Lightning Memo

Memo 2

The Power Grid response to Lightning, EMP Considerations

Larry West
Houston, TX USA

abstract

About 85-95% of faults in transmission and distribution networks are temporary. Lightning is the usual reason, causing overvoltages that trigger power-to-ground flashovers (arcs) across the insulators that seldom extinguish on their own. Overhead ground wires are never 100% effective. This means that the lines must be tripped open for de-ionization of the faults and then be re-energized, without the faults recurring. Adaptive reclosing prevents reclosure on permanent faults that can cause more damage. These devices have been used successfully over twenty years and have steadily been improved, however their momentary power trip is now a problem for modern digital electronics. A newer solution without the momentary glitches in power is transmission line arrestors that when installed on every pole literally eliminate lightning induced insulator flashovers. It is assumed that they will do the same for EMP induced flashovers. Now, throw in the Smart Grid and you have many connected elements to process. If it is not programmed to process many simultaneous erroneous signals such as a HEMP E1 event can cause, parts of the grid may lock up and black out without burst error control, fail-safe architecture, and a rolling reboot to reset everything. Battery backup in substations and reclosers is essential as well as emergency motor generators. Black startups are rehearsed on a regular basis.

Introduction

There are about 3,300 electric utilities in the US with about 200 providing power to the most consumers. [29] The US electric power system consists of more than 19,000 generators, 55,000 substations, 642,000 miles of high voltage transmission lines, and 6.3 million miles of distribution lines. [14] To treat the grid as a single entity is a mistake. Power transformers in substations have been lightning- and switching surge-proof for many years. The distribution and transmission lines are the only parts of the modern electrical power system that still need more protection to reduce the effects of lightning. (Note that the terms ‘transmission lines’ means those that emanate from the generator plants and are high voltage while ‘distribution lines’ are the lower voltage lines connected to customers. (See Figures 1 and 2, below.) Substation names follow, accordingly.) [1]

The International Electrotechnical Commission (IEC) has classified power line voltages into the following levels (IEC 60038):

Low Voltage	≤ 1kV
Medium Voltage	1kV - 35kV
High Voltage	35kV - 230kV
Extra High Voltage	230kV - 800kV
Ultra High Voltage	> 800kV

Transmission-level voltages are considered to be 110kV and higher. Lower voltages, such as 66kV and 33kV, are considered subtransmission voltages, but are occasionally used on long lines with light loads. Voltages less than 33kV are used for distribution. Voltages above 765kV are considered ultra high voltage and require different designs compared to equipment used at lower voltages. [6]

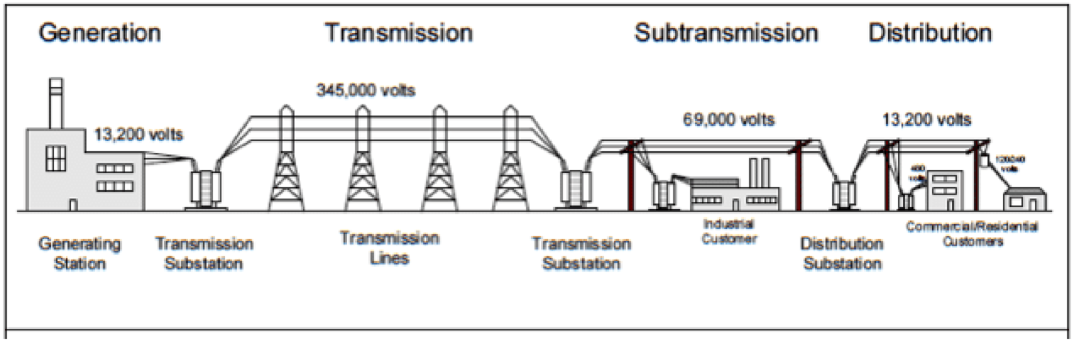

Figure 1. Typical Power Grid

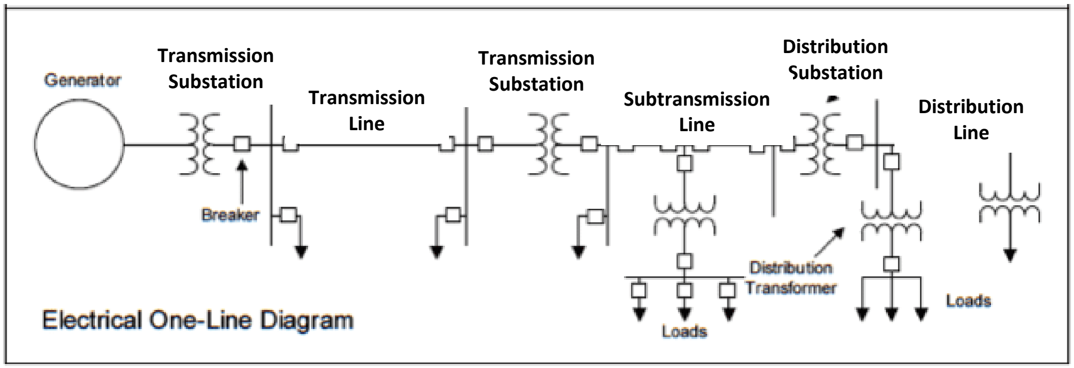

Figure 2. One Line Drawing of a Typical Power Grid

Lightning protection of the power grid has been overhead ground wires (OHGW), automatic circuit breakers, AKA ‘reclosers’, surge arresters, and high voltage withstand levels.

Transient outages are caused when an insulator flashes over, either in a forward or backward direction, from a lightning surge and is followed by an arc of the power line current. (See Figure 3, below.) <u>The power system current sustains the arc</u>. Such a power-to-ground fault on the distribution system requires a breaker to clear and end the event.

