Fundamentals of Lightning and Lightning Arrester Protection Zone Determination For Protection Engineers

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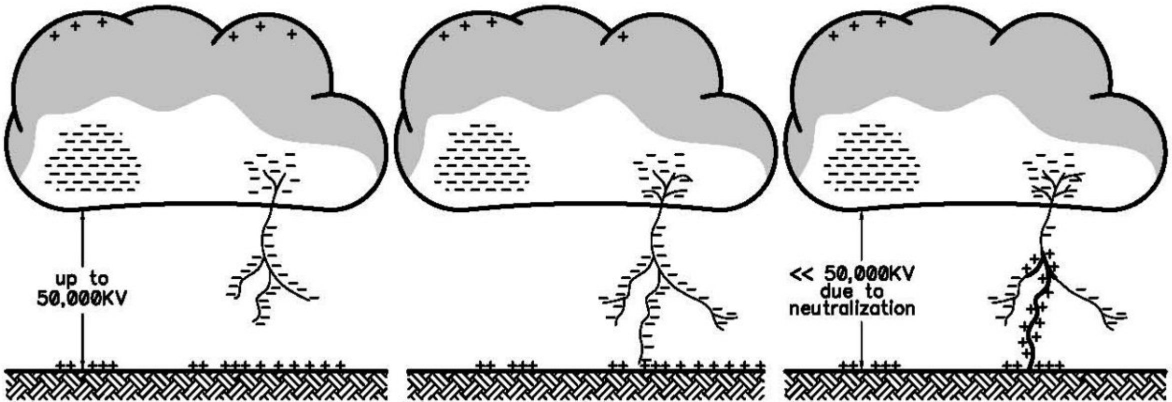
I. Introduction

Historically, lightning strikes have been one of the main electrical fault sources around the world. Lightning strikes an electrical facility or facilities frequently and it can temporarily cripple electrical systems. The lightning strike itself is a form of electrical surge and is so quick that conventional digital relays may not be able to detect it at all, but often times it results in a permanent ground fault. Therefore, the author strongly feels that it is important for relaying professionals to understand the lightning phenomena, lightning protection, lightning arresters, how lightning arresters work to protect electrical facilities against lightning strikes, how the surge analysis is different from the steady-state analysis, etc.

Lightning is a very broad topic, so the author plans to present only some specifics that relaying professionals may find interesting and useful. Highlights of this paper are:

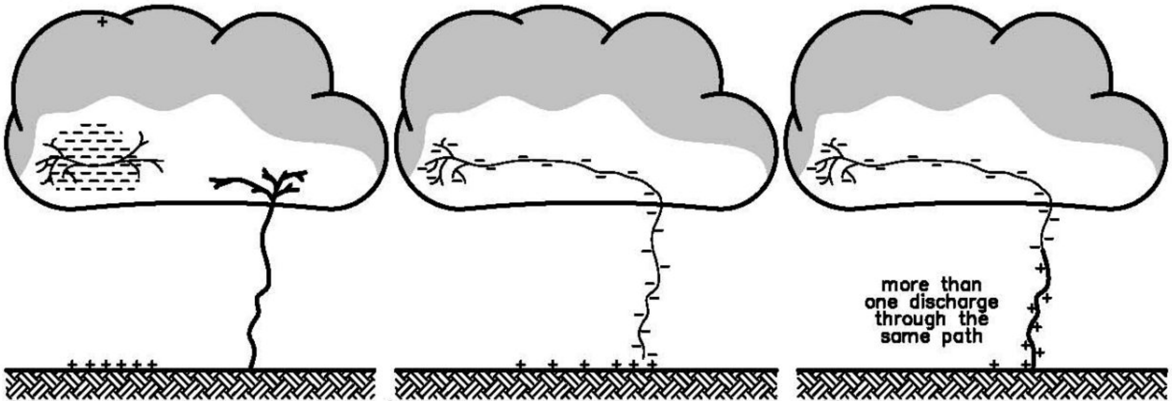
- Lightning phenomena
- Lightning surge vs. switching surge
- Surge analysis vs. steady-state analysis
- Surge impedances for surge analysis
- Dielectric insulation levels and correction factors
- Lightning protection: Overhead static wires (OHSW) vs. lightning arresters
- Lightning arresters: Silicon-carbide vs. metal-oxide-varistor (MOV)
- Lightning arrester protection zone determination
    - Graphical approach
    - Mathematical approach
- Wave front shaping with capacitors:
    - Surge protection for generator stator winding
    - Increase of circuit breaker interrupting rating
    - Converting a line circuit breaker to a generator circuit breaker
    - Circuit switcher sizing impacted by line length
- Faults involving lightning and lightning arresters:
    - Cross-country fault involving multiple lightning arrester failures
    - Ground fault involving a lightning arrester failure
    - Backflash
    - Bus differential relaying susceptible to misoperation



(a) Charge centers in cloud; **pilot streamer and stepped leader** propogate earthward; outward branching of streamers to earth. Lowering of charge into space beneath cloud

(b) Process of (a) almost completed; pilot streamer about to strike earth

(c) Heavy **return streamer**; discharge to earth of negatively charged space beneath cloud

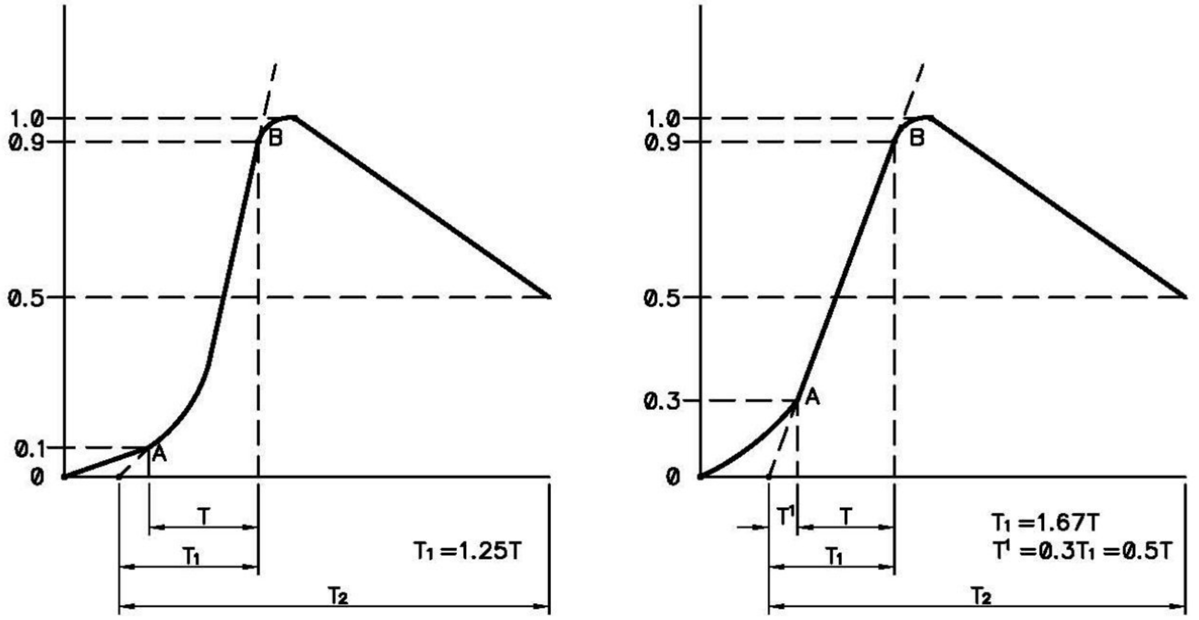


(d) First charge center completely dishcharged; development of **streamers between charge centers** within cloud

(e) Discharge between two charge centers; dart leader propogates to ground along original channel; **dart leader** about to strike earth; negative charge lowered and distributed along stroke channel

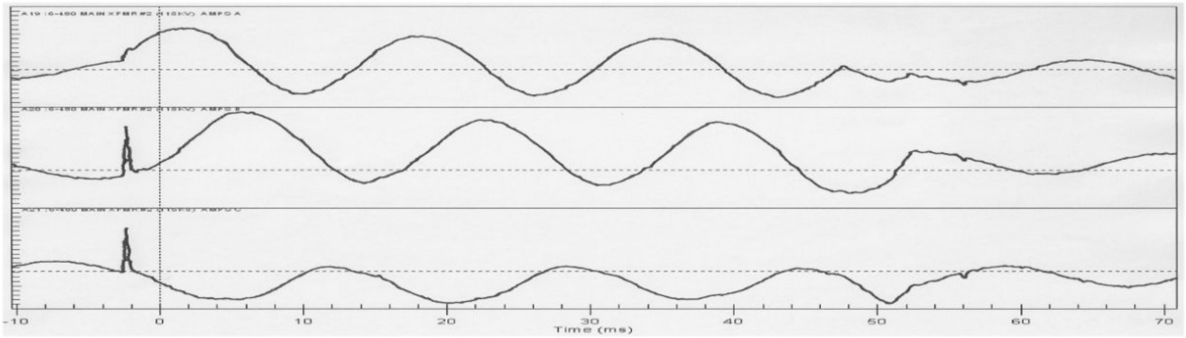
(f) Heavy **return streamer** discharge to earth of negatively charged space beneath cloud

Figure 1. Various stages of lightning discharge (*Note: Taken from Reference [1] and redrawn for clarity.*)

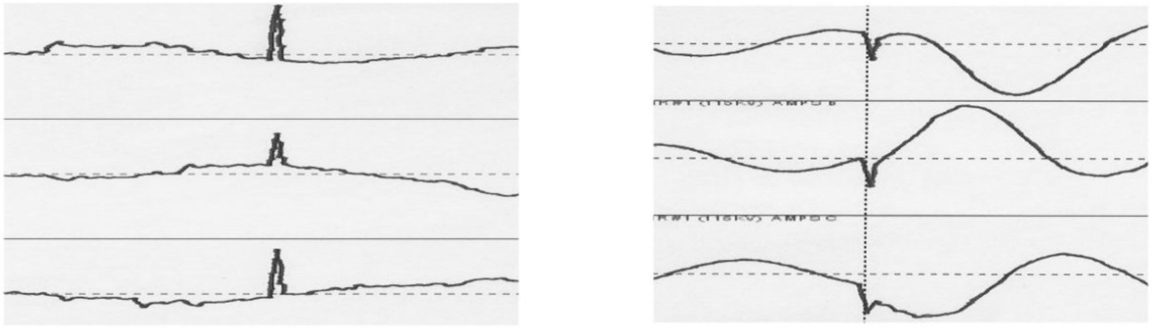


(a) Current Waveshape Standard

(b) Voltage Waveshape Standard



(c) Sample Recording 1
(Lightning causing 3—phase fault)



(d) Sample Recording 2

(e) Sample Recording 3

Figure 2. Standard lightning wave shapes and recorded lightning current wave shapes (*Note: Standard wave shapes taken from References [2,17] and redrawn for clarity. Not scaled for simplicity and illustration purposes.*)

II. Lightning and Switching Surges

A surge is basically a **sudden flow of trapped or stored charges**, charges in a thunder cloud for the lightning surge and charges in a form of capacitor for the switching surge. A main difference between them is that the front of wave (FOW hereafter) rise time of lightning surges is much faster than that of switching surges.

