

# **INSULATION COORDINATION AC HIGH VOLTAGE CIRCUIT BREAKERS**

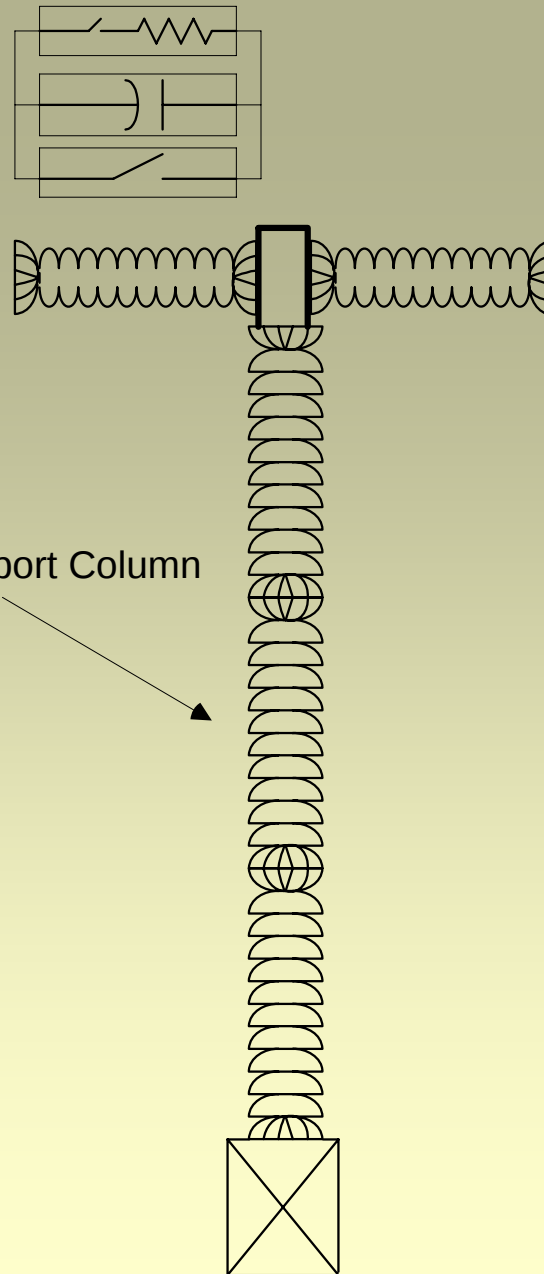
**STEPHEN R. LAMBERT  
SHAWNEE POWER CONSULTING, LLC**

1. Preinsertion Resistor

2. Grading Capacitor

3. Interrupter

4. Support Column



# *INSULATION PATHS*

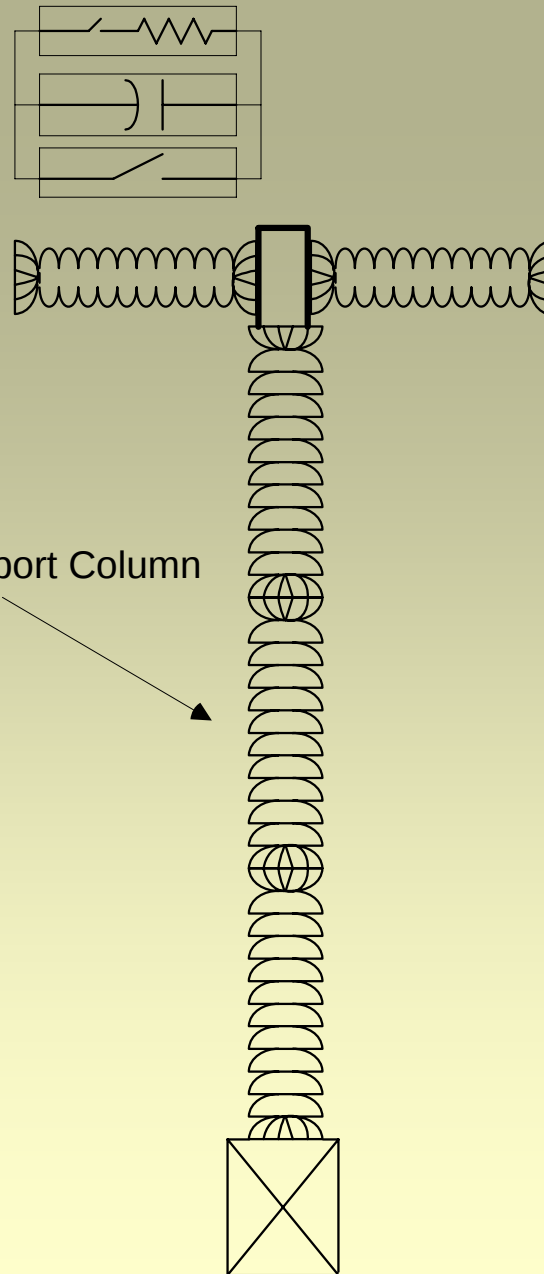
- PHASE TO GROUND
- ACROSS THE OPEN BREAKER
- PHASE TO PHASE

1. Preinsertion Resistor

2. Grading Capacitor

3. Interrupter

4. Support Column



