform, lightning, and other electrical transients.

Substation owners may assess the HEMP-related risk to IEDs by 1) identifying the withstand voltage limit of the IED insulation or isolation components and 2) using Table VI to determine the percentage of installed IED signal wire terminals that are statistically exposed to a transient voltage level that exceeds the IED withstand limit. IED manufacturers evaluate and provide the withstand voltage limit of an IED

through analysis and testing related to a voltage transient with a rise time/pulse width from 10/100 ns to 25/500 ns.

Given the phenomenal outcome of 50 kV/m radiated pulse type testing as well as the outcome of fast damped oscillatory wave type testing on a typical SEL protective relay, performing these type tests on similar IEDs is unnecessary and not recommended by the authors. The immunity and withstand type test requirements of IEC 60255-26 for the EMC EU directive and IEC 60255-27 for the low-voltage EU directive are sufficient for demonstrating IED HEMP resiliency.

The authors recommend using the design techniques for new substations provided in this paper to specify HEMP resilient substation designs. These design techniques are based on IEEE standards and also provide resiliency to lightning and other electrical transients. Implementing these design techniques for new substations provides ample margin for IED immunity if 1) HEMP events have significantly higher levels or faster rise times than the RF E_1 waveform specified in the HEMP standards, 2) the insulation property of isolation components degrades with time, and 3) shielding properties degrade with time.

The authors recommend not basing the decision to enhance or upgrade legacy substations on HEMP resiliency of substation-hardened IEDs. Instead combine HEMP resiliency improvements with other planned upgrades and improvements.

HEMP events with regard to substation IEDs should no longer be a concern for policy makers, grid operators, and others. Mitigation efforts for existing substations should be based on increasing lightning and switching transient resiliency of IEDs, which in turn increases HEMP resiliency.

VII. APPENDIX A: IEC HEMP STANDARDS AND TYPE TEST IMMUNITY LEVELS FOR HEMP RESILIENCY

The IEC Subcommittee 77 for EMC: High Power Transient Phenomena (SC 77C), published 21 HEMP-related standards, technical reports (TR), and technical specifications (TS) from 1996 to 2014 [59]. These publications are appropriate for substations and are applicable to IEDs in a substation control house.

The following subsections highlight the various aspects of the HEMP standards related to the substation control house, substation wiring, and IEDs in a control house.

A. Protection Concepts

The IEC HEMP standards use “protection concepts” to categorize a structure (i.e., control house) and the wiring entering the structure in order to assign IED immunity test levels for HEMP resiliency.

Table VIII lists the control house protection concepts based on the control house attenuation of the RF E_1 waveform and the cable system attenuation of the conducted disturbance from coupling of the RF E_1 waveform [14]. Table IX provides descriptions of control house protection concepts [14].

TABLE VIII
CONTROL HOUSE PROTECTION CONCEPTS

Protection Concept	Minimum Attenuation (dB)	
	Electric and Magnetic Field	Conducted Current
1A	0	0
1B	0	20
2A	20	0
2B	20	20
3	20	40
4–6	40+	40+

TABLE IX
CONTROL HOUSE PROTECTION CONCEPT DESCRIPTION

Protection Concept	Description
1	Above-ground wooden, brick, or concrete block building or structure with large windows and doors without rebar or other explicit shielding.
2	Above-ground concrete building or structure with rebar, or buried brick or concrete building or structure.
1 or 2	A Lack of conducted lightning protection (overvoltage protection without filtering).
	B Presence of conducted lightning protection (overvoltage protection without filtering).
3	Shielded enclosure with minimal RF shielding effectiveness. Typical equipment box with small apertures. Nominal lightning overvoltage and EMI conducted penetration protection (filtering).

New substation designs meet protection concept 2B for the control house building and general signal wiring and protection concept 3 for the cables originating beyond the substation yard fence (see Table X). We use these protection concepts to determine the immunity levels identified later in this appendix.