2.1 Lightning Surges

It has been estimated that the potential difference between a thunder cloud and the earth is in the order of 5 to 50 MV, referring to Figure 1. With the development of a high-conducting path between the cloud and the earth and the neutralization of the negative ions due to positive return streamers, the potential difference is lowered considerably [1,2]. For all practical purposes of lightning protection and sizing of lightning arresters, an FOW up to 2000 kV/μs is typically considered.

Referring to Figure 2, in the impulse wave shape designation of T_1/T_2 μs, T_1 is an index of the wave front and the virtual duration of the wave front in microseconds. T_2 is an index of the wave tail and the time in microseconds from the virtual zero to the instant at which one-half of the crest value is reached on the wave tail [16]. Commonly used values are **1.2/50 μs** for the lightning voltage and **8/20 μs** for the lightning current.

Figure 2 has 3 sample lightning current impulse recordings of a lightning-caused 3-phase fault and it is noteworthy that all 3-phase impulses had the same polarity and lasted only less than a millisecond.

2.2 Switching Surges

Referring to Figure 3, should the current be interrupted at the first zero on the transient wave, the capacitor will be left charged at a voltage of 3 times normal in the lossless case (2.2 times normal for 60% overshoot). This represents a danger peculiar to capacitor switching. Successive interruptions and restrikes can result in a gradual buildup of the overvoltage and recovery voltage. Figure 3, representing an initial current interruption at T1, clearly illustrates the consequences of such a sequence of interruptions and restrikes [4].

If at time T2 a restrike and a successive high-frequency current interruption leaves the capacitor charged to 3 times normal peak voltage, another restrike occurring at T3 will cause the voltage in the undamped circuit to swing over to 5 times normal. If again the arc extinguishes at the first high-frequency current zero, the capacitor will remain charged to 5 times normal peak voltage, and so on.

Of course, the probability of occurrence of such a uniquely timed series of interruptions and restrikes is very small since many conditions in sequence must be met. Specifically all restrikes must occur exactly at the peaks of recovery voltages, and the currents must always be interrupted at the first high-frequency current zeros. Furthermore, the system must be undamped to provide the overshoot ratio of 100% and otherwise the buildup of voltage is much smaller.

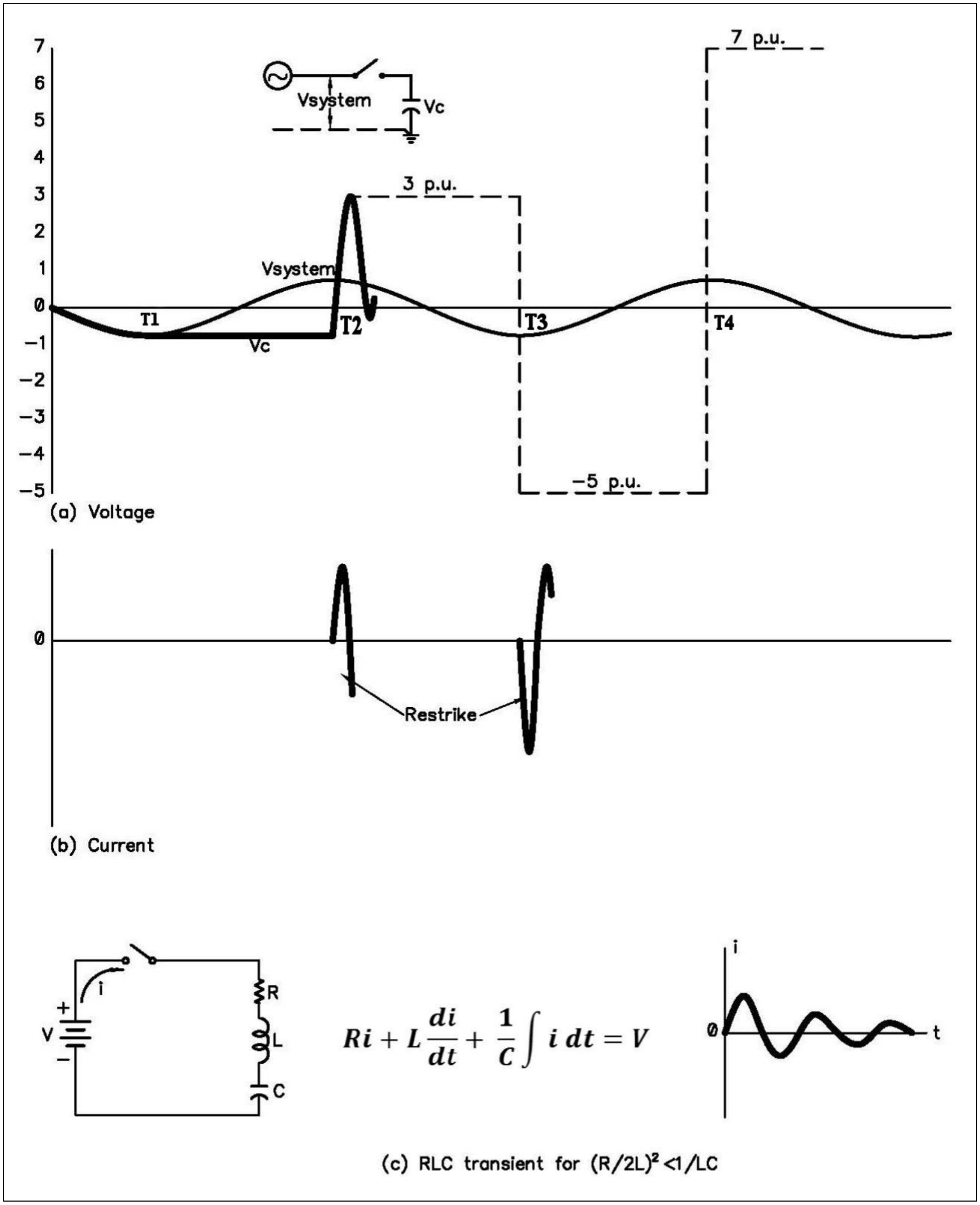
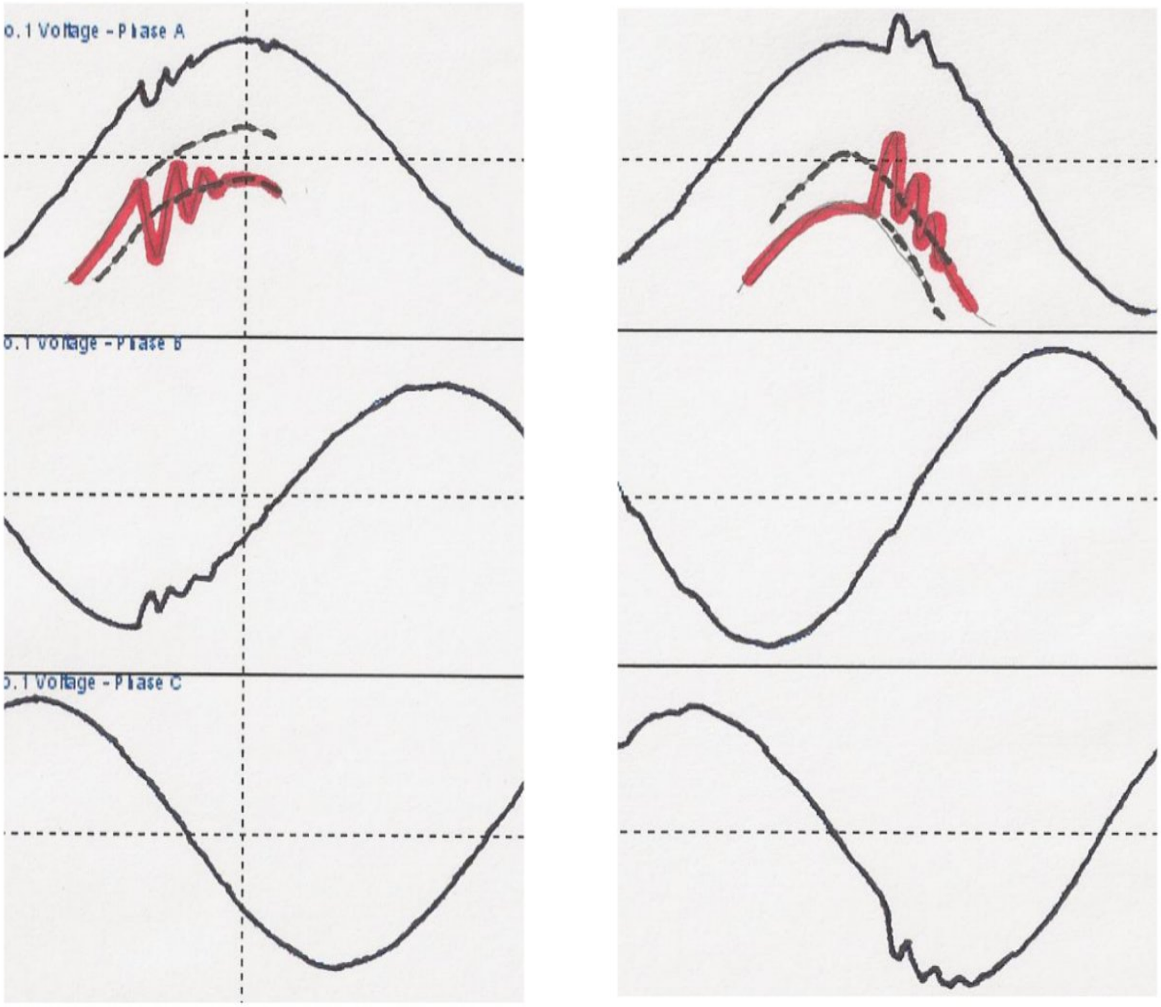


Figure 3. Switching surge magnification and oscillatory decaying (*Note: Taken from References [4,5,6,8,26] and redrawn for clarity. Not scaled for simplicity and illustration purposes.*)



a) Simple switching surge
@ fault initiation

a) Simple switching surge
@ fault clearing

Figure 4. Simple switching surges at fault initiation and fault clearing (*Note: Taken from two separate fault events.*)

Figure 4 above illustrates that both the fault initiation and the fault clearing result in trapped charges, the trapped charges are suddenly discharged through R, L, and C as a form of switching surge, and the discharge currents are oscillatory due to $(R/2L)^2 < 1/LC$ as shown in Figure 3(c). As expected and seen above, the switching surge FOW rise times are much slower than the typical lighting impulse FOW rise time of 8 µs. It is interesting to note, based on the author's research, that Manufacturer A uses the switching surge current rise time of 30 µs and Manufacturer B uses 45 – 60 µs. Nevertheless, both rise times are clearly much slower than the 8-µs rise time.