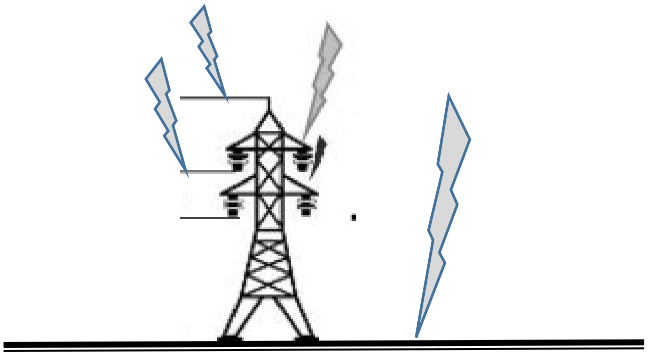

Figure 3. Lightning Strikes on the Lines, on the Overhead Ground Wire, on the Tower, or Nearby Cause Insulator Flashover

Overhead Ground Wires (OHGW)

Overhead ground wires have been the main lightning protection of power lines for over 90 years. They are intended to draw the lightning strikes to themselves and from there to ground/earth. (See Figure 4, below.) They're simply extensions of the 'Franklin rod'. Their success is measured in percentages.

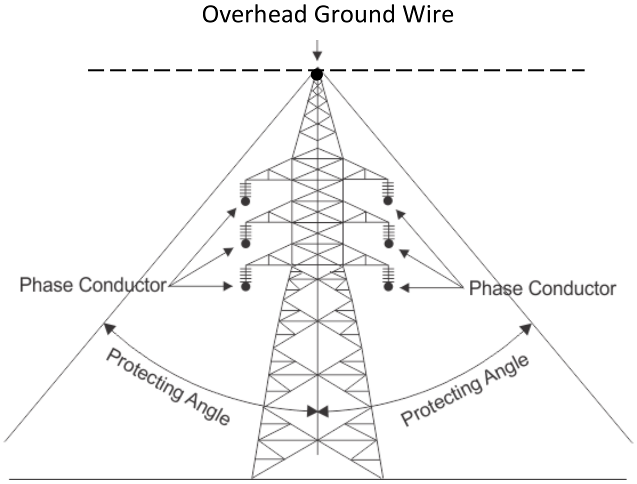

Figure 4. Overhead Ground Wire with Protecting Angle

The oldest paper found on the subject is by Bewley, "Critique of Ground Wire Theory" in 1931. [16] That implies that they had been around for a while.

In 1823 Gay-Lussac proposed a cone of protection with a radius of twice the height of the air terminal. [9] In 1880, Preece conducted experiments to measure the actual electric field about a vertical air terminal. Preece concluded: "…a lightning rod protects a conic space whose height is the length of the rod, whose base is a circle having its radius equal to the height of the rod, and whose side is the quadrant of a circle whose radius is equal to the height of the rod". [10]

Report of the Lightning Rod Conference in 1882: "All accidents may be said to be due to a neglect of these simple elementary principles. The most frequent sources of failure are conductors deficient either in number, height, or conductivity, bad joints, or bad earth connections. There is no authentic case on record where a properly-constructed conductor failed to do its duty." [11]

From the bulk of evidence by the 1950's the conclusion was that lightning protection systems, as embodied in the national codes and standards of the day, were very effective in preventing damage due to lightning. [13]

The use of overhead ground wires (OHGW) with their zone of protection has been around before the 1930s. Before about 1951, a shielding angle of 30^0 was usually employed for transmission lines. This produced acceptable lightning performance on lines up to 230kV. In the mid-1950s, the angle had to be reduced for 345kV lines because they were taller. [15]

Overhead Ground Wires provide effective protection only if the following are met:

(1) Good insulation design practices are used on the power line insulators (250–300kV Critical Flashover Voltage (CFO));

(2) Low resistance to ground/earth is obtained (< 10Ω); and,

(3) A sufficient shield angle is used to protect the power lines ($\leq 45^0$).

Even with 350kV insulator critical flashover voltage (CFO) and 20Ω ground resistance, there is still a 10% chance of backflash and an outage. [1] (A backflashover occurs when a lightning flash hits an OHGW or a tower structure and then arcs over to the power lines. A backflash is typically caused by large stroke currents, high tower surge impedances (tall towers), and/or high footing resistance.) (See Figures 5a & 5b, below.)

The flashover (FO) rate of insulators on a line that are directly struck is about 99% according to IEEE 1410. This means that if a line is struck by lightning the critical flashover voltage (CFO) or basic insulation level (BIL) of the insulators does not matter; they will flashover.

The flashover rate from nearby lightning is much higher than that the direct strike rate. (Because there are more nearby flashes than direct strikes and because of OHGW when in place)

Ideally, the towers are single conductors with low resistance connected through a low resistance connection to ground/earth. However, the towers are not a single conductors. They are multiple pieces of steel with many bond joints holding them together mechanically and electrically. Over 50-67% of the electrical resistance top-to-bottom is in the joints. When struck by lightning, the lightning current will 'track' through the low conducting oxidized joints. Therefore, the high current resistance is less than the low current resistance. The connection to ground/earth is likewise through joints. Bottom line: the higher the resistance from the lightning attachment point to earth, the higher the voltage along the tower and the higher the likelihood of back flashover from the tower to the power lines. Time increases the oxidation and the joints' resistance exacerbating the problem no matter how good when new.

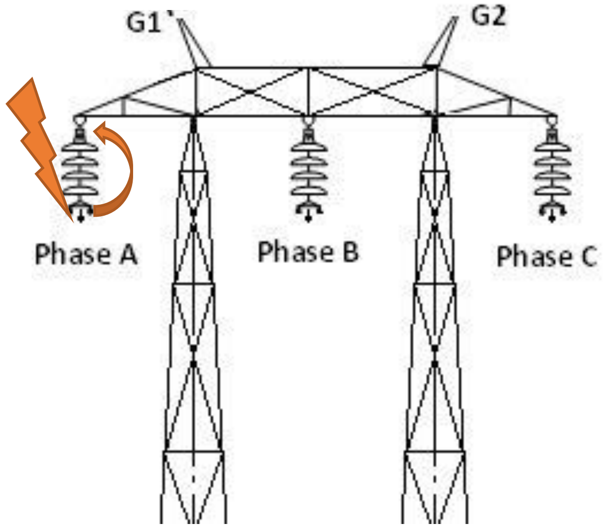

Figure 5a. Example of Insulator Flashover
Lightning Strikes the Power Line
Then Flashes over the Insulator to the Tower