# *VOLTAGE STRESSES*

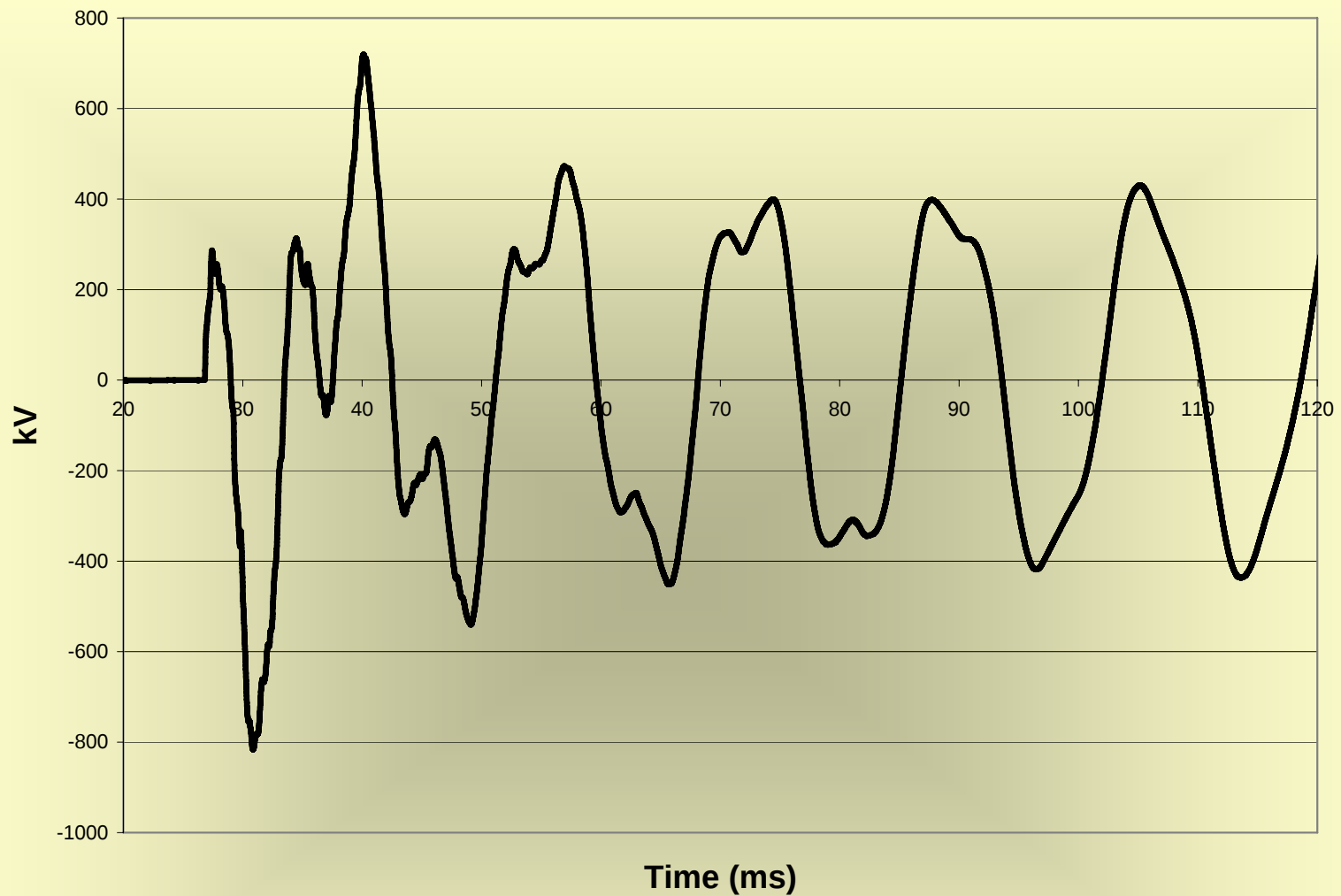
- 60 Hz
- SWITCHING SURGES
- LIGHTNING SURGES

# *60 Hz Overvoltages*

- UNGROUNDED SYSTEMS – 1.73 PU  
WITH FAULTS
- ACROSS OPEN BREAKER – 2.2 PU

# *SWITCHING SURGE OVERVOLTAGES*

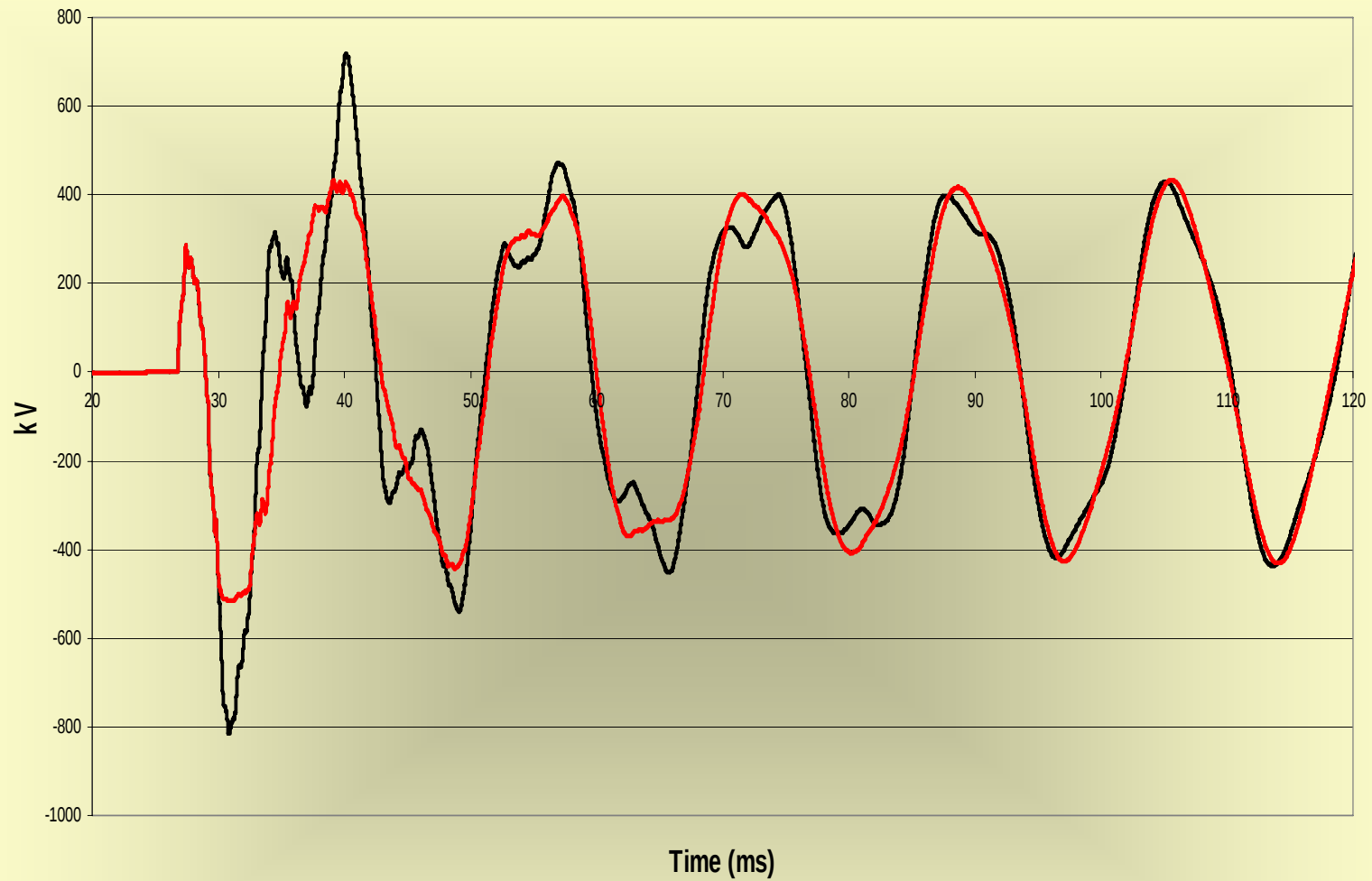
- NO SURGE CONTROL
  - ◆ ENERGIZING – 3.0 PU
  - ◆ RECLOSING (trapped charge) – 4.0 PU
- WITH PREINSERTION RESISTORS – 2.2 PU
- SURGE ARRESTERS LIMITING – 1.9 PU