2.3 *Time-based Power System Analyses*

Table 1 and Figure 5 below show typical operation and response times and imply that switching transients, not to mention the lightning surges, cannot be analyzed with the load flow, short circuit, or even dynamic analysis.

Table 1
Typical operation and response times

	Typical timing		Typical timing
Generator governor control response	Slow and typically in S	Partial discharge rise time	1 – 5 nS
Generator excitation control response	≥ 1 cycle or ≥ 16.7 mS	Electrical noise pulses	Smaller than 20 MHz
Interarea oscillation	0.1 to 1.0 Hz	Lightning impulse rise time	1 µS
Local plant oscillation	1.0 – 2.0 Hz	Switching impulse current rise time for transmission systems	20 – 500 µS
Sub-synchronous oscillation	8 – 55 Hz	Underfrequency load shedding response	14 cycles
Control oscillation	15 to 100 Hz	Power frequency rise time	4.167 mS for 60 Hz

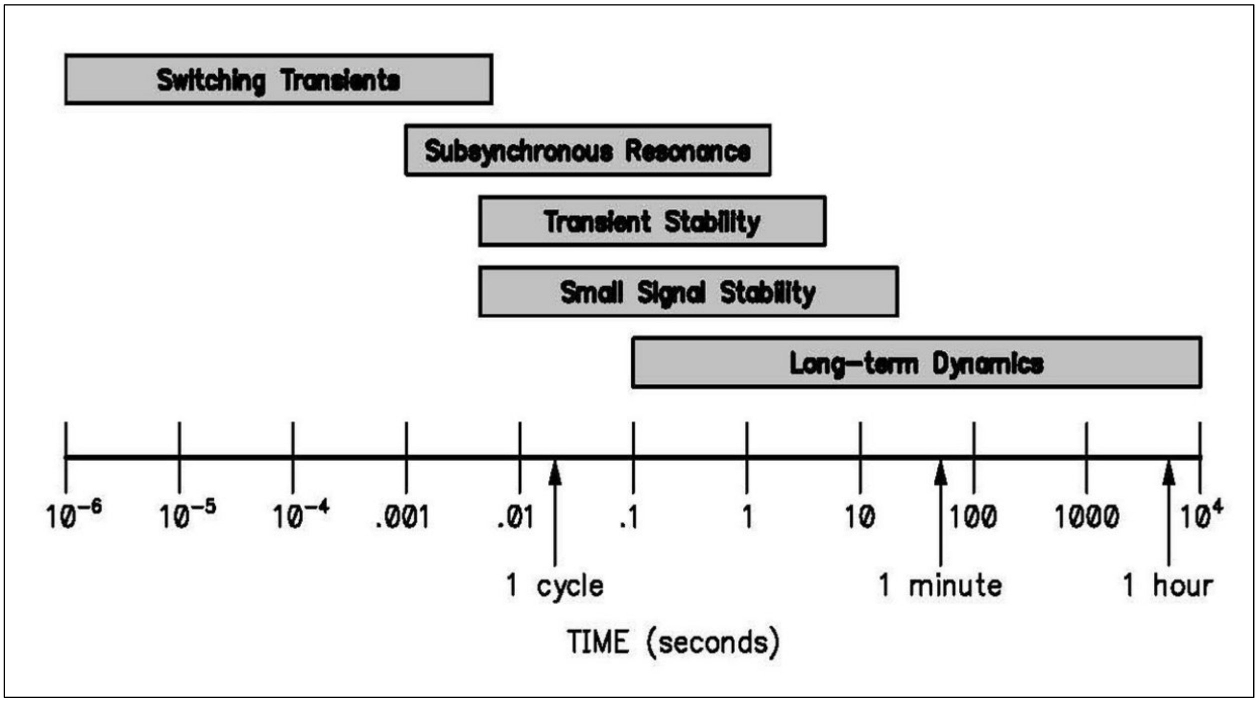
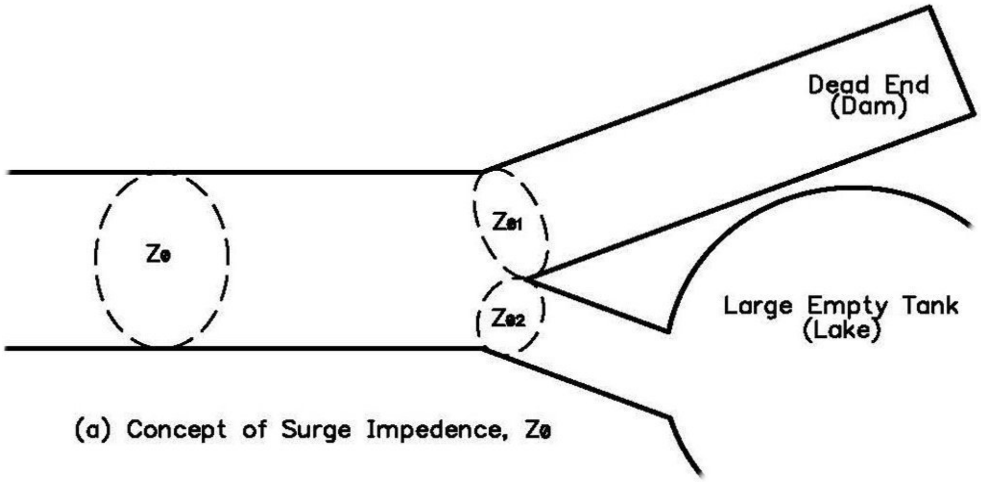
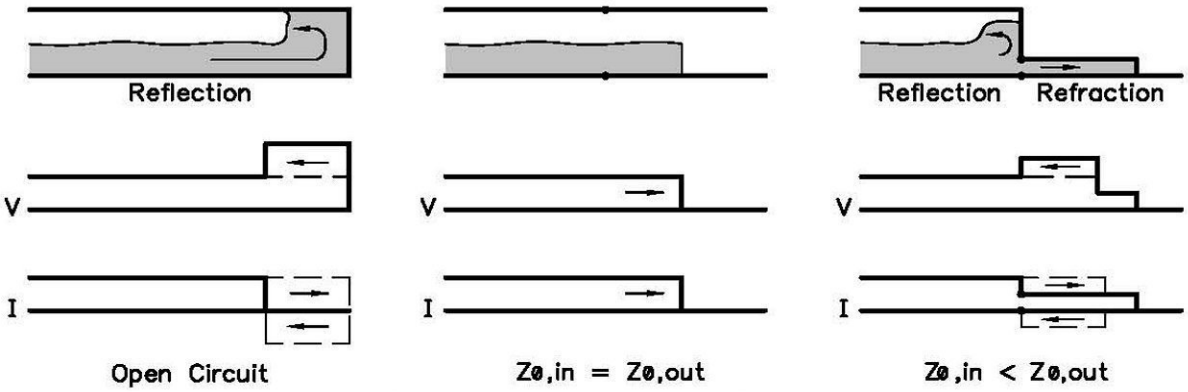


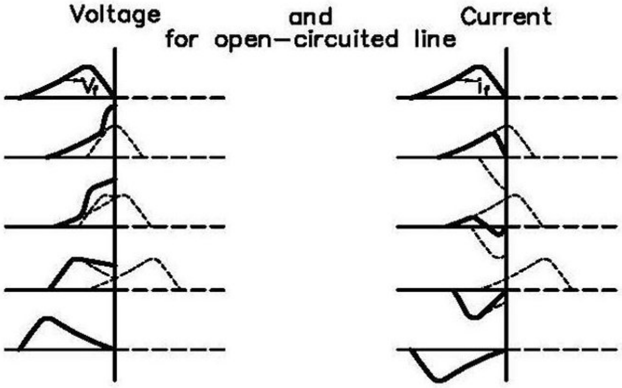
Figure 5. Power system dynamic scales (*Note: Power system dynamic scales taken from Reference [23] and redrawn for clarity.*)



(a) Concept of Surge Impedence, Z0



(b) Surge Reflection and Refraction



(c) Surge Reflection

Figure 6. Concept of surge impedance (*Note: Surge reflection taken from Reference [1] and redrawn for clarity. Not scaled for simplicity and illustration purposes.*)

Table 2
Characteristics of R, L, and C

	For DC	At 60Hz	At high harmonics	At high temp	For surge analysis
R	< 1 p.u. (0.65 p.u. for 1000kCM Cu cable)	1 p.u.	» 1 p.u. (2.5 p.u. @ 13th for 1000kCM Cu cable)	> 1 p.u. (1.6 p.u. for a field winding @ full load)	Surge impedance in ohms, $\boldsymbol{Z_0 = \sqrt{\frac{L}{C}}}$, $\boldsymbol{Z_0 = \frac{276}{\sqrt{k}} \log \frac{d}{r}}$, (k = relative permittivity of insulation between conductors) (400 – 600 ohms for OH and 20 – 60 ohms for UG)
$\boldsymbol{L = 0.74 \log \frac{GMD}{GMR}}$ $\boldsymbol{in\ mH/mi}$, (2 mH/mi or 0.4 μH/ft for 115kV lines)	short circuit	$X_L = 1$ p.u.	X_L » 1 p.u.		
$\boldsymbol{C = \frac{0.039}{\log \frac{GMD}{GMR}}}$ $\boldsymbol{in\ \mu F/mi}$, (0.013 μF/mi or 2.5 pF/ft for 115kV lines)	open circuit	$X_C =$ 1.p.u.	X_C « 1 p.u.		

2.4 Surge Impedance for Surge Analysis

Literally, a surge is a surge or impulse and it is **not associated with any particular frequency and line length**. It does not know what is behind what it faces. Referring to Figure 6(a), it does not know how long Branch 1 is and does not know the fact that Branch 1 is dead-ended. It sees the opening of Branch 1 (i.e., surge impedance Z_{01}) and that of Branch 2 (i.e., surge impedance Z_{02}). For the purpose of steady-state analysis, the Branch 1 impedance is infinite and so a steady-state current cannot flow through it, while for the purpose of surge analysis the Branch 1 surge impedance is finite and so a surge can flow into Branch 1.

Figures 6(b) and 6(c) depict how surges respond to what they face and in both figures it is important to understand that the surge voltage is a **total number of charges built-up** at any given point and the surge current is a **net flow of charges** at any given window.

Table 2 shows that R, L, and C are frequency-dependent except for the surge analysis and the frequency dependency can be significant. For example, if a 15kV 1000kCM Cu cable resistance is 1 p.u., the DC resistance is only 0.65 p.u. but the 780Hz resistance is 2.5 p.u. In addition, Table 2 also shows that the temperature dependency of the generator field winding, unlike others, can be significant. As shown in Table 2, surge impedance is quite different from others and is not associated with any frequency or line length. That is why surge impedances must be used for surge analysis.