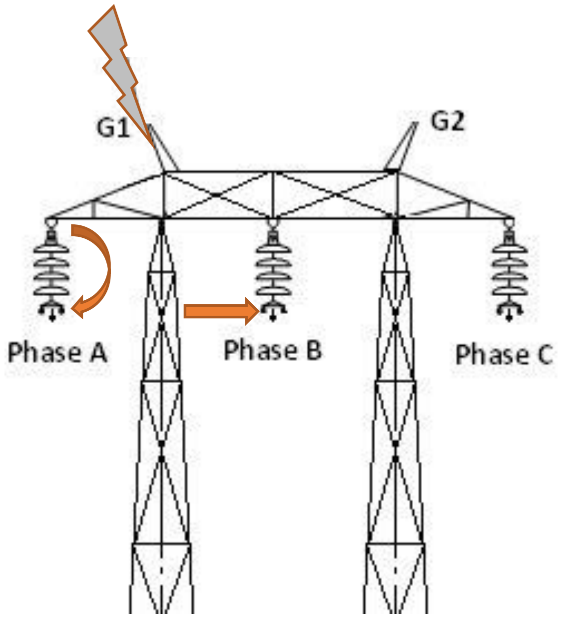

Figure 5b. Examples of Back Flashover
Lightning Strikes the Tower or OHGW
Then Flashes over to the Power Line from the Tower

This concludes discussion of overhead ground wires (OHGW). No lightning rod, mast, or overhead wire provides 100% protection.

BIL (Basic Insulation Level)

Insulators on different voltage lines have different voltage withstand levels and lightning withstand levels. The American Standard (lightning) impulse overvoltage wave shape is 1.5/40µs. The 1.5/40µs impulse wave represents a unipolar wave which rises to its peak value from zero in 1.5µs and then falls to 50% of peak value in 40µs. The 'basic insulation level' or BIL of an electrical equipment determines the principle dielectric quality of the apparatus and is expressed by the peak value of the 1.5/40µs impulse withstand voltage. <u>BIL is the Lightning Withstand Voltage</u>. See Table 1, below.

In electrical generating power stations, power is generated at medium voltage level that ranges from 11kV to 25kV. That is stepped up for transmission to consumers where it is stepped down for use.

The lightning critical flashover voltage (CFO) is the peak value of a standard lightning impulse for which the insulation exhibits 50 % probability of withstand.

All insulation voltage withstand levels depend upon altitude, pollution, moisture, and age.

Table 1. Nominal and BIL Voltages [25]

Nominal (kV)	**BIL (kV)**
25	150
69	350
138	650
144	650
240	1050
500	1800

The BIL of the protected element is used to estimate the lightning current withstand level for the purpose of designing lightning protection. This in turn is used to define the zone of protection and the radius of the rolling sphere tool. [26]

$$I_s = \frac{BIL \cdot 1.1}{Z_0/2},$$

where I_s is he peak value of a lightning stroke that an insulated element can withstand and Z_0 is the power line impedance.

The straight line angle of protection is still used however more refined methods were developed. The electrogeomagnetic model came out in 1963 and the rolling sphere method came out in 1977 and is the standard today. The smaller the sphere, the better the protection. [8] See Table 2, below.

Table 2. Minimum Current allowed by the Rolling Sphere Radius

Protection Level	Minimum Current (kA)	Rolling Sphere Radius (m)	Probability Strike Current is over the Minimum
I	3	20	99%
II	5	30	97%
III	10	45	91%
IV	16	60	84%

Insulator Flashover

Air breakdown occurs in microseconds. Even though the E1 pulse is short, the induced transient on long power lines is microseconds due to the additive line voltage. (In Albuquerque, I used to see the power line insulators spark when a nearby EMP simulator would fire.)

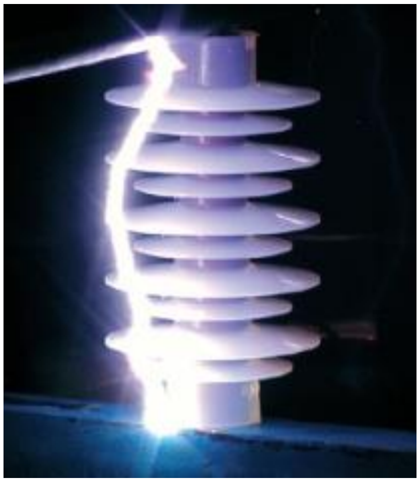

Figure 6. Insulator Flashover

Insulators used in transmission and distribution systems can withstand an "impulse" voltage of 3 to 12 times the line voltage (with the higher multiples applying to the lower line-voltages). The breakdown conditions are different when the wire is positive from when it is negative. The ratio of insulator puncture voltage to flashover voltage is ≈ x10. [30] Insulator damage is not a problem.

Reclosers

Reclosers were invented in the mid-1900s in the USA. They were originally oil filled hydraulic devices with rudimentary mechanical protection relaying capabilities. The advent of semiconductor based electronic protective relays in the 1980s resulted in increased sophistication, allowing for differing responses to the various cases of abnormal operation or faults on distribution networks. Reclosers are often used as a key component in a smart grid when they are computer controlled and can be remotely operated and interrogated using SCADA (supervisory control and data acquisition) or other communications. This capability allows utilities to aggregate data about their network performance, and develop automation schemes for power restoration. This automation can either be distributed (executed at the remote recloser level) or centralized (close and open commands issued by a central control room to be executed by remotely controlled automatic circuit reclosers (ACRs)). [18]

The breakers may be the rapid reclosing type (about 20 cycles or 0.4s) or the delayed (about 5-30s) auto reclosing type. For the rapid reclosing type it is not required to check phase synchronism before reclosing however for delayed reclosing synchronism should be checked before reclosing. For this purpose synchronizing relays are employed. [18]

The number of reclose attempts is limited to a maximum of four by recloser standards. [18]

Surge immunity tests for reclosers are 2kV line-to-line and 4kV line-to-earth. [19]

A group of intelligent reclosers can be programmed to operate in a pre-defined sequence to automatically restore service to sections of the distribution system. [18]

Battery power is used for backup power when AC power is lost on ABB reclosers. [23] On Hubbell reclosers, battery power is used for these functions: [24]

- To close the recloser after installation or lockout;
- To power the communication modules if load current is less than 10 amps;
- Powering the controller during extended reclose times; and,
- Flashing the beacon (light) (so ground crews can see a locked out recloser).