TABLE X
PROTECTION CONCEPTS FOR NEW SUBSTATION DESIGNS

	Radiated RF E_1 Minimum Attenuation	E_1 Conducted Disturbance Minimum Attenuation	Protection Concept
Control house	20 dB	---	2B and 3
Substation yard signal wires	---	20 dB	2B
Cables originating beyond the substation yard fence	---	40 dB	3

The control house building provides at least 20 dB average attenuation of the electric and magnetic fields. There is no need for the substation control house to attenuate both the electric and magnetic fields of the RF E_1 waveform. Attenuating either one by 20 dB attenuates the other. For a structure, plane wave (i.e., TEM wave) attenuation is nearly

the same as the electric field attenuation and is fairly constant below a frequency of 1 MHz [38] [60].

Using shielded cables that are grounded on both ends for the signal wiring between the control house and the yard equipment provides at least 20 dB attenuation of the conducted current (compared to no shield).

B. Coupling to Elevated and Buried Conductors

For long cables leaving the substation yard, new substation designs meet protection concept 3 by providing additional shielded transformer isolation and/or transient protection of ac station power feeds and telecommunications cables (including pilot wires and power line carriers) originating from beyond the substation yard fence.

Determining the common mode coupling into cables with respect to earth ground is arduous, since the cable separation from the return current in the earth is not electrically short compared to the shortest wavelength of the RF E_1 waveform spectrum.

The width of the 23 ns waveform propagating at the speed of light is a little under 7 m. If the RF E_1 waveform is propagating vertically down on an aerial cable that is 10 m off the ground, most of the waveform interaction with the cable has come and gone before the wave front impinges on the earth.

Table XI presents probabilistic coupling calculation levels for the RF E_1 waveform [61]. The short-circuit current and open-circuit voltage values correspond to the peak of the traveling wave on the transmission line resulting from the coupled RF E_1 waveform. The open-circuit voltage divided by the short-circuit current equates to the characteristic (source) impedance of the transmission line.

TABLE XI
E₁ COMMON MODE COUPLING TO CABLES

	Elevated Conductors	Buried Conductors
Short-circuit current	1500 A	400 A
Open-circuit voltage	600 kV	20 kV
Source/characteristic impedance	400 Ω	50 Ω
Conductor length	> 200 m	> 10 m
Waveform (rise time/50% width)	10/100 ns	25/500 ns

Statistically, 90 percent of the coupling calculation results (referenced in IEC 61000-2-10) are less than the values for the elevated conductor (10 m high) in Table XI [61]. The buried conductor values are the higher values corresponding to the lowest earth conductivity (10^{-4} S/m) and are also valid for cables up to 0.3 m above the ground [61] [62]. The coupling of the RF E_1 waveform of Fig. 2 results in a slightly filtered waveform, which has a slower rise time and is wider (see Table XI).

C. Immunity Type Tests for IED HEMP Resiliency

An IEC standard identifies five immunity type tests for demonstrating HEMP resiliency (see Table XII) [63]. Air ESD, Electrical Fast Transient/Burst (EFT/B), and Surge are

requirements of the EMC EU directive for placing the CE mark on a substation control house IED.

TABLE XII
FIVE IMMUNITY TYPE TESTS DEMONSTRATE HEMP RESILIENCY

	Immunity Type Test (IEC 61000-6-6) ¹	EMC Requirement (IEC 60255-26)
Radiated pulse (2.5/25 ns)	IEC 61000-4-25 ¹	Not required
Air ESD (8 kV)	IEC 61000-4-2	IEC 61000-4-2
EFT/B (5/50 ns)	IEC 61000-4-4	IEC 61000-4-4
Surge (1.2/50 μs)	IEC 61000-4-5	IEC 61000-4-5
Fast damped oscillatory wave	IEC 61000-4-25 ¹	Not required

¹These IEC standards are presently not harmonized and therefore not required for placing the CE mark on an IED

Air discharge ESD immunity type tests are 8 kV for both the EMC requirement and HEMP resiliency (all protection concepts). The HEMP resiliency level for the radiated pulse is 5 kV/m for protection concepts 2 and 3 and 50 kV/m for protection concept 1.