III. Fundamentals of Lightning Protection

3.1 Dielectric Insulation Levels and Correction Factors

Table 3
Airgap, gap factor, and BIL
(*Note: Gap factors taken from Reference [13]*)

Airgap in inches	60Hz kVrms (wet)	BIL in kV (positive)	kVnominal
5		110	15
7		150	25
20	170	350	69
33	282	550	115
57	489	900	230
76	640	1175	345
110	902	1675	500

Gap configuration	Average gap factor
Vertical rod – horizontal plane (under)	1.0
Horizontal conductor – horizontal plane (under)	1.15
Horizontal conductor (inside) – structure window	1.2
Horizontal conductor – horizontal truss structure (under)	1.3
Crossarm end – horizontal conductor (under)	1.55
Horizontal conductor – vertical rod (under) at 10-foot elevation	1.65
Horizontal conductor – vertical rod (under) at 20-foot elevation	1.9

Insulating material	Typical insulation value	Insulating material	Typical insulation value
Transformer oil	2.5 kV_{BIL} / mil	Air	200 kV_{BIL} / ft
X-link poly or EPR rubber	0.55 kV_{BIL} / mil	Dry wood	100 kV_{BIL} / ft
Porcelain	20 kV_{BIL} / inch	Water	10 kV_{BIL} / ft

In Table 3 above, the vertical rod-horizontal plane (under) represents the most unfavorable condition, i.e., its withstand voltage is lower than other gap configurations and so the average gap factor value is greater than 1.0 for all other gap configurations. For example, the actual BIL of 33-inch airgap between a horizontal conductor and a horizontal truss structure (under) is 715 kV (i.e., 550 kV_{BIL} for 33-inch airgap X 1.3 gap factor = 715 kV_{BIL}). In addition to the above, the following rules of thumb may be of interest:

- Practical maximum switching impulse = 2 x 1.414 x $kV_{\text{line-neutral rms}}$
- Maximum switching impulse = 2 x 1.414 x 1.15 x $kV_{\text{line-neutral rms}}$
- Lightning impulse attenuation ≈ 50% per every 2 miles
- Minimum required airgap in inches ≈ $kV_{\text{60Hz line-line rms}}$ / 3.5

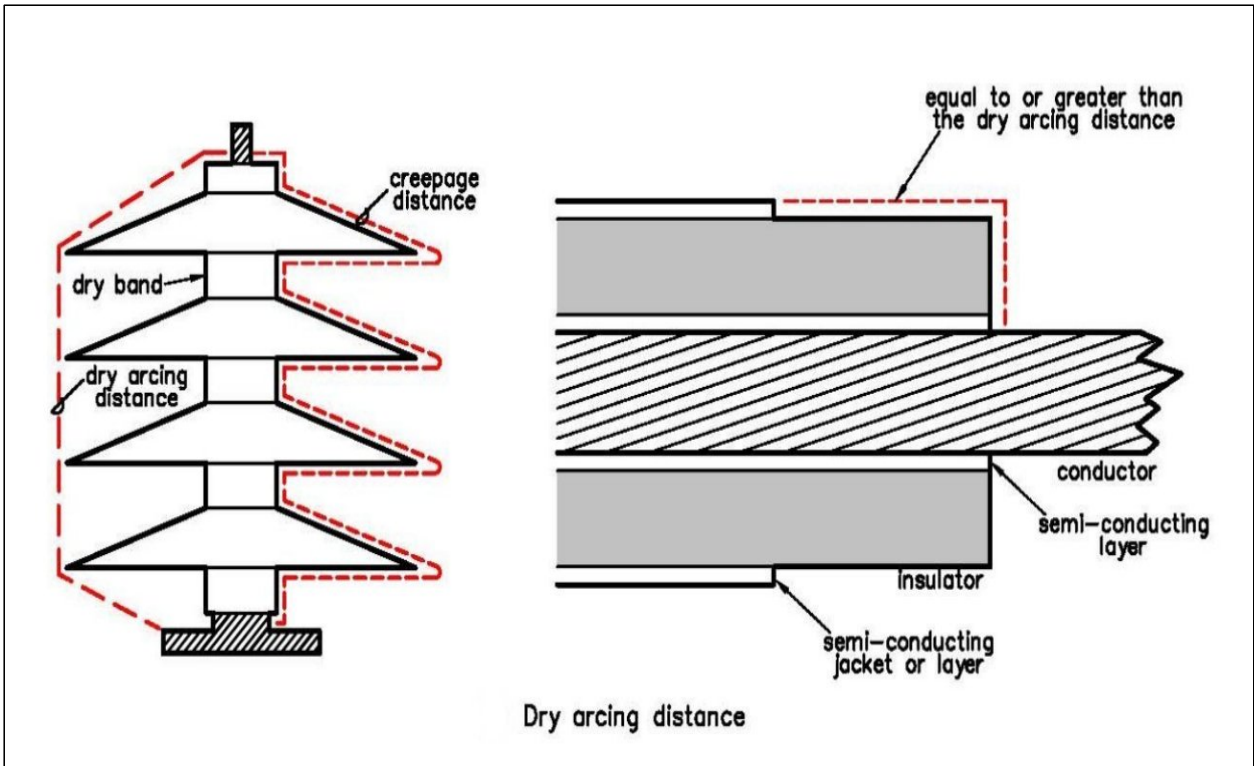


Figure 7. Dry arcing distance (*Note: Not scaled for simplicity and illustration purposes.*)

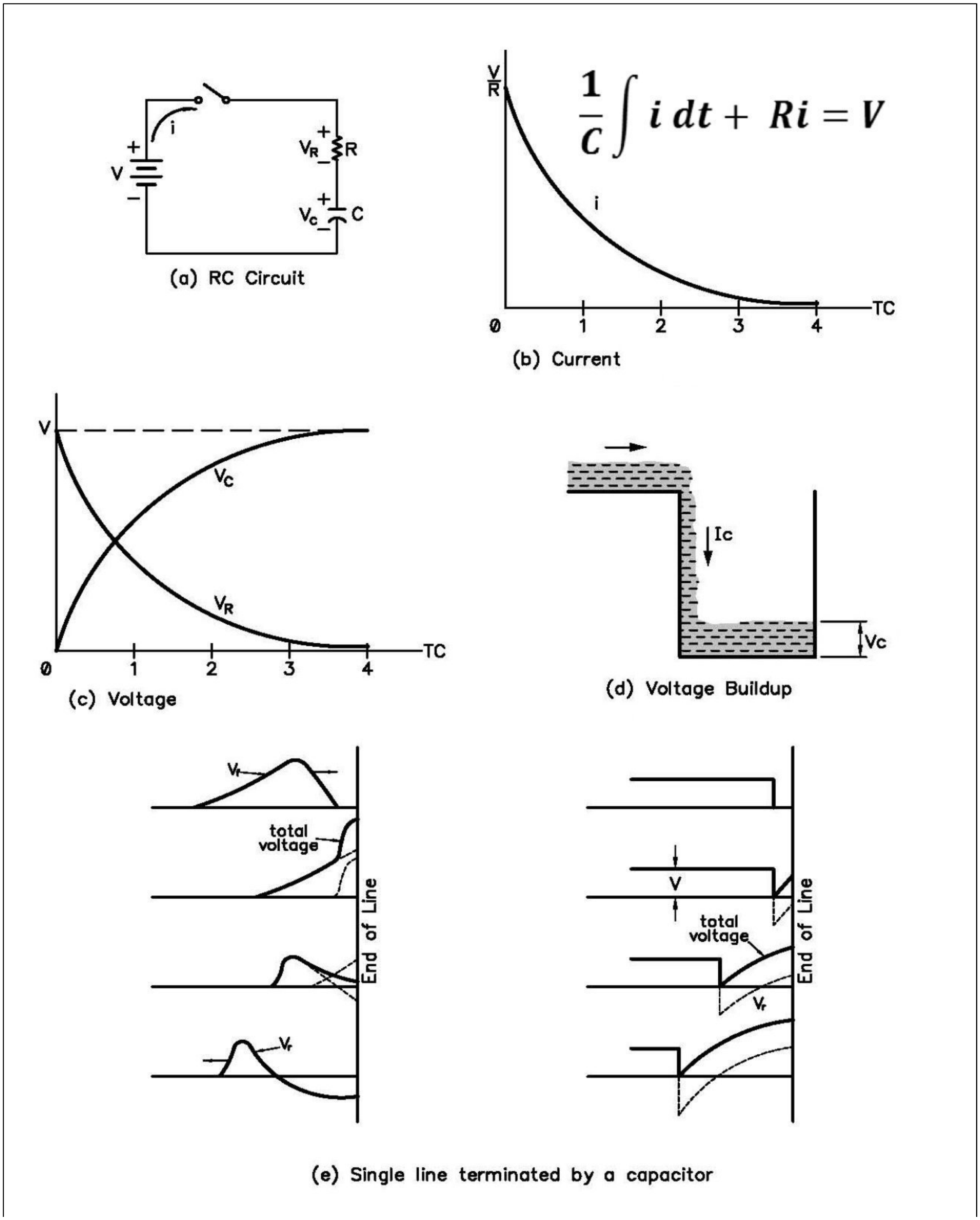
The dry arcing distance for outdoor insulators is basically the same as the minimum required airgap and as shown in Figure 7 the airgap between an energized conductor and the grounded material must be greater than the minimum required airgap, no matter what kind of and how good an insulating material is present between them.

3.2 Characteristics of Capacitance

As stated previously in Section II, a surge is basically a **sudden flow of trapped or stored charges**, charges in a thunder cloud for the lightning surge and charges in a form of capacitor for the switching surge. For the same reason, a fully charged battery is also a surge source which can generate a surge when it is suddenly connected to R, L, and/or C, as shown in Figures 3(c), 8 and 9. Therefore as shown in those three figures, the surge response of R, L, or C can be easily demonstrated by closing the on-off switch and monitoring the time-variant voltage and current.

Figure 8(d) illustrates that a flow of charges is the surge current and a total number of charges built-up is the surge voltage. The surge voltage at the capacitor is not built up instantaneously, but is gradually built up over time. Therefore, a capacitor, distributed capacitance or canned capacitor, has **an effect of lowering the incoming surge voltage FOW rate of rise** (*Note: Termed as "**wave front shaping**" later in this paper.*).