There is much more to reclosing than is discussed herein.

Figure 7. Reclosers on a Pole

Figure 8. Pole Mounted Recloser

When RTE (Rural Transformer and Equipment Company) received a patent on the 15kV loadbreak elbow (recloser) design in 1966, its potential growth was probably unrealized at the time. It is estimated that there are well over 10,000,000 such elbows in service today. [39]

Transmission Line Arresters

The development of the Metal-Oxide Varistor (MOV) disc in 1967 was a new method for overvoltage protection. [27] Advancement of the MOV technology led to an evolution in power system arrester design and functionality.

The 1992 introduction of the polymer-housed MOV arrester gave empatis to the practice of lightning protection of the transmission lines (TLA) themselves. Overhead ground/shield wires had been the only cost-effective means of mitigating the effects of direct lightning until then. Since then, TLA have eliminated lightning induced outages where installed. [1] (See Figures 9, 10, & 11, below.)

The margin of safety (insulator BIL on the transmission voltage) permits the use of lightning arresters whose firing voltage is considerably larger than the transmission voltage, yet low enough that the lightning arrester fires before insulator flashover. This looks like our best first-cut EMP fix. And, they're already proliferating around the US and the world. Overhead ground wires have recurring problems with inclement environments like wind and ice plus cost and maintenance.

When a line is fitted with arresters on each tower and each phase, **the tower ground resistance becomes a non-factor** in the lightning protection, unlike the OHGW. [1]

Arrester designs are available for line voltages ranging from 2.4kV to 800kV. [5]

Since 2011, momentary interruptions have been completely eliminated on Pennsylvania Power & Light (PPL) Electric Utilities on over 3,000 miles of 69kV and 138kV lines protected with line surge arresters - down from 164 interruptions to zero. [1]

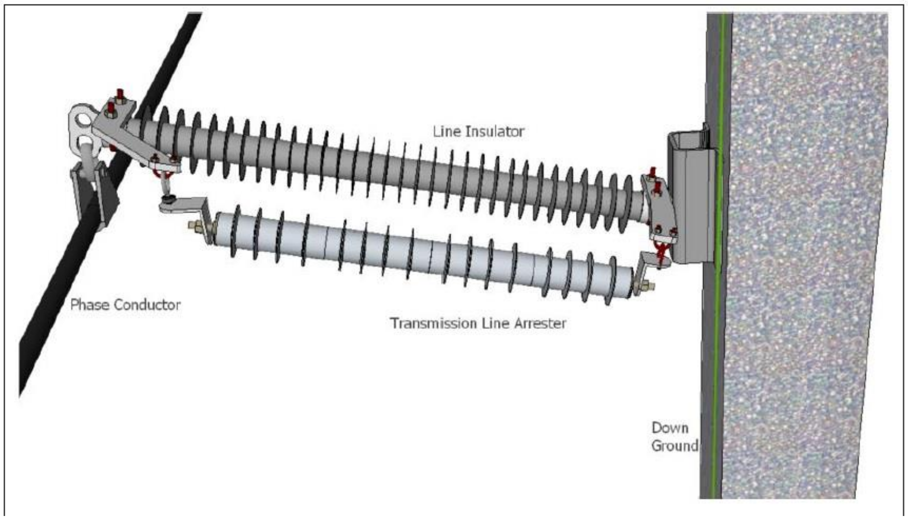

Figure 9. Transmission Line Arrestor

Figure 10. Transmission Line Arrestors

Figure 11. Romanian Tower-Mounted 400kV Transmission Line Arrestors (with grading rings)

The mountainous 80 mile 400kV Romanian Gutinas-Brasov line saw 4 to 10 lightning induced outages per year before arresters were installed, but over the period 2006 to 2015 and thereafter, no outages were recorded. [3] (See Figure 11, above.)

Reliability of MOV arresters has been called into question in the past. However, since the introduction of the MOV arrester 30 years ago, the failure rate of these devices is about .02 percent or lower, as reported by quality manufactures of the devices. This translates to about one failure every 11 years on a 10-mile line. [1]

Power Station Generators, Tripping & Recovery

The three-phase power leaves the generator and enters a transmission substation at the power plant. This substation uses large transformers to convert or "step up" the generator's voltage to extremely high voltages for long-distance transmission. Voltages for long distance transmission range from 155kV to 765kV. Maximum transmission distances are about 300 miles. [4]

Generators cannot withstand short-circuit fault for more than ≈ 5sec. Transmission and distribution flashovers should be reclosed before the generator ever sees them. Here comes the transmission substations located near the generators.

The transmission substation transformers support the transmission system and the smaller sub-transmission and distribution substation transformers.

The transmission substation contains equipment used to sectionalize the electric transmission system when a fault or short circuit develops on one of the circuits.

I was concerned about faults close to generating stations until I found the following about transmission substations (the ones the step-up the voltage at the generator location for the high voltage transmission lines). [4]

Circuit breakers in the transmission substation are used to switch generating and transmission circuits in and out of service. A faulted circuit is switched out of service automatically and de-energized, protecting the remaining portion of the transmission network from trouble. This works both ways for generator and line faults. This is essential for preventing cascading faults leading to blackouts, i.e. removing/tripping the generators from the transmission and distribution systems that are experiencing only temporary faults.

Functions of a substation may include one or more of the following:

To isolate a faulted element from the rest of the utility system;

To allow an element to be disconnected from the rest of the utility system for maintenance or repair;

To change or transform voltage levels from one part of the utility system to another;
To control power flow in the utility system by switching elements into or out of the utility system;
To provide sources of reactive power for power factor correction or voltage control; and,
To provide data concerning system parameters (voltage, current flow, power flow) for use in operating the system.

The heart of a substation is the battery bank. If this were to fail, this is what could happen:

(1) An electric utility could expose all feeders associated with the station to a condition where they could not ever trip in a fault.