D. Comparison of EMC and HEMP Resiliency Immunity Levels for IEDs

The EMC electrical transient immunity levels for IEDs are higher than the HEMP resiliency levels for new substation designs (compare Table XIII and Table XIV respectively).

TABLE XIII
EMC ELECTRICAL TRANSIENT IMMUNITY LEVELS FOR IEDS

	EFT/B	Surge	SDOW
Signal (PTs, CTs, I/O)	± 4 kV	± 4 kV	2.5 kV
Signal (Serial comm.)	± 2 kV	± 2 kV	1 kV
Power (dc)	± 4 kV	± 4 kV	2.5 kV
Power (ac)	± 4 kV	± 4 kV	2.5 kV
Telecommunications	± 2 kV	± 4 kV	---
Antenna	± 2 kV	± 4 kV	---

The EFT/B and Surge type test standards are the same for EMC and HEMP resiliency immunity tests (although different levels). The EMC immunity test requires a slow damped oscillatory wave (SDOW) instead of the fast damped oscillatory wave (FDOW) for HEMP resiliency. The transient immunity levels in Table XIV correspond to the listed protection concept for interior cable lengths of 20 m (serial communications cables are 10 m) [63]. The protection concepts in Table XIV are for new substation designs (see Table X). IEDs in a new substation control house have a radiated pulse immunity level of 5 kV/m for HEMP resiliency.

The HEMP standards do not contain creepage distance and clearance requirements for IEDs. However, the creepage distances and clearances associated with the IED isolation components are a key element of designing HEMP-resilient IEDs.

TABLE XIV
HEMP RESILIENCY ELECTRICAL TRANSIENT IMMUNITY LEVELS FOR IEDS
(NEW SUBSTATION DESIGN)

	Protection Concept	EFT/B	Surge	FDOW
Signal (PTs, CTs, I/O)	2 (A or B)	± 2 kV	---	2 kV
Signal (Serial comm.)	2 (A or B)	± 2 kV	---	1 kV
Power (dc)	3	± 2 kV	± 1 kV	2 kV
Power (ac)	3	± 2 kV	± 2 kV	2 kV
Telecommunications	3	± 1 kV	± 1 kV	---
Antenna	3	± 1 kV	---	4 kV

Substation IEDs that comply with the low-voltage EU directive fulfill the creepage distance and clearance requirements of IEC 60255-27. Classifications of typical substation-hardened IEDs for determining these IEC 60255-27 requirements are the following: pollution degree 2, overvoltage category III, rated insulation voltage of 300 V, and an altitude of up to 2,000 m [64]. The creepage distance and clearance requirements apply to the internal isolation circuitry and isolation components that interface with the IED terminals.

The IED manufacturer's Declaration of Conformity that lists the 60255-26 standard for the EMC EU directive and the 60255-27 standard for the low-voltage EU directive contends that the IED complies with the type test immunity and withstand levels of Table III and Table IV.

E. Electrical Transient Immunity Levels for HEMP Resiliency of IEDs in a Legacy Substation Design

Legacy substation designs may provide little attenuation of the RF E_1 waveform by the control house (protection concept 1) and little shielding of signal and other wires from the control house to substation yard equipment (protection concept 1A). The electrical transient immunity levels for IED HEMP resiliency in legacy substation designs are higher than IEDs in new substation designs (see Table XV) [63].