2.90 PU Phase to Ground Switching Surge  
345 kV System

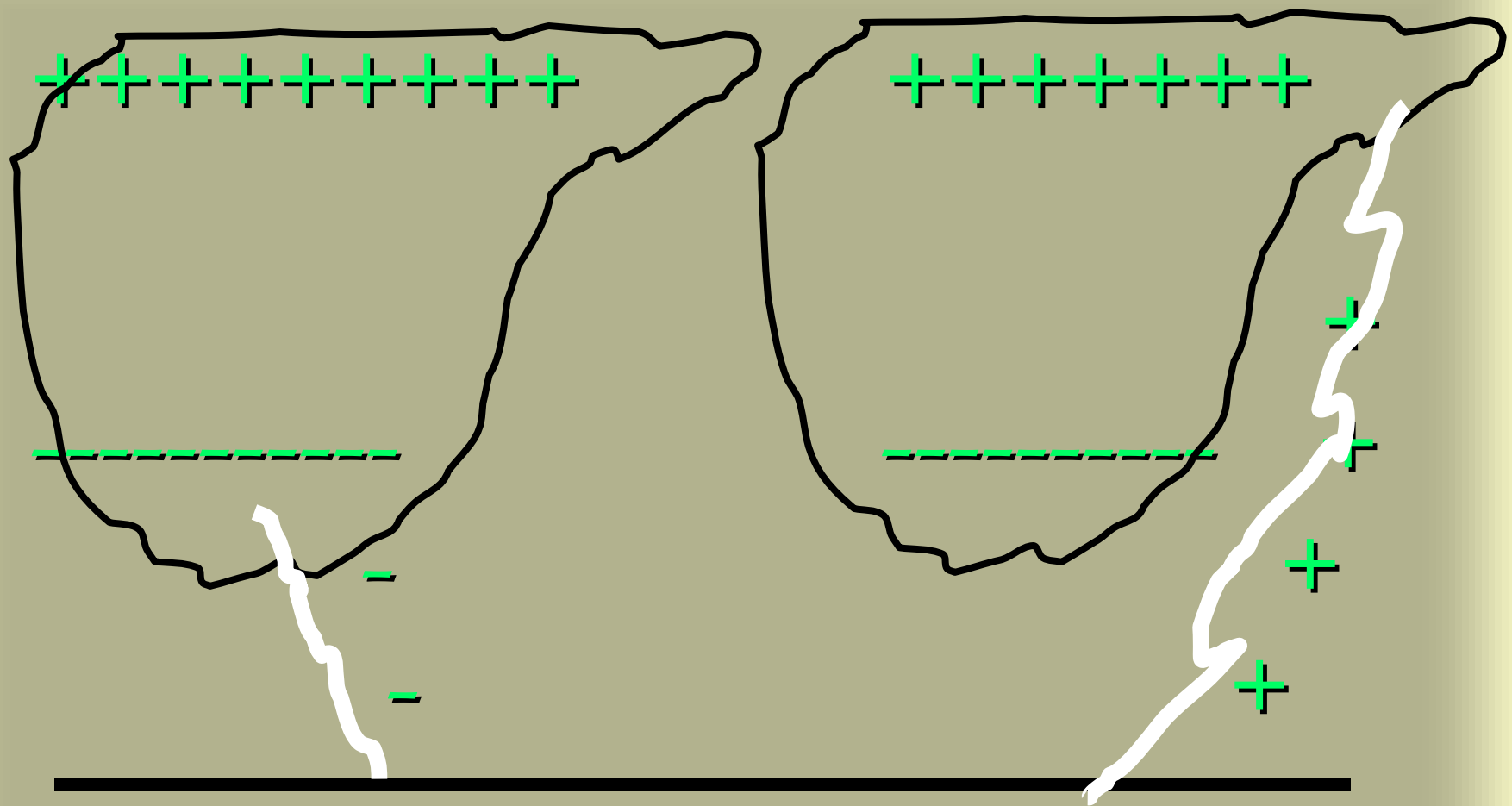


Application of 276 kV Surge Arrester  
1.83 PU



Application of 276 kV Surge Arrester  
1.83 PU

# LIGHTNING FLASH CHARACTERISTICS



Neg Flash

Pos Flash

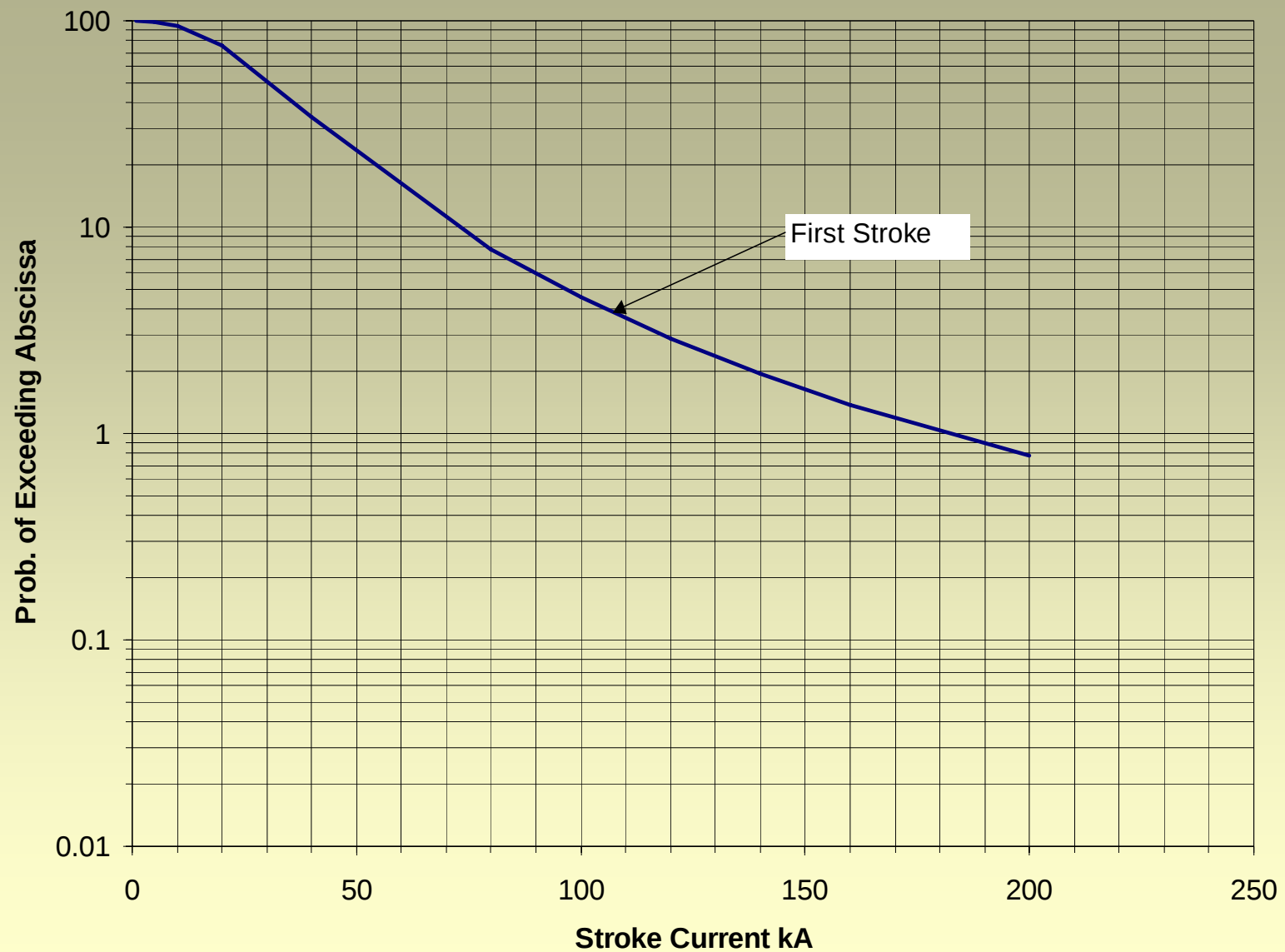
# *FLASH STATISTICS*

- 55% OF FLASHES HAVE MORE THAN ONE STROKE
- 90% OF FLASHES HAVE LESS THAN NINE STROKES
- MEAN NUMBER OF STROKES/FLASH - THREE
- 80-90% OF STROKES ARE NEGATIVE