(2) Any backup devices, such as the main breaker on the low-voltage side or the high-voltage side protection of the power transformer, would all be inoperative. [20]

As a result of faults, the AC auxiliary voltage may not be available, because the incoming feeders may have tripped. After such situation, re-energizing of the substation is solely depending on the DC auxiliary power available, i.e. batteries. [21]

A “black start” is the process of restoring a power unit(s) to operation without relying on external electric power from the transmission/distribution network. Typically, a plant coming online requires electricity for startup units and control equipment. When the entire grid is down, plants have no external sources of power to restart, and thus rely on dedicated black start diesel generators. In order to maintain readiness, designated plants are required to routinely test their black start capabilities. [31]

To provide a black start, some power stations have small diesel generators, normally called the black start diesel generator (BSDG), which can be used to start larger generators (of several megawatts capacity), which in turn can be used to start the main power station generators. Generating plants using steam turbines require station service power of up to 10% of their capacity for boiler feedwater pumps, boiler forced-draft combustion air blowers, and for fuel preparation. It is uneconomical to provide such a large standby capacity at each station, so black-start power must be provided over designated tie lines from another station. Often hydroelectric power plants are designated as the black-start sources to restore network interconnections. [wiki] One method of black start (based on a real scenario) might be as follows:

1) A battery starts a small diesel generator installed in a hydroelectric generating station;
2) The power from the diesel generator is used to bring the generating station into operation;
3) Key transmission lines between the station and other areas are energized;
4) The power from the station is used to start one of the nuclear/fossil-fuel-fired base load plants; and,
5) The power from the base load plant is used to restart all of the other power plants in the system.

Lightning arresters protect generators and substation equipment from lightning strikes and switching surges. The lightning arresters are installed in a substation near the termination of aerial circuits and close to the more valuable pieces of equipment, such as power transformers.

Smart Grid

Electronic controls have been used in most three-phase reclosers since the mid-1980s and are still in operation today. [22]

The ‘Smart Grid’ started with this paper on January 27, 1998: "Toward a Secure and Smart Self-Healing Grid," (M. Amin), EPRI Research Advisory Committee.

The first official definition of Smart Grid was provided by the Energy Independence and Security Act of 2007 (EISA-2007), which was approved by the US Congress in January 2007, and signed to law by President George W. Bush in December 2007.

The American Recovery and Reinvestment Act of 2009 put $4.5 billion into the Smart Grid.

A large storm or other meteorological event can cause multiple faults within a short time in the distribution system. Some of these faults are temporary and can be cleared by reclosers, others are repetitive, and some are permanent. The maximum number of allowable reclosing operations may be exceeded during repetitive or permanent faults. In this situation, most reclosers are locked open, leaving feeders and sections of the distribution system without power. During and after a storm, a group of intelligent reclosers can be programmed to operate in a pre-defined sequence to automatically restore service to sections of the distribution system that have not been permanently affected. [28]

Historically, substation automation has employed multiple different protocols, often proprietary, which lacked interoperability across different vendors' devices. This has led to the creation of a new international specification, IEC 61850, defining a common platform for substation automation networking based on Ethernet technology. IEC 61850 defines a distributed ring topology supporting zero switchover time in case of single failure, known as High-availability Seamless Redundancy (HSR).

Enhanced EMC performance delivers industrial-strength physical layer reliability in the harshest environments, even when operating over low-cost unshielded cabling. [42]

Summary and Preliminary Conclusions

I was pessimistic until I ran into the fact that substations and reclosers have battery backup and even motor generator emergency power for generator black startups. I was worried about many simultaneous flashovers at the same time. Now, I'm worried about the computerized Smart Grid. Can it process many simultaneous fault indications? If the Smart Grid is connected by Ethernet or its equivalent, then the links have error detection and correction codes or with a demanding BER requirement. Since rogue EMP will probably be a onetime event, we don't have to worry about too many and their effects like we did in Cold War days.

Smart Grid and Microgrid: The development of Smart Grid is a form of hardening that is slowly being implemented by utilities across the country. Smart Grid allows utilities to quickly identify outage areas and use crews and resources more efficiently. A Microgrid is a less common form of hardening, yet still effective. A Microgrid is an isolated "island" of electricity generation, transmission, and distribution. Microgrids are able to disconnect from the grid and operate independently for an extended period of time. [31]

Because of different orientations of power lines and station internal cables, I see no more than half of those coupling to a strong EMP field. How many of the affected systems go down as a result is anyone's guess. Current limiting on shielded cable transmission lines rule out serious vulnerabilities. i.e.

$$I_{cable} \le \frac{\mu_0 \cdot 2 \cdot H \cdot h}{L'},$$

where H = 133A/m (x2 for reflection), h = cable height above a groundplane, and L' = cable inductance per unit length (nominally 200nH/m), ignoring cable resonances and building attenuation. Note the independence of cable length. Power designers don't route cables far away from structure or cable trays therefore h = small ≈ a couple of inches at most. That limits EMP induced cable shield current to about 84A. A shield transfer impedance of 1Ω results in 84V divided across the two loads common mode. That won't shut down the grid.

The extremely large EMP induced transients on power lines are only east and west of ground zero, with lines running towards GZ, and for poorly conducting soil. All others are at least x8 less on lines oriented in the right directions. [2]

And then we have the wisdom of Ed Vance from his Cold War research into EMP on power systems: [2]

- “Lightning arresters appear to be effective protective devices for the fast-rising EMP transients as well as the slower-rising lightning transients.”
- “Power-system components have the advantage, from the EMP-hardening point of view, that they must be inherently immune to lightning and switching transients. Hence, the additional protection required to reduce their vulnerability to EMP-induced transients may be quite minimal.”
- “The primary EMP-protection policy for the transmission and distribution lines, transformers, and switchgear is an effective lightning-protection policy.”

This viewpoint and the research that went into it has been ignored by present-day doomsday-sayers with far less expertise … far less. You never see it referenced. Not the party line.

With widespread use of transmission line arrestors, the power system is literally immune to transient faults no matter how many. They simply don’t happen.