TABLE XV
ELECTRICAL TRANSIENT IMMUNITY LEVELS FOR IED HEMP RESILIENCY
(LEGACY SUBSTATION DESIGN)

	Protection Concept	EFT/B	Surge	FDOW
Signal (PTs, CTs, I/O)	1 (A or B)	± 8 kV ¹ (10 m)	---	4 kV (10 m)
Power (dc)	1 (A or B)	± 16 kV ² (20 m)	± 4 kV (20 m)	4 kV (20 m)
	2A	± 4 kV (20 m)	± 4 kV (20 m)	4 kV (20 m)
	2B	± 4 kV (40 m)	± 4 kV (80 m)	4 kV (20 m)

¹Single pulse, the authors recommend alternatively using direct ESD contact discharge

²Single pulse, the authors recommend alternatively using direct ESD air discharge

VIII. APPENDIX B: RF COUPLING INTO SUBSTATION CONTROL HOUSE WIRING

This appendix provides the modeling basis used for simulating RF coupling into substation control house wiring.

RF transients, including the RF E_1 waveform, couple to a signal wire from both the electric field (E) and magnetic field (H) components. For an electrically small loop, the electric field component couples into the capacitance of the loop. The magnetic field component induces a voltage in the loop from the magnetic flux time rate of change through the loop (magnetic field component via Faraday's Law) [65].

The distance between signal wires and ground in a substation control house is typically less than 0.3 m. This is electrically short with regard to the RF E_1 waveform. However, the length of signal wires is not. As such, coupling in the control house signal wires is more complicated than coupling in electrically small loops.

Coupling into substation control house wiring is a combination of coupling into the monopole antennas and the transmission lines of the signal wires (see Fig. 7). The following subsections generalize the RF coupling models for the monopole antenna, rectangular loop antenna, and transmission line section (all considered electrically small).

A. Monopole Antenna Model

The open terminal voltage of a monopole antenna is proportional to the E component that is parallel to the antenna. Fig. 8 shows a field-to-circuit model and an equivalent model for the monopole antenna.

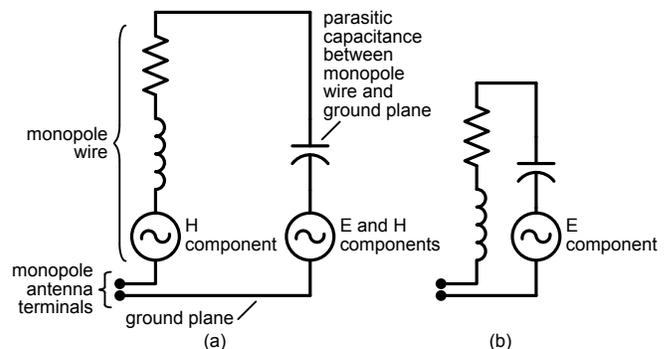


Fig. 8. Monopole antenna: (a) field-to-circuit model (b) equivalent model

The H component of the field-to-circuit model in Fig. 8(a) couples as a series voltage source in both the monopole wire and the parasitic capacitance between the monopole wire and ground plane. In Fig. 8(a), the H components of the voltage sources are equivalent and sum to zero for the monopole antenna open terminal voltage. This leaves only the E component of the voltage source in Fig. 8(b).

B. Rectangular Loop Model

Although small rectangular loops are not typically found in substation control house wiring, understanding the model for the rectangular loop is helpful for understanding the transmission line section model.

A rectangular loop antenna is a combination of four shorted dipole antennas [66]. Any E component that is coupled to one of the dipole legs is shorted, generating a current around the

loop containing the parasitic capacitance between the wire ends (similar to shorting the antenna terminals of Fig. 8).

The reactive current flow from the E component coupling contributes little to the loop antenna terminal voltage. Therefore, we can reduce the loop antenna equivalent model (see Fig. 9). The loop antenna terminal voltage is the sum of the four H component voltage sources around the loop and is equivalent to the induced voltage in the loop per Faraday's law. We can further reduce the model of Fig. 9 to a single magnetic field voltage source in series with a single resistor and inductor.