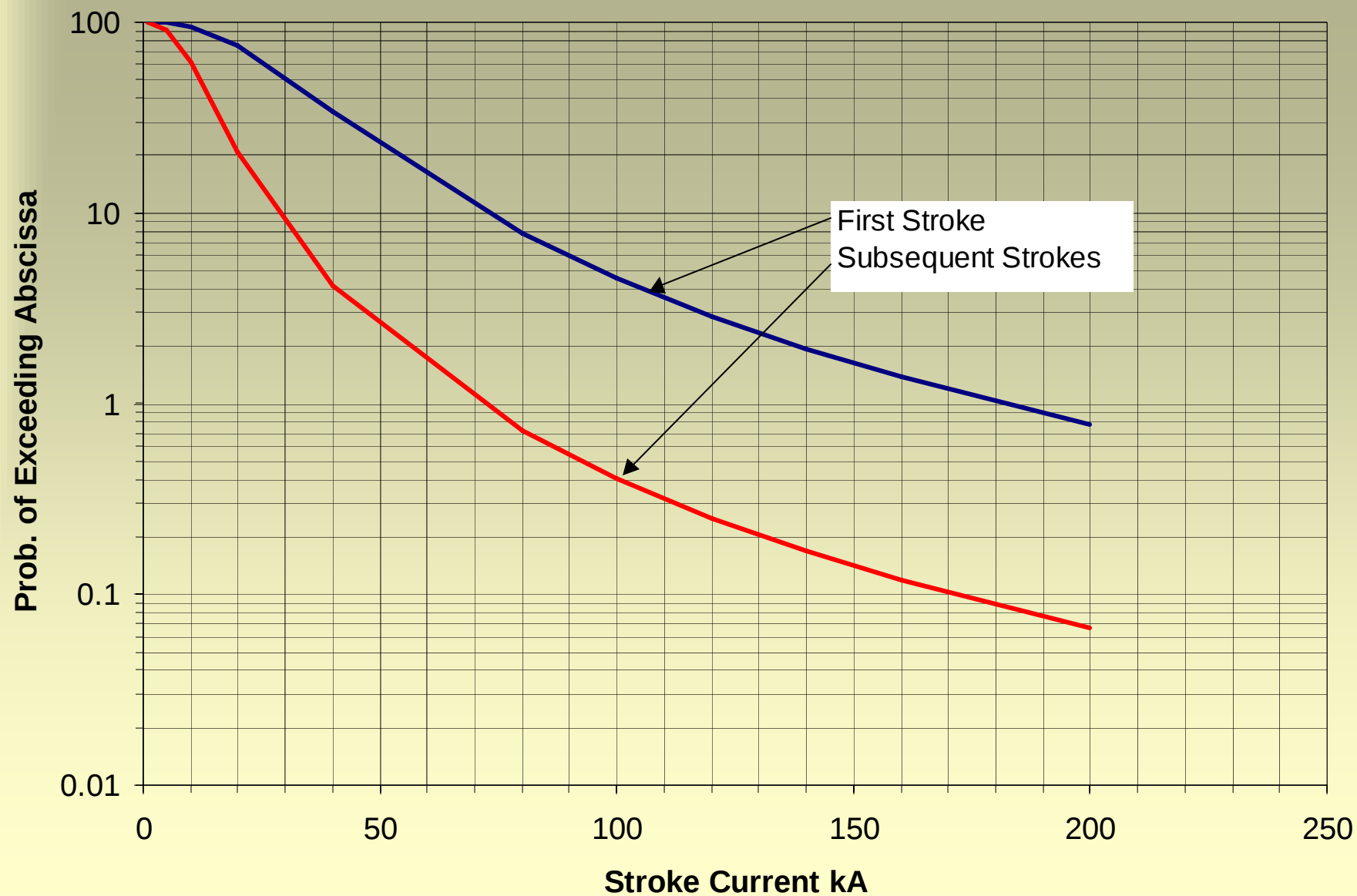
# *LIGHTNING*

- CHARACTERIZED BY
  - ◆ CURRENT MAGNITUDE
  - ◆ STROKE RISE TIME
  - ◆ KERAUNIC LEVEL OR FLASHES/km<sup>2</sup>