If the Smart Grid can handle many simultaneous burst errors on its cables, then we’re home free. Right now, the Smart Grid is more hype than substance and has the earmarks of naïveté. The electrical loads are more likely to be vulnerable to EMP than the electrical supply. However, here comes Ethernet.

Metatech reported that an Ethernet port on a PC was upset at 3kV CM and damaged at 4.5kV. The Ethernet switch was upset at 2-2.5kV and was restored with a power reboot. [41] This describes robust modern circuitry <u>not</u> a million times weaker than those 40 years ago, more like a couple of thousand times stronger. This is fantastic for a system that operates at ±2.5V max with 2-16 PAM levels! If the Smart grid runs on this kind of circuitry, we’re home free. Ethernet Cat6a with one shield, S/UTP or U/STP, is at least 20dB better, Cat7 (S/STP) 40dB. Ethernet researchers also discovered that their I/O circuits don’t withstand 4-8kV CM surges. Breakdown was more common in the 2kV rated RC CM termination capacitors (Smith caps) than in the isolation transformers. (See Figure 12, below.) Efforts are underway to put a 6kV/100A 2/10µs CM surge specification on the Ethernet I/Os (for indirect lightning surges). [40] See a standard Ethernet magnetic module, below, on both send and receive I/O circuits. High voltage rating requires attention to trace spacing and parts placement, e.g. the parts may survive but the traces can melt or arc over. With the magnetic modules built into the cable connectors, the breakdown voltages are probably lower.

It’s hard to believe that over fifty years ago we argued vehemently over a 1.5kV EMP pin spec!

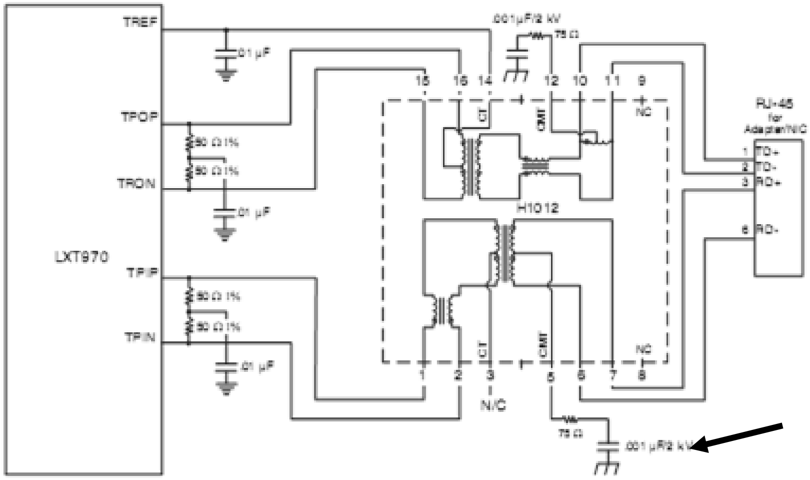

Figure 12. Common Ethernet Magnetic Module (on rcv &xmt)
Xfmr rated at 1.5kVrms (good to surge 4kV - 8kV) (8-30pF interwinding capacitance)
Smith cap rated at 2kVdc

Apology

The above discussion is oversimplified. Putting a power system together and making it work reliably is quite complicated. I can't believe that as a student I considered such studies low on the food chain.

Epilogue:

I got into this issue because of some exaggerated positions old friends were taking about the possible effects of HEMP E1 and their total omission of lightning effects. Two such opinions are the following:

"A single nuclear burst 250 miles (400 kilometers [km]) above Kansas could destabilize much, if not most, of the U.S. power grid." "A nationwide blackout lasting one year could kill millions, perhaps prove fatal to most Americans, by starvation, disease, and societal collapse." Also, "…modern electronics are over 1 million times more vulnerable to EMP than the electronics of 1962." (William R. Graham, Chairman of the Commission to Assess the Threat to the United States from EMP Attack) [32]

The basis for this is the following:

Worst case E1 HEMP power system cable voltage levels are ~300kV and the worst-case internal induced cable voltages are ~20kV when there is no building shielding from the penetrating fields (the reduction is because the wiring inside of a building is not perfectly straight for hundreds of meters). (The Metatech authors believed that only E-fields parallel to cables couple to them.) This author is OK with the 300kV on long power lines but 20kV on premise cables is at least an order-of-magnitude too high. You can't get 50kV/m E-field internally, maybe 500V/m; 133A/m H-field, yes. The penetrating E-field is killed by reflections and the many metallic field termination points. The H-field slithers right through and can double with reflection. Even then, the cable excitation is independent of length, only height above a groundplane. Shielded cables' transfer impedance is dependent upon length. Power grid engineers don't hang cables in mid-air in their toxic EMI environments. Ignoring cable resonances and premise shielding:

$V \leq E \cdot h \approx 380V$ on an unshielded cable
$I \leq \mu_0 \cdot H \cdot h/L' \approx 63A$ on a shielded cable

h = height above a groundplane (small) and L' is the cable inductance per unit length (≈200nH/m).

The max short circuit current source on power lines entering a facility is 15kA with a time-to-peak of 100ns and a source impedance of 25Ω early to 300Ω late. [33] Lightning induced transients on the same lines are about 10kA-40kA. [34] [35] No problem.

Probably the single most influential thing about EMP versus lightning is Figure 13 that's become EMP folklore for almost 30 years. [32] The lightning environment pictured there is about 6kV/m from a stroke 200m to 2km distance. Neither environment is from accepted standards.

The engineers and scientists who work the power grid take lightning quite seriously. It would help the cause for EMP hardening if the EMP analysts would do so, too. Vance did.

Figure 13 is this author's comparison of EMP versus lightning using accepted standard waveforms. There at most 73 lightning restrikes with the same spectra above 1MHz … yes, 73! [38]

It seems advisable to learn how much lightning protection actually exists in the power grid and what they are doing about the effects. From two separate studies, 22 years of 240 lightning events did not take any nuclear power plants permanently out of service or otherwise endanger their operation; they observed the following: [36] [37]

- “It does not appear that the effects from electrical transients which have occurred could compromise the safe shutdown of licensed nuclear power plants;”
- “The most significant impact on plant operations was from local strikes;” and,
- “High-frequency voltage transients created on the transmission system by lightning did not cause significant equipment misoperation or damage.”