Overall, the basic surge response characteristics of C are: the surge current decays gradually over time and the surge voltage is built up gradually over time.



$$\frac{1}{C}\int i\,dt + Ri = V$$

(a) RC Circuit

(b) Current

(c) Voltage

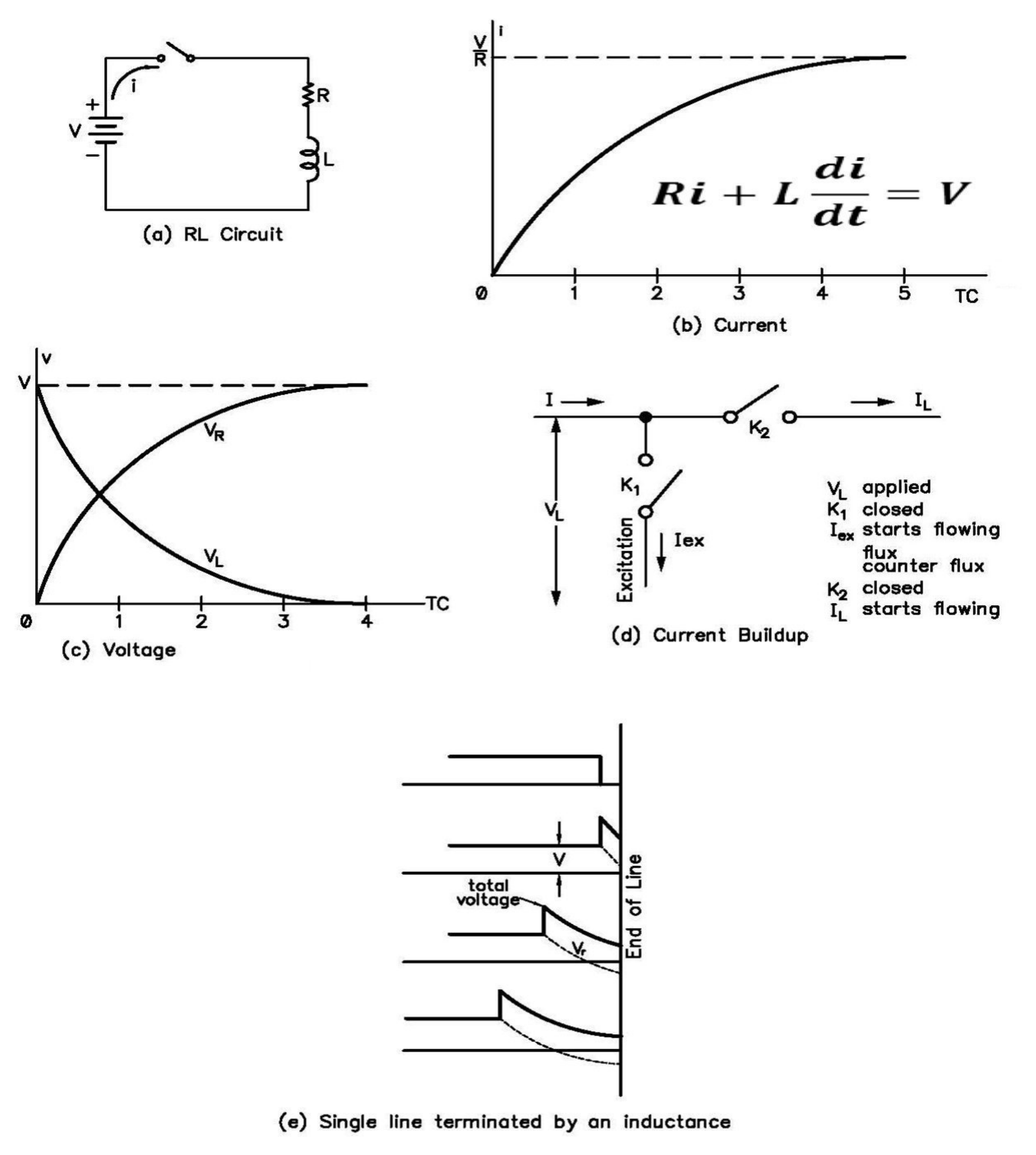
(d) Voltage Buildup

(e) Single line terminated by a capacitor

Figure 8. Characteristics of capacitance (*Note: Taken from References [1,6,8,24,26] and redrawn for clarity. Not scaled for simplicity and illustration purposes.*)

3.3 Characteristics of Inductance

Figure 9 below illustrates the basic surge response characteristics of L which are: the surge current is built up gradually over time and the surge voltage decays gradually over time.



(a) RL Circuit

(b) Current

(c) Voltage

(d) Current Buildup

(e) Single line terminated by an inductance

Figure 9. Characteristics of inductance (*Note: Taken from References [1,6,8,24,26] and redrawn for clarity. Not scaled for simplicity and illustration purposes.*)

3.4 Overhead Static Wire(s)

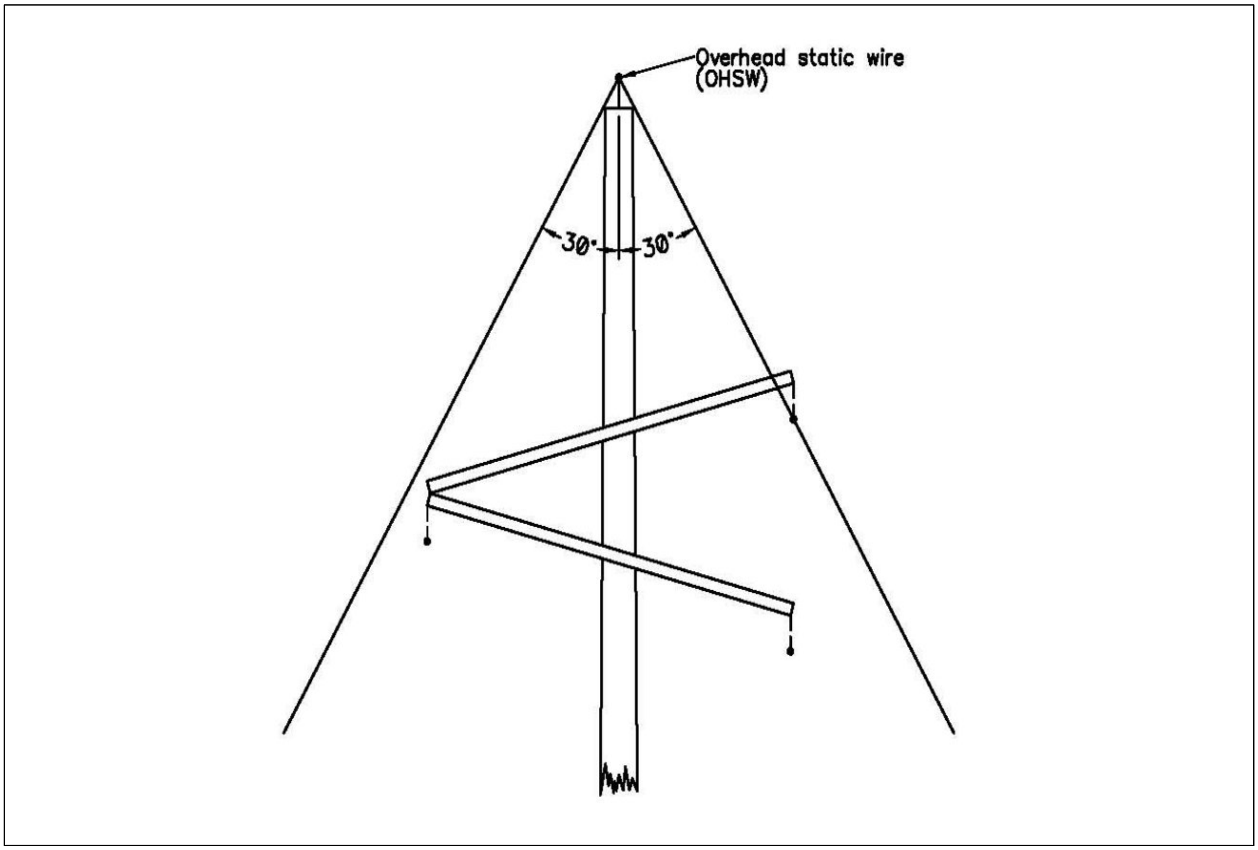


Figure 10. Lightning protection with overhead static wire(s) (*Note: Taken from Reference [1] and redrawn for clarity. Not scaled for simplicity and illustration purposes.*)

As illustrated in Figure 10 above, a strategically placed and spaced OHSW or wires protect conductors against lightning strikes satisfactorily. However, a poorly placed and spaced OHSW or wires may induce a surge to one or more phase conductors due to electromagnetic coupling and occasionally result in temporary outages. In addition, backflashing may occur, as explained later in this paper, which is more prevalent at steel structures than wood poles.

3.5 Lightning Arresters: Silicon-Carbide vs. Metal-Oxide Varistor

Figure 11 illustrates fundamental differences among gapped silicon-carbide arresters, MOV arresters, and gapped MOV arresters in a very simple and easy-to-understand manner, but the following may be of interest:

- The sparked-over airgap voltage is practically zero, so the gap is primarily used to control sparkover voltage.
- The resistance of either silicon-carbide or metal oxide (i.e., zinc oxide) is non-linear in nature, as seen in Figure 11(c).

- The ungapped MOV arrester does not require the series gap structure present on gapped silicon-carbide arresters because at normal line-neutral voltages the MOV conducts only milliamps vs. the hundreds of amps in a silicon-carbide block, as shown in Figure 11(c) [9].
- In general, the sparkover voltage and residual voltage after sparkover of gapped MOV arresters are lower than those of other types of arresters. However, it does not mean and it must not be assumed that the gapped MOV arresters are superior to other types of arresters in all applications.
- In lightning arrester applications, two important things are: proper sizing of the arrester and adequate placement of the arrester.
- Proper sizing of the lightning arrester requires a set of data: Vn = nominal system voltage, Vm = maximum system operating voltage, I_f = maximum available fault current, BIL, and $V_{f,\text{unfaulted-phase}}$ = maximum unfaulted-phase voltage due to unfaulted-phase voltage rise for both line-ground and line-line-ground faults.
- The maximum continuous overvoltage (MCOV hereafter) must be larger than the maximum system operating voltage. The maximum sparkover voltage must be smaller than 50% of the surge-protected equipment BIL (*Note: This requirement is explained later in this paper.*). The lowest temporary overvoltage (TOV hereafter) or 140% of MCOV must be larger than the maximum unfaulted-phase voltage. The maximum unfaulted-phase voltage can be calculated as follows [21,22]:

  - The **unfaulted-phase voltage rise in case of SLG faults** can be estimated with a simple formula, where K is defined as Z_0/Z_1 ratio:

$$\boldsymbol{V_{f,unfaulted} = \sqrt{0.75 + \left(0.5 + \frac{K-1}{K+2}\right)^2}}$$

  - The **unfaulted-phase voltage rise in case of LLG faults** can be estimated with a simple formula, where K is defined as Z_0/Z_1 ratio:

$$\boldsymbol{V_{f,unfaulted} = \frac{3K}{2K+1}}$$

- A lightning arrester should be placed as close to the surge-protected equipment as possible. If not allowed for some reasons, a lightning arrester protection zone determination formula, as presented later in this paper, can be used.
- Caution must be exercised when the manufacturers' lightning arrester ratings are reviewed. It is interesting to note, based on the author's research, that for the switching protection level rating, Manufacturer A uses the switching surge current rise time of 30 µs but Manufacturer B uses 45 – 60 µs.
- For a given application, the arrester selected should have a pressure/fault current capability greater than the maximum short-circuit current available at the intended arrester location. This fault current rating of arrester capability should include appropriate allowances for future growth in the surge-protected system [11].