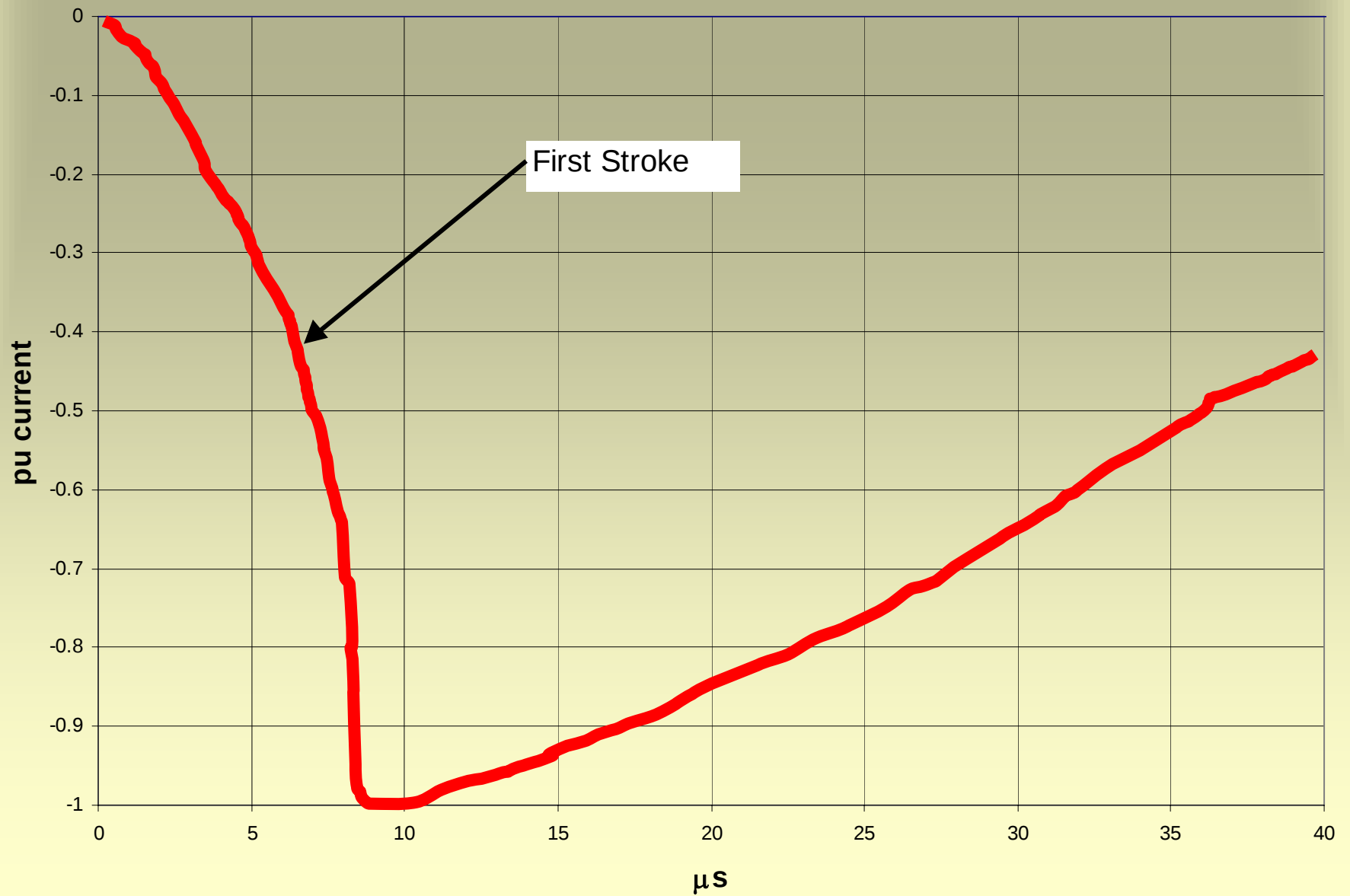
# *STROKE MAGNITUDES*



# *STROKE MAGNITUDES*



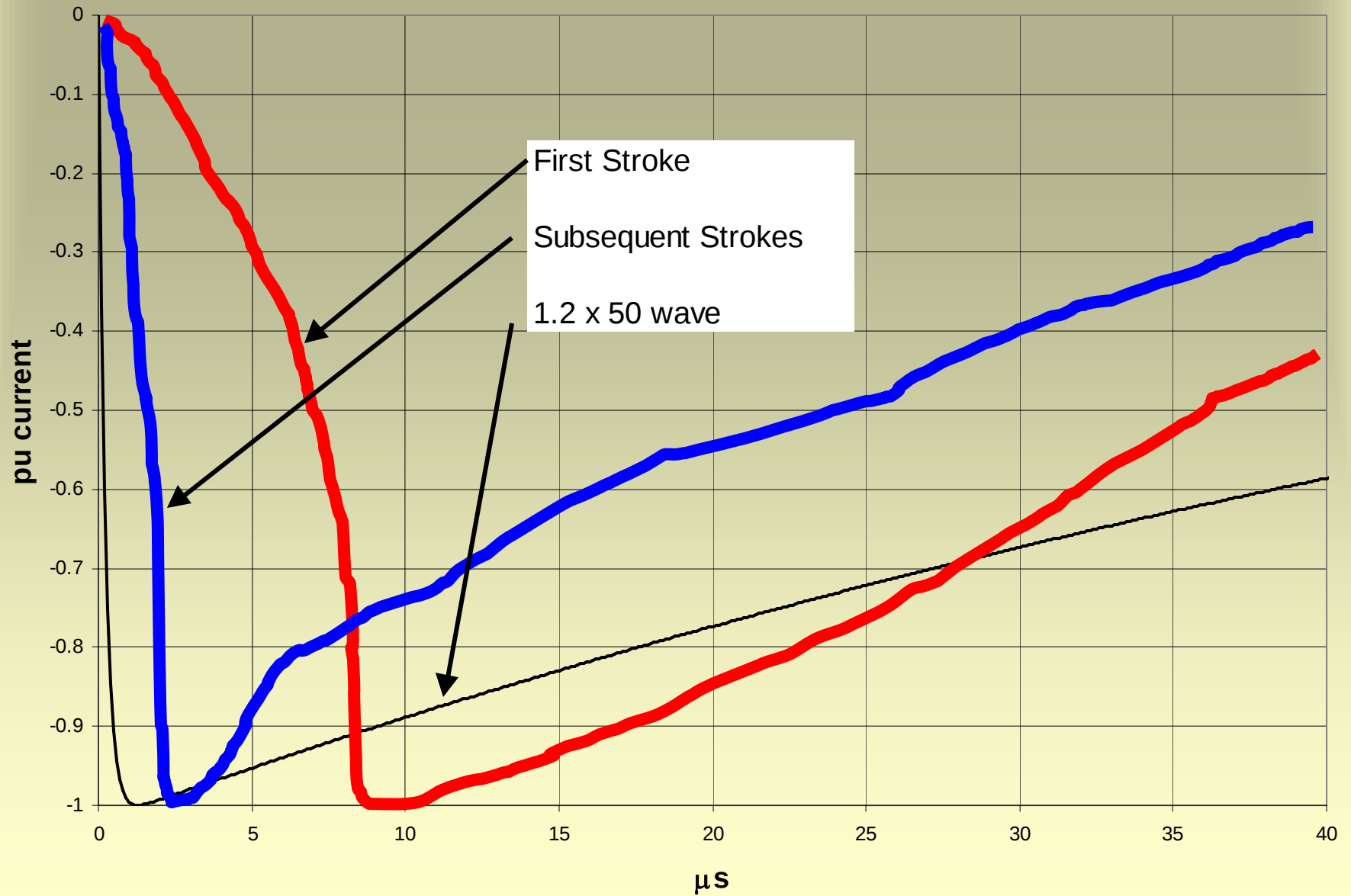
# *TYPICAL FIRST STROKE*



# *SUBSEQUENT STROKES*



# *1.2 x 50 