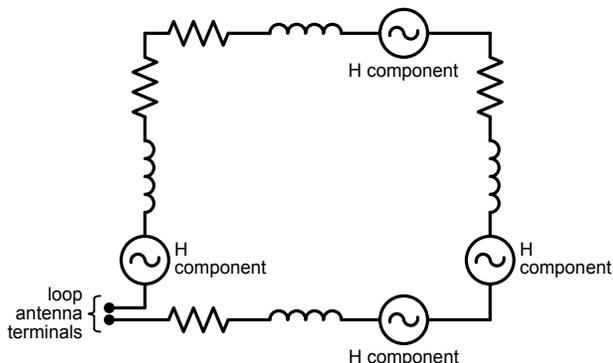


Fig. 9. Loop antenna equivalent model

C. Transmission Line Section Model

Attaching a signal wire to the bend point of the monopole antenna of Fig. 7, slightly increases the effective length of the antenna from the additional capacitance of the transmission line wire, similar to a monopole antenna with a top hat [46].

The RF E_1 waveform couples to the monopole antenna at the IED terminal, producing a voltage transient that appears across the IED isolation component and also travels down the transmission line away from the IED. Reflections occurring at the other end of the transmission line produce a voltage transient waveform that travels back to the IED terminal.

If the signal wire is bent back toward the chassis or panel metal at some point, it forms another monopole antenna in the opposite direction. The voltage transient picked up by this monopole antenna travels on the transmission lines both toward and away from the IED.

The RF E_1 waveform may also couple to the parallel portion of the signal wire of Fig. 7. Since this length is not electrically short (with regard to the RF E_1 waveform frequency spectrum), the coupling is more complicated than the coupling to the monopole antennas at the IED terminal.

The signal wire of Fig. 7 may be broken into many electrically short (0.3 m) segments connected in series. We view each signal wire segment as a shorted dipole antenna, in parallel with and capacitively coupled to the ground plane below. The coupling of the RF E_1 waveform E and H components are represented by the voltage sources shown in Fig. 10.

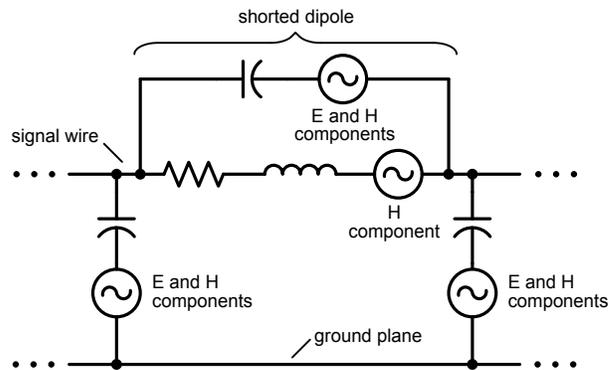


Fig. 10. Signal wire transmission line section

The E component of the voltage sources between the signal wire and ground plane is proportional to both the electric field that is perpendicular to the signal wire and the height of the signal wire that is above the ground plane. The E component of the voltage source that is parallel to the signal wire is proportional to the electric field that is parallel to the signal wire and the length of the transmission line segment. The H components of the voltage sources around the loop sum to the induced voltage in the loop per Faraday's law. However, the complexities of the voltage sources that are parallel and perpendicular to the signal wire and related to the H component of the RF E_1 waveform are beyond the scope of this paper [67].

Using the transmission line coupling model of Fig. 10 and a model for the monopole antenna of Fig. 8(b), we perform simulations of the RF E_1 waveform coupling into the signal wire of Fig. 7. Simulations for a monopole height of 0.1 m, signal wire length up to 30 m, and RF E_1 waveform peak of 5 kV/m (inside the control house) result in a transient voltage up to 1 kV peak across the IED isolation component.

Results from coupling simulations show that the rise time of the RF E_1 waveform does not appreciably affect the peak of the transient voltage coupled to signal wires. The RF E_1 waveform is approximately an impulse function producing an impulse response of the wiring system.

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