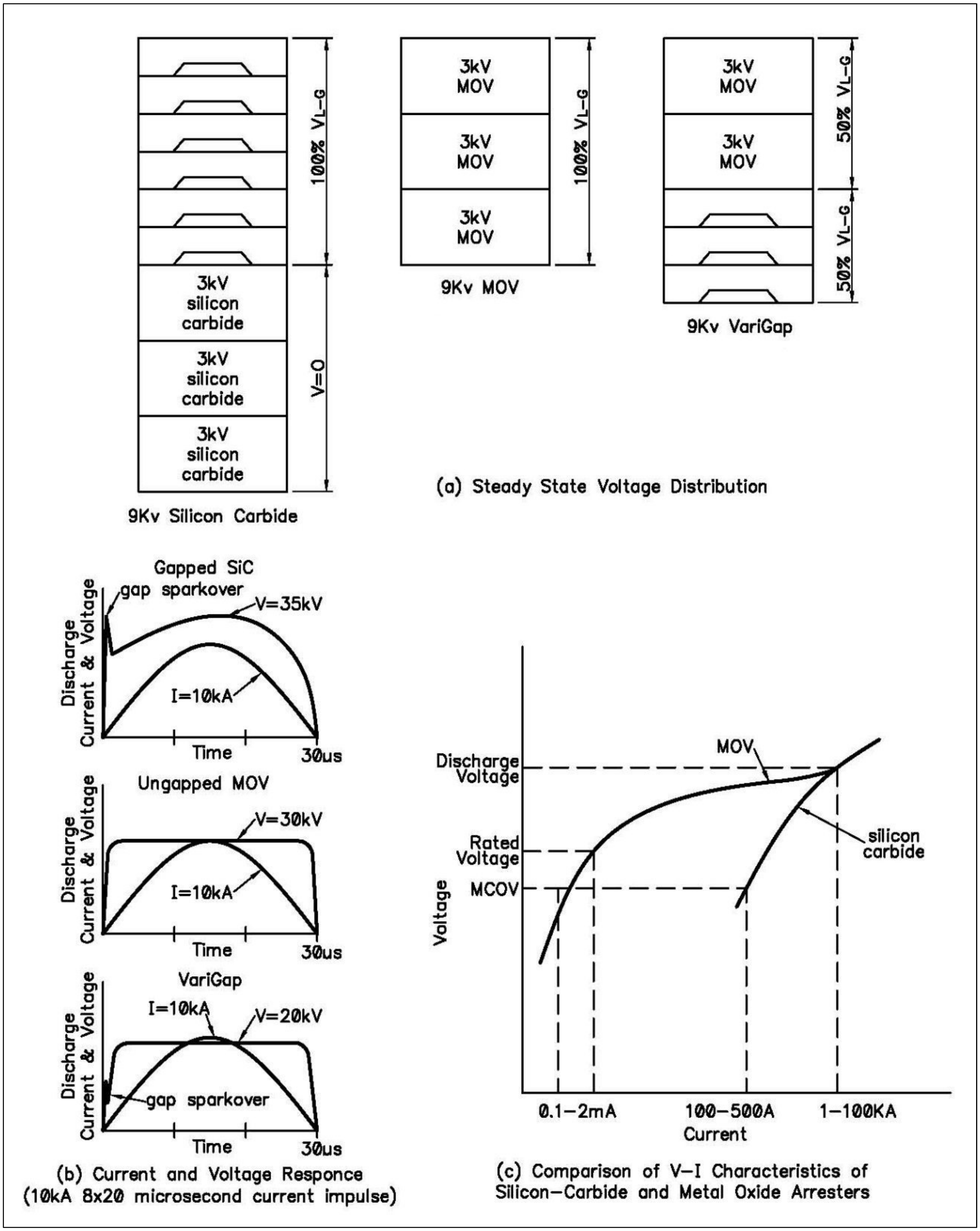


Figure 11. Comparison of lightning arresters (*Note: Taken from Reference [9] and redrawn for clarity. Not scaled for simplicity and illustration purposes.*)

Table 4
Station-class lightning arrester ratings
(*Note: Only for ABB Type XPS silicone-housed arresters*)

Power frequency voltage, kV rms						**Maximum residual voltage with current wave, kV peak**						
Nom	Max	Rating	MCOV	TOV		SPL	LPL, 8/20 µs					FOW
Vn	Vm	Vr		1s	10s	30/60 µs	3 kA	5 kA	10 kA	20 kA	40 kA	.5 µs
13.8	14.5	**18**	15.3	21.5	20.5	36.9	41.4	42.8	45	49.3	55.4	51.3
115	123	**96**	76	114	109	189	213	221	231	255	285	251
230	245	**192**	152	221	211	388	424	438	461	507	567	498

Vn = nominal system voltage
Vm = maximum system voltage
Vr = duty cycle rated voltage
MCOV = maximum continuous operating voltage
TOV = temporary overvoltage with no prior energy
SPL = switching protection level
LPL = lightning protection level
FOW = front of wave

3.6 Graphical Determination of Lightning Protection Zone

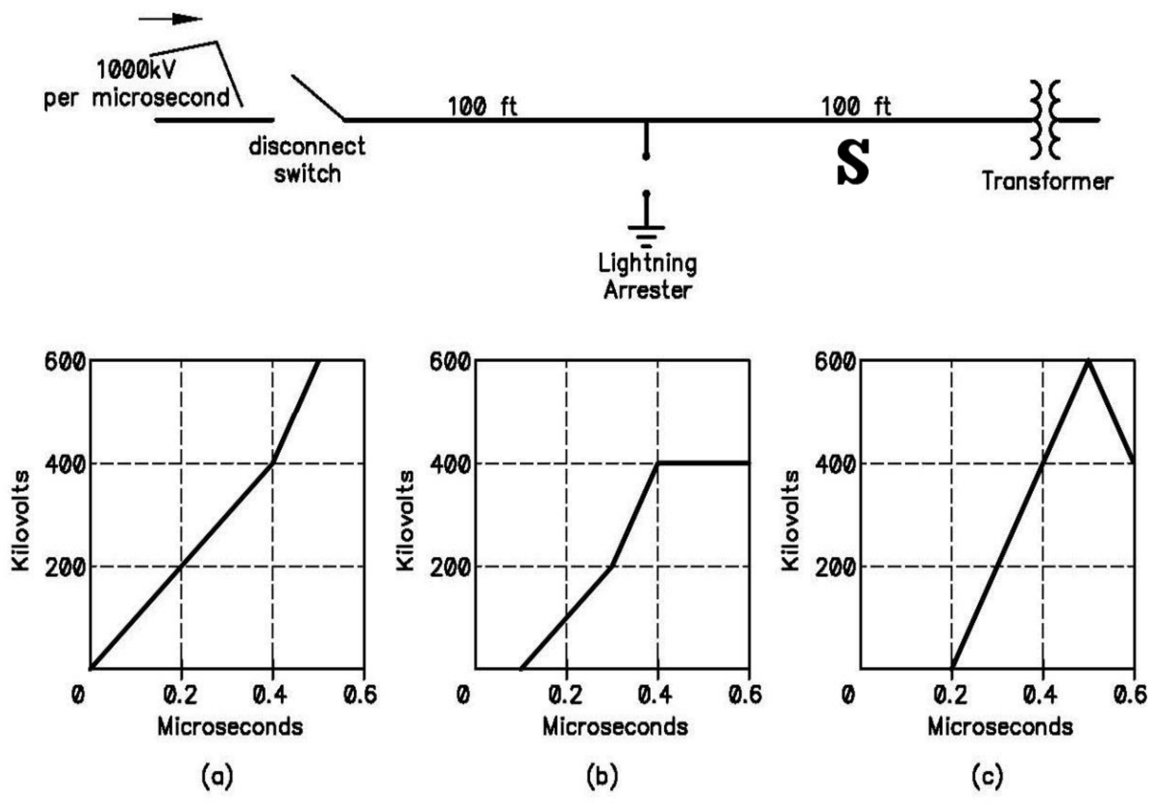


Figure 12. Graphical display of lightning protection with lightning arresters (*Note: Taken from Reference [1] and redrawn for clarity. Not scaled for simplicity and illustration purposes.*)

A lightning arrester should be placed as close to the surge-protected equipment as possible. If not allowed for some reasons, the above graphical method shown in Figure 12 or the formula below in Section 3.7 may be used. No matter which method is used, the following fundamentals are the same for both methods:

- In general, an adequately placed lightning arrester does not spark over for the initial incoming surge FOW rise.
- The incoming surge FOW voltage is reflected at the surge-protected equipment (*Note: Termed typically as "**voltage doubling effect**" due to capacitance.*) and so the surge FOW voltage magnitude after reflection is doubled, as shown in Figures 6(c), 8(e) and 9(e).
- An adequately sized and placed lightning arrester sparks over for the doubled surge FOW voltage. Therefore, the sparkover voltage must be smaller than 50% of the surge-protected equipment BIL so that the surge-protected equipment may be adequately protected without any damage.

3.7 Mathematical Determination of Lightning Arrester Protection Zone

The following is taken from Reference [19] and the formula for S below is a mathematical model of the above graphical determination method. Its appearance is somewhat different from a formula or method appearing in Reference [18], but the following mathematical modeling and formula have been verified for accuracy and adequacy:

$$\frac{de}{dt} = rate\ of\ rise\ of\ incoming\ surge, kV/\mu S$$

$$(Note: Rate\ of\ rise\ of\ incoming\ surge\ in\ kV \approx 11\frac{kV}{\mu S}\ per\ kV\ MCOV\ rating\ to\ a\ maximum\ of\ 2000\ \frac{kV}{\mu S}\ per\ IEEE\ Std\ C62.11-1987)$$

$$E_k = lightning\ arrester\ sparkover\ voltage, kV$$

$$Z = line\ surge\ impedance, ohms$$

$$(Refer\ to\ Table\ 5\ in\ IEEE\ Std\ C62.11-1987)$$

$$\frac{di}{dt} = maximum\ rate\ of\ rise\ of\ arrester\ current$$

$$L\frac{di}{dt} = arrester\ lead\ voltage, kV$$

$$E_d = peak\ line-neutral\ system\ voltage, kV$$

$$E_s = maximum\ voltage\ change\ at\ arrester\ location, kV$$

$$E_x = maximum\ voltage\ change\ at\ transformer, kV$$

$$= E_d + chopped-wave\ test\ kV$$

$$(Note: Chopped-wave\ withstand\ of\ transformers\ in\ kV$$

$$= 1.1 * BIL\ per\ ANSI\ C57.12.00-1987)$$

$$E_y = maximum\ voltage\ change\ at\ switch, kV = E_d + 1.15 * BIL\ kV$$

$$L = inductance\ of\ arrester\ lead\ \approx\ 0.4\ \mu H/ft$$

$$(Note: In\ reality, the\ arrester\ lead\ L\ is\ not\ contant\ due\ to\ its\ vertical\ to\ ground.)$$

$$v = propagation\ velocity = 984\ ft/\mu S$$

$$R = \frac{arrester\ discharge\ voltage\ at\ recommended\ kA}{recommended\ kA}$$

$$S = 984\frac{E_x - E_s}{2\frac{de}{dt}}\ feet$$

$$= 984\frac{chopped\text{−}wave\ test\ kV - E_k - L\frac{2\frac{de}{dt}}{Z+R}}{2\frac{de}{dt}}\ feet$$

- IEEE Std C62.11-1987 recommends 11 kV per kV MCOV up to a maximum of 2000 kV/µs for de/dt. However, the author normally suggests that 250 kV/µs for the area with the smallest mean annual number of thunderstorm days be used and 2000 kV/µs for the area with the largest mean annual number of thunderstorm days be used. The mean annual numbers of thunderstorm days can be taken from the latest Isokeraunic Map published by the National Weather Service.
- IEEE Std C62.11-1987 also recommends 0.4 µH/ft to calculate the arrester lead voltage. However, the inductance of arrester lead cannot be constant due to its vertical-to-ground orientation, so the author recommends that ½ of the calculated arrester lead voltage be used in calculating for S.