IMPULSE SHAPE*



# GROUND FLASH DENSITY

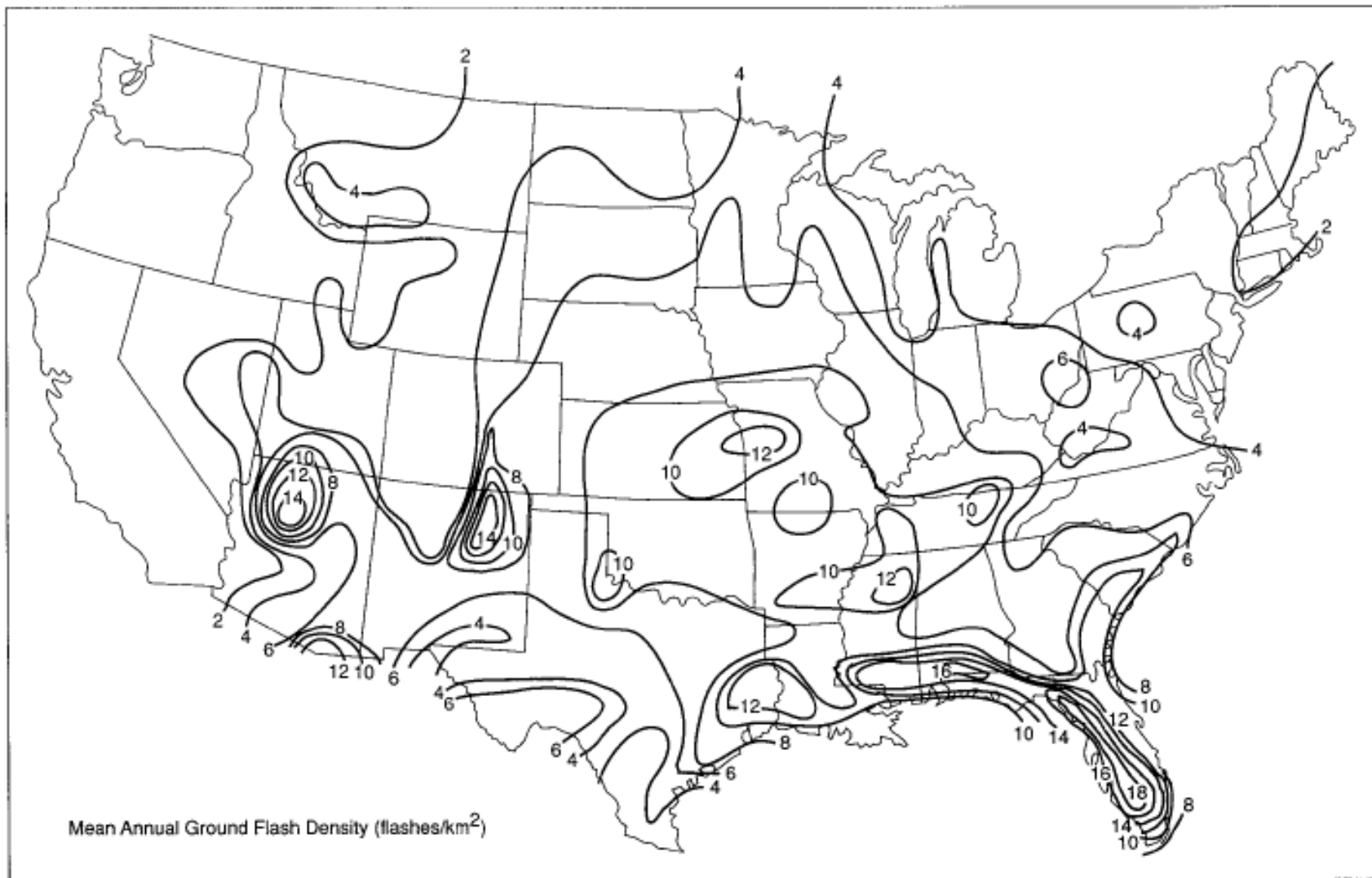
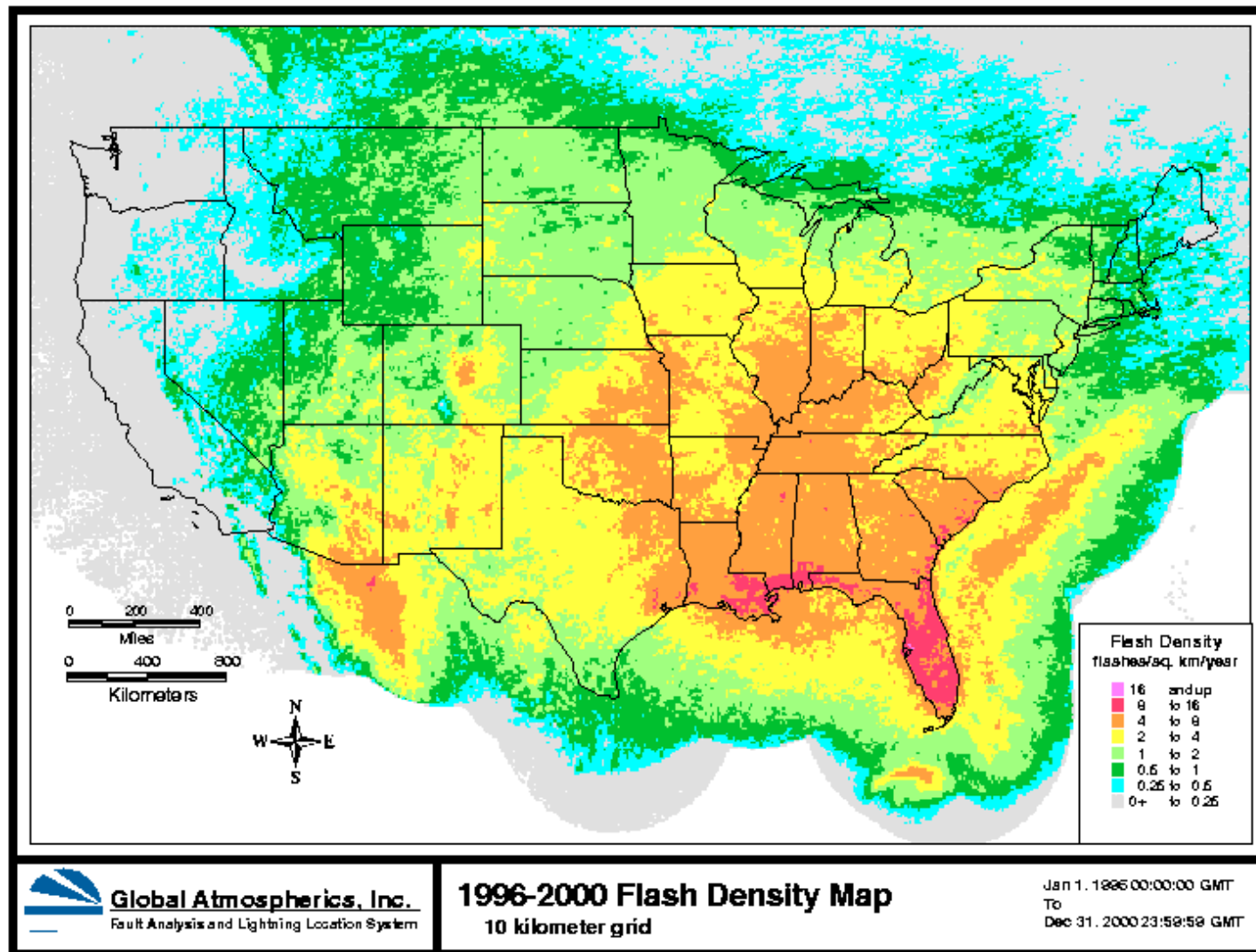


Figure 2. Contour Map of Mean Annual Lightning Strike Density.