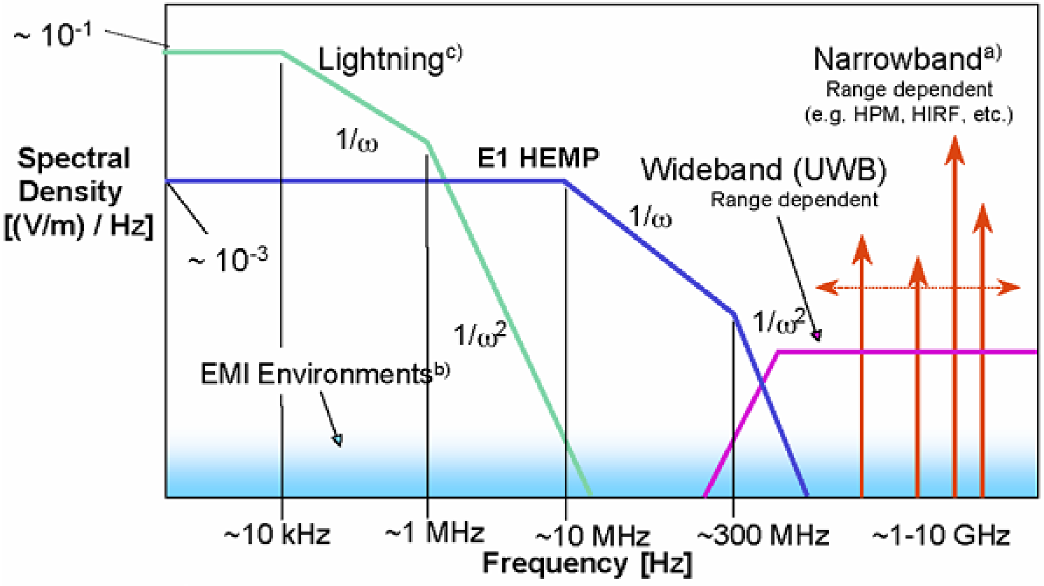

Figure 13. An EMP View of the Lightning versus HEMP Environments [32]

This author’s comparison of EMP versus lightning is depicted in Figure 14, below, using accepted standard waveforms. Please note that the lightning environments are for the 200kA Waveform A at 1m, 10m, 100m, and 400m plus EMP peak at the tangent plus vertical EMP (east & west of ground zero). It also is the spectrum above 1MHz of lightning Waveform A and multiple restrikes Waveform D and Waveform H for as many as 73 times per flash. [38]

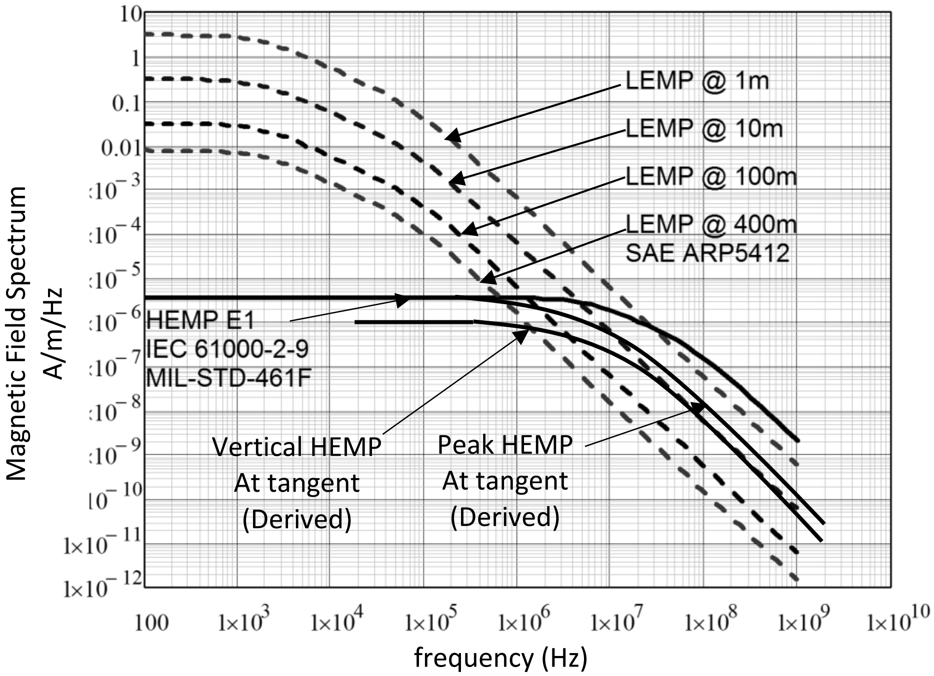

Figure 13. Lightning Fields (LEMP) versus High Altitude HEMP E1 H-Field Spectra [38]

HEMP E1 H ≡ 133A/m, 1.67ns x 25ns, (IEC 1000-2-9 (1996) used 2.5ns x 23ns composite)

LEMP Waveform A (WFA) H-field ≡ 200kA/2·π·R, 1.5μs x 88μs, (US standard SAE/ARP5412)

Final

The power grid needs to (1) apply IEC-61850 (Communication networks and systems for power utility automation) across the board, (2) install as many TLA as possible, (3) make sure the Smart Grid can handle many simultaneous fault indications, and (4) develop a fail-safe architecture and procedure(s).

For HEMP E1 protection, investigators should focus on the parts of the grid with low lightning protection and important loads since they will likely be more vulnerable.

It seems that the electrical loads on the power grid need more HEMP E1 protection than the grid itself, HEMP E3 the exception. Those innocuous little Surge Protector Power Strips, Figure 14, below, in most homes and offices, may be the unheralded saviors of our society against HEMP E1.