IV. Wave Front Shaping with Capacitors

A capacitor, distributed capacitance or canned capacitor, has an effect of lowering the incoming surge voltage FOW rate of rise (*Note: Termed here as "wave front shaping.*), as illustrated in Figure 8 and explained in Section 3.2. The following four sections show how this wave front shaping is used.

4.1 Surge Protection for Generator Stator Winding

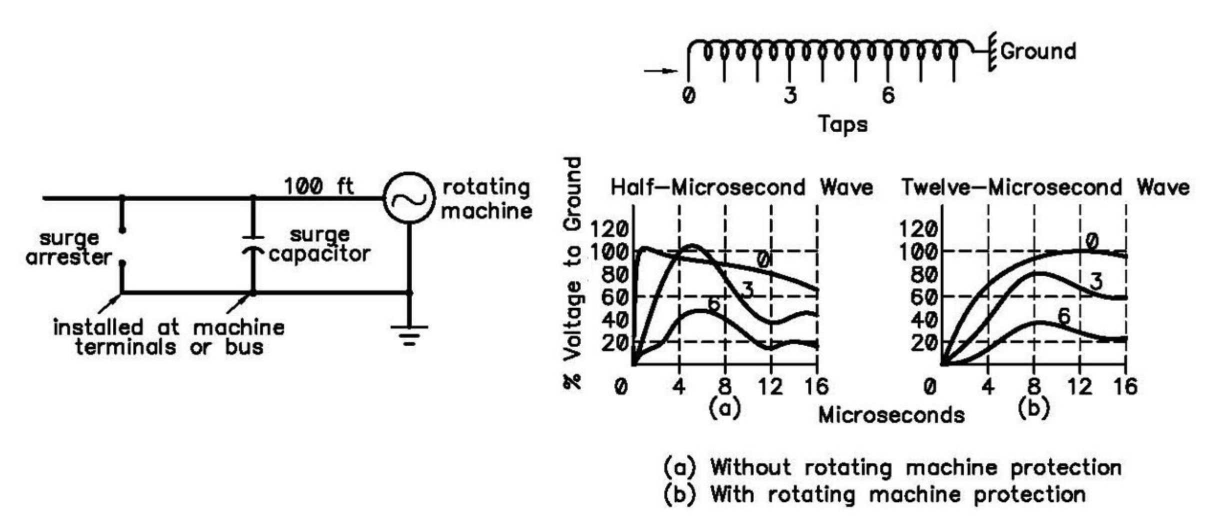


Figure 13. Generator winding surge protection with surge capacitors and lightning arresters (*Note: Taken from Reference [1] and redrawn for clarity. Not scaled for simplicity and illustration purposes.*)

4.2 Increase of Circuit Breaker Interrupting Rating

In general, wave front shaping with shunt capacitors can reduce the transient recovery voltage across main contacts of a circuit breaker and so the interrupting rating of the circuit breaker can be increased. This concept has been implemented by many circuit breaker manufacturers.

4.3 Upgrading a Line Circuit Breaker to a Generator Circuit Breaker

In general, the wave front shaping with shunt capacitors can reduce the transient recovery voltage across main contacts of a circuit breaker, as mentioned previously, and so the circuit breaker with shunt capacitors strategically placed will not be exposed to any high transient recovery voltages across main contacts. This concept has been implemented as a cost-effective means of facility modernization.

4.4 Circuit Switcher Sizing Impacted by the Line Length

Table 5
Fault interrupting rating impacted by line length
(*Note: Taken from Reference [12]*)

Application Class	**Qualifications**	**Maximum Amps, Interrupting, RMS symmetrical**
Fault Interrupting	Line or bus faults – with the total connected length of all lines (in all directions) on the source side of circuit-switcher **not less than** that indicated in footnote. (Connected cable may reduce or eliminate the line length requirement. Refer to the nearest Sales Office.)	7000 or 8000
	Line or bus faults – with the total connected length of all lines on the source side of circuit-switcher **less than** that indicated in footnote	4000

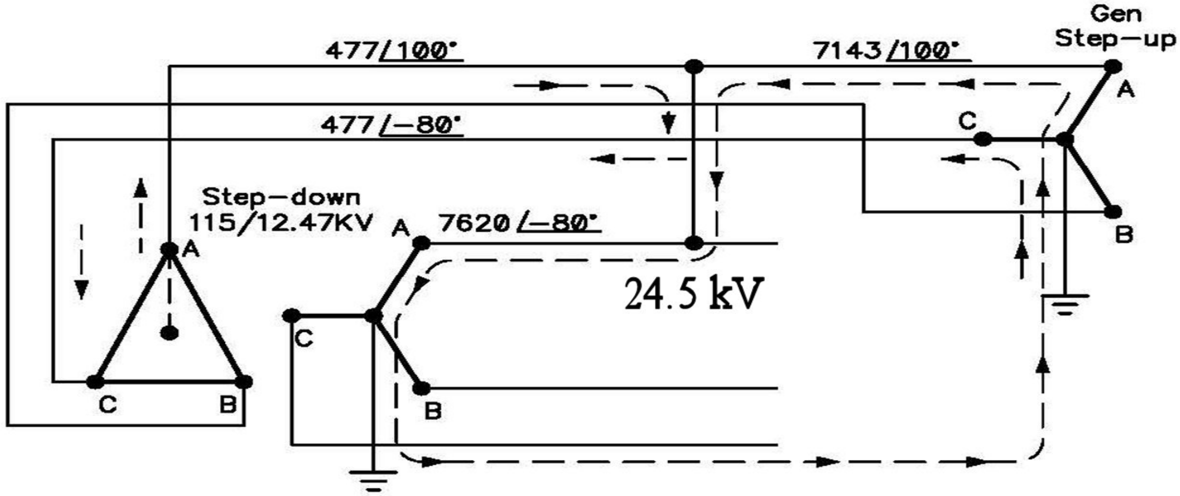
It is interesting to see the above qualifications for the fault interrupting rating and it appears, based on the author's research, that the higher fault interrupting rating is a very smart use of the distributed capacitance's wave front shaping characteristic.

V. Faults Involving Lightning and Lightning Arresters

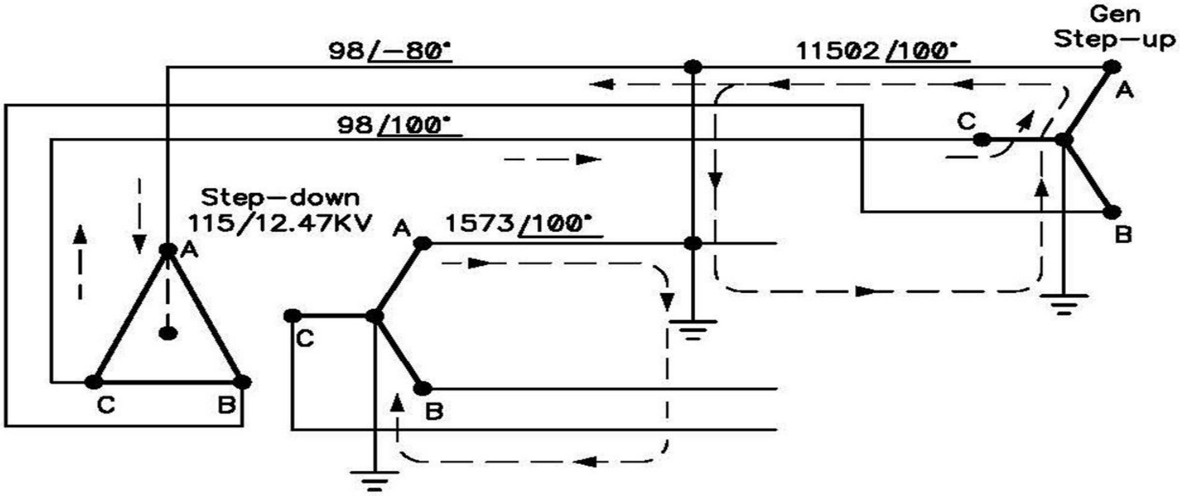
5.1 Cross-country Fault Involving Multiple Lightning Arrester Failures

Figure 14 illustrates that a cross-country fault between A-phase of 115kV line and A-phase of 12.47kV line underbuilt is evolving to two simultaneous faults, A-phase to ground fault on

115kV line and A-phase to ground fault on 12.47kV line because the contact point voltage has exceeded the distribution-class MOV arrester sparkover voltage and so all arresters within approximately one-mile radius have failed (*Note: They have failed because they have been exposed to a very high voltage beyond their TOV capability.*). It is quite interesting though that no silicon-carbide arresters have failed because their sparkover voltage is higher than that of the MOV arresters [20].



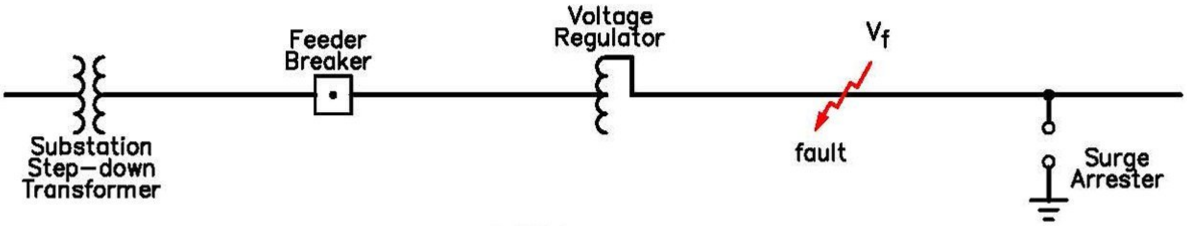
(a) 115kV A—Phase to 12.47kV A—Phase Cross—Country Fault
(prior to surge arrester operation)



(b) 115kV A—Phase to 12.47kV A—Phase Cross—Country Fault
(after surge arrester operation)

Figure 14. Cross-country fault analysis (*Note: Taken from Reference [20] and redrawn for clarity. Not scaled for simplicity and illustration purposes.*)

5.2 *Ground Fault Involving a Lightning Arrester Failure*



For SLG faults,

$$V_{f,unfaulted} = \sqrt{0.75 + \left(0.5 + \frac{K-1}{K+2}\right)^2}$$

For LL faults,

$$V_{f,unfaulted} = \frac{3K}{2K+1}$$

$$K = \frac{Z_0}{Z_1}$$

Figure 15. Simple distribution feeder one-line diagram (*Note: Drawn to illustrate an undue lightning arrester failure due to poor understanding of distribution system responses and poor sizing of the lightning arrester.*)

Referring to Figure 15 above, this is a classic case of improper arrester sizing. For an A-phase-to- ground fault, a B-phase lightning arrester failed because all 3-phase lightning arresters had been conducting prior to the fault due to unusually high system operating voltage beyond the voltage regulator and then the significant B-phase voltage rise due to the A-phase-to-ground fault resulted in failure of the B-phase lightning arrester [20,21,22].