# GROUND FLASH DENSITY

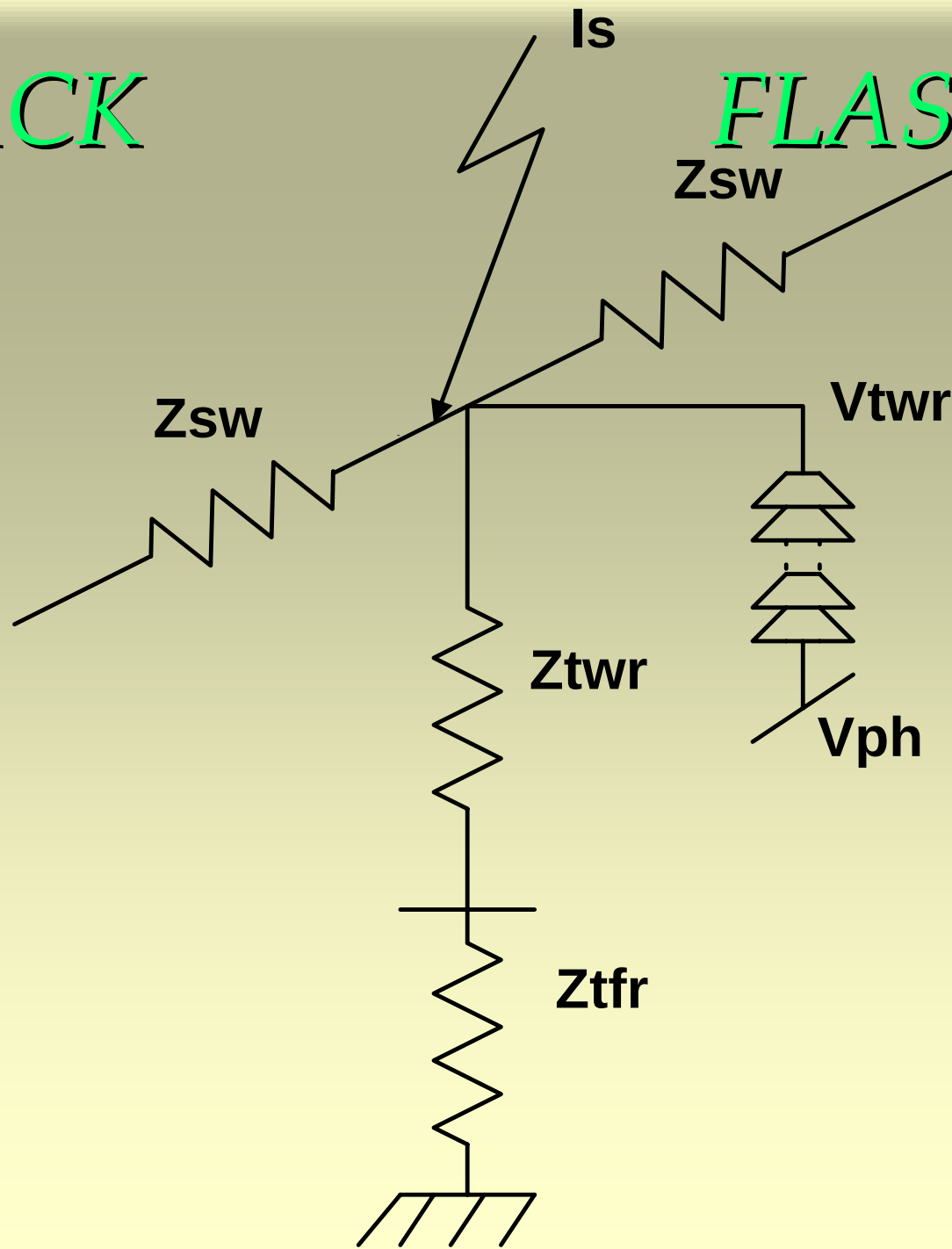


# *HOW DOES LIGHTNING GET INTO THE SYSTEM?*

- SHIELDING FAILURES
- BACKFLASHOVERS
- INDUCED

*BACK*

*FLASHOVER*

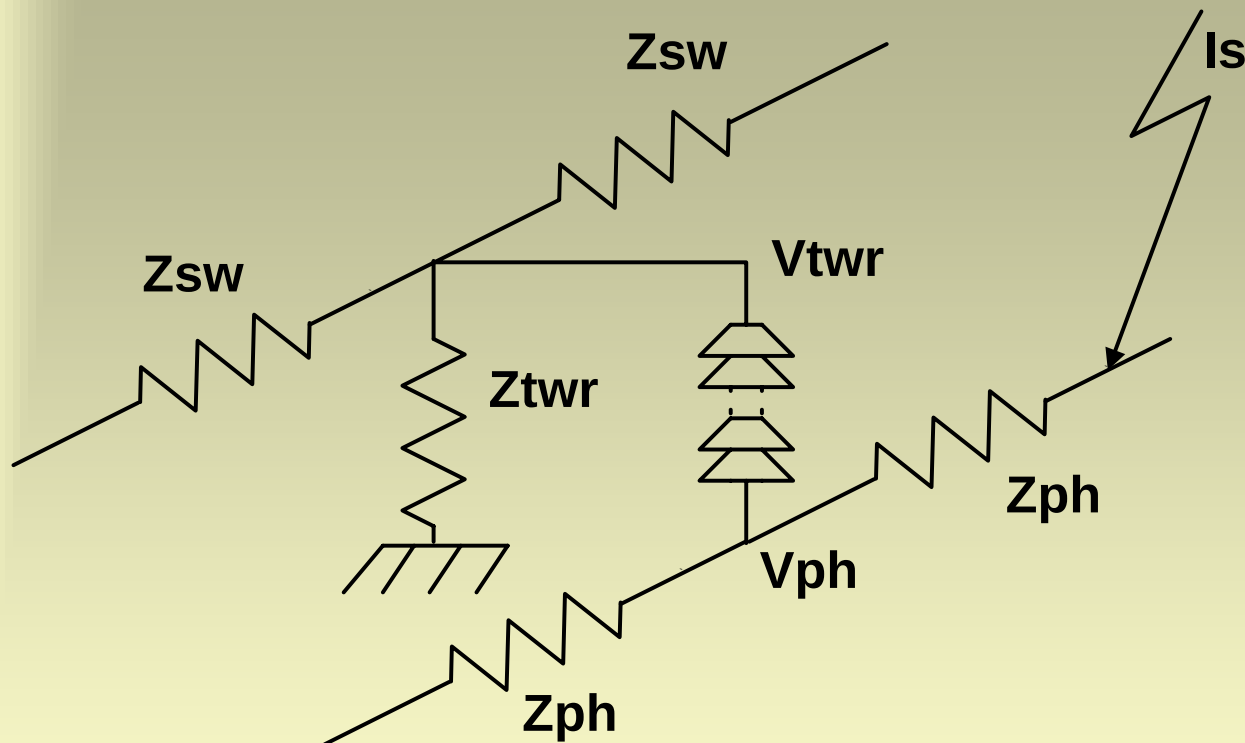