Figure14. Surge Protector Power Strip

Larry West

References

1. “The Lightning-Proof Distribution Line”, NEMA, National Electrical Manufacturers Association

2. “Electromagnetic-Pulse Handbook for Electric Power Systems”, Edward F. Vance, Stanford Research Institute, Prepared for: Defense Nuclear Agency, 4 February 1975

3. “Application Experience with Transmission Line Arresters”, INMR, July 6, 2019

4. “How Power Grids Work, The Transmission Substation”, Marshall Brain & Dave Roos, https://science.howstuffworks.com/environmental/energy/power4.htm

5. “Line Surge (LSA)”, Hubbell Power Systems, Inc.

6. “Electric Power Transmission”, Wikipedia

7. “Specification – Insulators”, Horizon Power Inc., April 2016

8., Electrical Know How, “Course Lightning-2: Lightning Protection System Design and Calculations”, https://www.electrical-knowhow.com/2014/05/Rolling-Sphere-Method-for-Lightning-Protection-Design.html

9. Gay-Lussac, F. and C. Pouillet: "Introduction sur les paratonneres, adoptee par L'Academie des Sciences", 1823

10. Preece, W. H.: "On the space protected by a lightning conductor", Phil. Magazine, 9, Jan 1881, pp. 427-430

11. Symons, G. J., editor: “Report of the Lightning Rod Conference”, (with delegates from the following societies, viz, Meteorological Society, Royal Institute of British Architects, Society of Telegraph and of Electricians, Physical Society), 1882

12. Lee, R.H., “Protection Zone for Buildings against Lightning Strikes using Transmission Line Practice”, IEEE Transactions on Industry Applications, Vol. IA-14, No. 6, November/December 1978, p.465

13. “The Basis of Conventional Lightning Protection Technology”, A review of the scientific development of conventional lightning protection technologies and standards, Report of the Federal Interagency Lightning Protection User Group, June 2001

14. “Solid State Power Substation Roadmap”, Klaehn Burkes, Joe Cordaro, Tom Keister, Kerry Cheung, December 2017, Prepared for the U.S. Department of Energy

15. “Shielding Angle of Transmission Line Overhead Ground Wire (OHGW)”, Transmission Lines Design and Electrical Engineering Hub (no date)
http://www.transmission-line.net/2011/05/shielding-angle-of-transmission-line.html

16. Bewley, “Critique of ground wire theory” [J], Transactions of the American Institute of Electrical Engineers, 1931

17. “Performance & Revenue Line Surge Arresters” by Ryan C. Freeman, Application Engineer, ©2017 Hubbell Incorporated

18. “Reclosers”, Wikipedia

19. IEEE Standard C37.60, 2003, IEEE Standard Requirements for Overhead, Pad-Mounted, Dry Vault, and Submersible Automatic Circuit Reclosers and Fault Interrupters for Alternating Current Systems Up to 38kV

20. “Substation Batteries: The Key to Reliability”, Gary Wright, Jun 05, 2013, T&D World

21. Electrical Engineering Portal, Energy and Power/”Power Substation, Substation DC Auxiliary Supply – Battery and Charger Applications”, Edvard Csanyi, September 21, 2015

22. “Reclosers: Fundamentals of Reclosers”, Eaton Power Industries,

23. GridShield® 3P/3SP 15/27/38 kV Vacuum Recloser – Descriptive Bulletin, ABB

24. https://hubbellcdn.com/catalogfull/10EE-VTII-Recloser.pdf, “Versa-Tech® II Recloser”, Catalog 10EE January 2014

25. “Insulation Coordination in the Alberta Interconnected Electric System, Part 1”, Ligong Gan, P. Eng., Transmission Engineering & Performance, Alberta Electric System Operator (AESO)

26. “Rolling Spheres Method for Lightning Protection”, EPOW 6860, Surge Phenomena, Fall 2007, Joe Crispin (International Power System Transients Conference)

27. History_of_Arresters_on_Power_Systems_1965-Present.pdf, Jonathon Woolworth, 2011

28. “Severe Weather and Distribution Grid Automation”, NEMA

29. “Largest energy utility companies in the U.S. based on market value 2019”, T. Wang, Jul 30, 2019 https://www.statista.com/statistics/237773/the-largest-electric-utilities-in-the-us-based-on-market-value/

30. Electrical Concepts, “Insulator Failures – An Overview”, May 30, 2016, https://electricalbaba.com/insulator-failures-an-overview/

31. “United States Electricity Industry Primer”, Office of Electricity Delivery and Energy Reliability, July 2015

32. “Electromagnetic Pulse (EMP) Protection and Resilience Guidelines for Critical Infrastructure and Equipment”, Version 2.2, Developed by the National Coordinating Center for Communications (NCC), February 5th, 2019

33. Lee, K. S. H., Editor, *EMP Interaction: Principles, Techniques, and Reference Data*, Taylor & Francis, NY, 1995

34. ANSI/IEEE C62.41, “Recommended Practice on Surge Voltages in Low Voltage Power Circuits”

35. NFPA 780, “Standard for the Installation of Lightning Protection Systems”

36. Matthew Chiramal, “Lightning Events at Nuclear Power Plants”, AEOD/E605, Office for Analysis and Evaluation of Operational Data, Nuclear Regulatory Commission, Apr. 1986.

37. Chris Rourk, “A Review of Lightning-Related Operating Events at Nuclear Power Plants”, IEEE Transactions on Energy Conversion, Vol 9, No. 3, Sept. 1994

38. Larry West, Lightning Memo 1, “Lightning Environments for EMP Analysts”, 15 Jan 2020, www.ece.unm.edu/summa/

39. https://www.eaton.com/us/en-us/company/about-us/our-heritage/cooper-power-series.html, “History”

40. Joseph Randolph, “Designing Ethernet Cable Ports to Withstand Lightning Surges”, December 29, 2016,
https://incompliancemag.com/article/designing-ethernet-cable-ports-to-withstand-lightning-surges/

41. Meta-R-320, “The Early-Time (E1) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid”, Edward Savage, James Gilbert, William Radasky, January 2010, https://www.ferc.gov/industries/electric/indus-act/reliability/cybersecurity/ferc_meta-r-320.pdf

42. “Smart Grid - Substation Automation, Network Topology and Redundancy”, https://www.microchip.com/design-centers/ethernet/ethernet-devices/applications/industrial/smart-grid, 1998-2020 Microchip Technology Inc.