5.3 *Backflash*

A backflash is a flashover originating from the pole or tower ground across the insulator onto the phase conductor as shown in Figure 16. With a line lightning arrester installed in parallel with the insulator, the surge current is uneventfully transferred onto the phase conductor. No ionizing arc is produced, so there is no power frequency fault and no blink or momentary outage. In all cases, the line lightning arrester application inhibits insulator flashovers and in turn eliminates momentary outages [27].

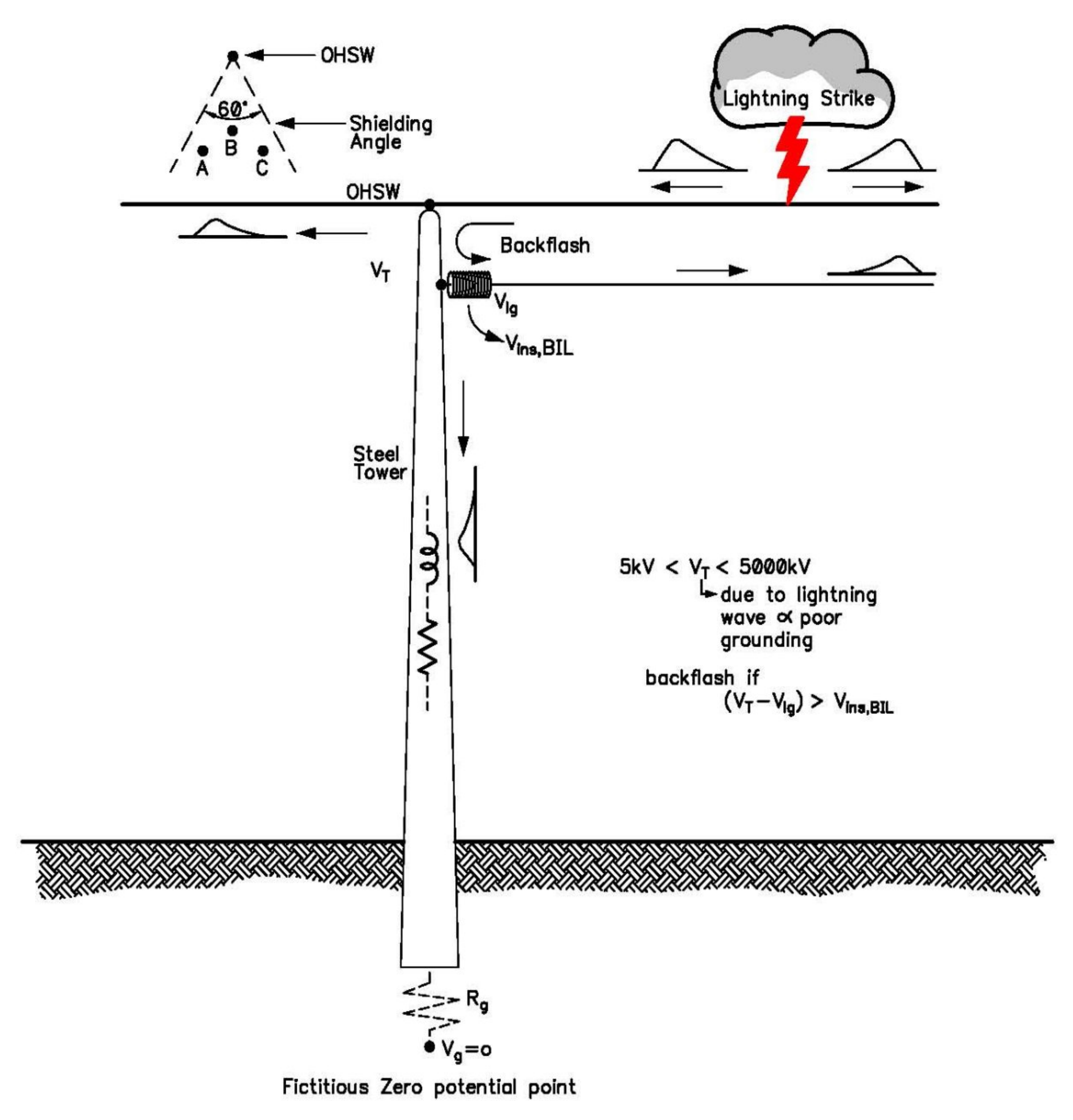


Figure 16. Backflash (*Note: Not scaled for simplicity and illustration purposes.*)

5.4 Bus Differential Relaying Susceptible to Misoperation

Referring to Figure 17, a lightning strike occurred outside the bus differential relaying zone and surge currents on all three phases, as shown in Figure 2(c), propagated into the bus differential relaying zone. Based on all available data and a careful review of all recorded transient waveforms, the bus differential relaying operated properly due to apparent mismatch probably caused by **discharging through the bus lightning arrester(s), reflection, refraction and/or skewed sampling of the bus differential relay**.

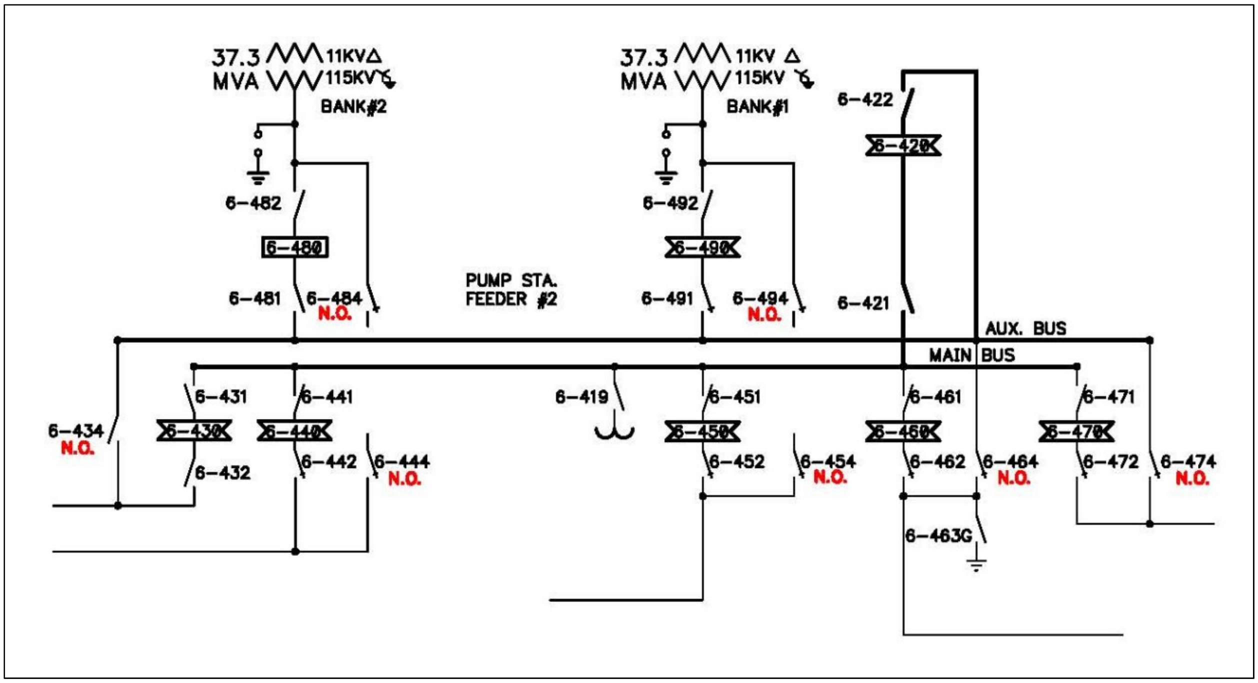


Figure 17. Simple generating station one-line diagram (*Note: Drawn to illustrate the bus differential relaying susceptible to misoperation due to close-in lightning strikes outside the bus differential relay protection zone. Not scaled for simplicity and illustration purposes.*)

VI. Conclusion

Since the introduction of NERC reliability standards, electrical utility relay engineers are required to analyze all bulk electric system relay operation events and develop some corrective action plans for misoperations. A set of tools relay engineers use are the load flow analysis, short circuit analysis, and dynamic analysis for system stability. However, lightning strikes have been one of main electrical fault sources around the world and certain lightning-caused fault events should be analyzed with surge analysis. To perform surge analysis properly, it is essential for relay engineers to have a thorough understanding of the lightning phenomena, switching surge, surge impedance, BIL, gap factor, lightning arresters, sizing of the lightning arresters, adequate placement of the lightning arresters, and lightning protection. Due to this very broad spectrum of knowledge and skills needed for the surge analysis, the author has touched only on some specifics summarized as follows:

- A surge is basically a sudden flow of trapped or stored charges, charges in a thunder cloud for the lightning surge and charges in a form of capacitor for the switching surge.
- It appears that 1.2/50 µs for the lightning voltage and 8/20 µs for the lightning current are commonly used.
- The surge analysis requires the use of the surge impedance. Unlike R, X_L, and X_C for the steady-state analysis, the surge impedance is not associated with any frequency or line length.

- The surge voltage is a total number of charges built-up at any given point and the surge current is a net flow of charges at any given window.
- The basic surge response characteristics of C are: the surge current decays gradually over time and the surge voltage is built up gradually over time.
- The basic surge response characteristics of L are: the surge current is built up gradually over time and the surge voltage decays gradually over time.
- Proper sizing and adequate placement of lightning arresters are of utmost importance to ensure adequate surge protection against all harmful surges. The placement of a lightning arrester may be determined graphically or mathematically.
- A capacitor, distributed capacitance or canned capacitor, has the effect of lowering the incoming surge voltage FOW rate of rise (*Note: Termed as "wave front shaping" in this paper.*) and this wave front shaping with capacitors can be used to increase the interrupting rating and to protect the generator winding against any harmful surges.
- A backflash is a flashover originating from the pole or tower ground across the insulator onto the phase conductor as shown in Figure 16. This backflash problem may be mitigated by installing a line lightning arrester in parallel with the insulator.
- The bus differential relaying is susceptible to misoperation due to mismatch caused probably by discharging through the bus lightning arrester(s), reflection, refraction and/or skewed sampling of the bus differential relay.

The author sincerely hopes that this technical paper may be of some value to the 38th Western Protective Relay Conference attendees and may help all relaying professionals understand surge analysis.

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