# SHIELDING FAILURE

- $Z_{ph} 400 \Omega$

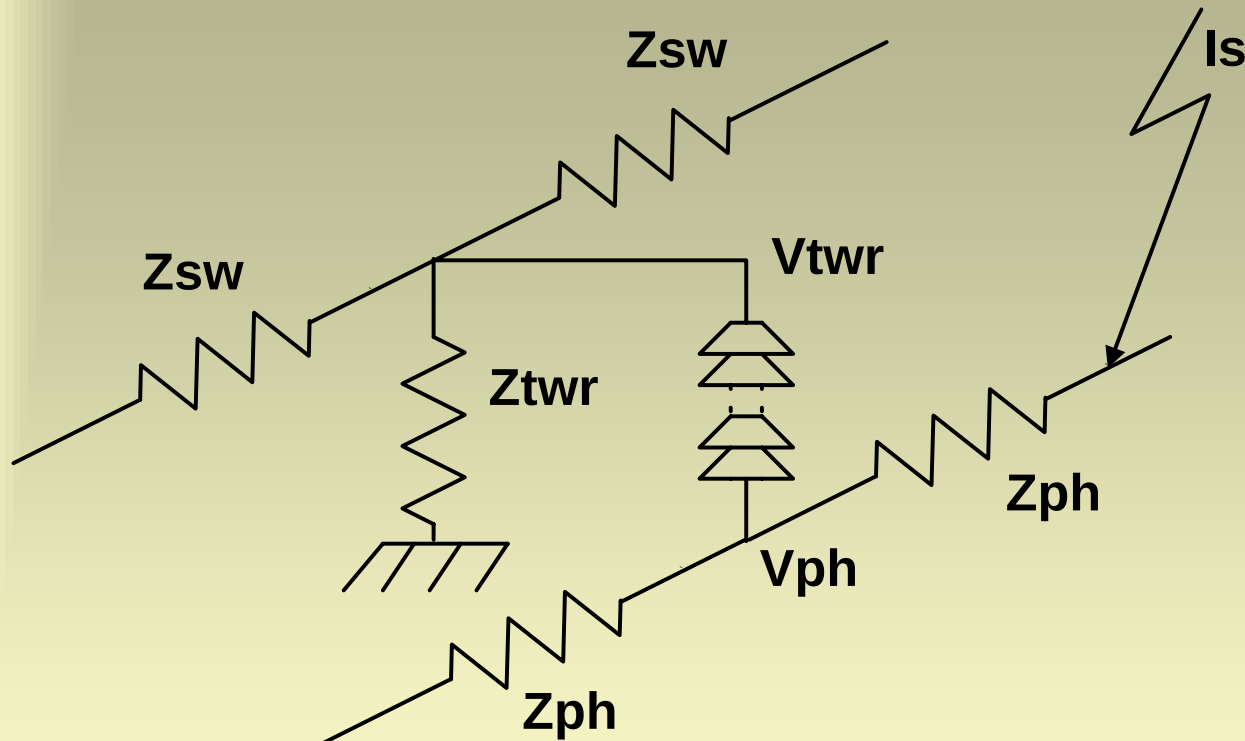
- $I_s = 10 \text{ kA}$

- $V_{ph} = ?$

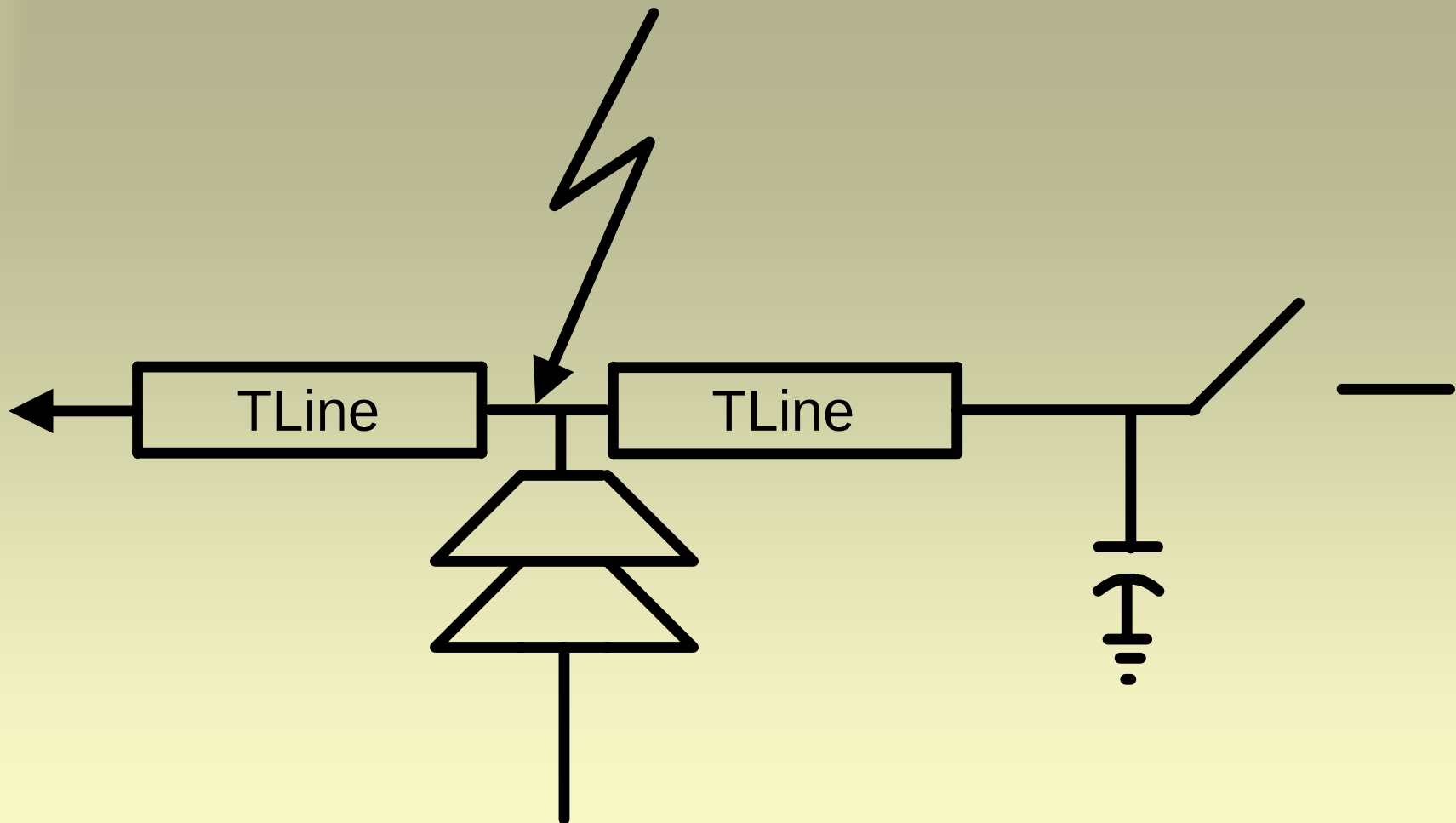


# SHIELDING FAILURE

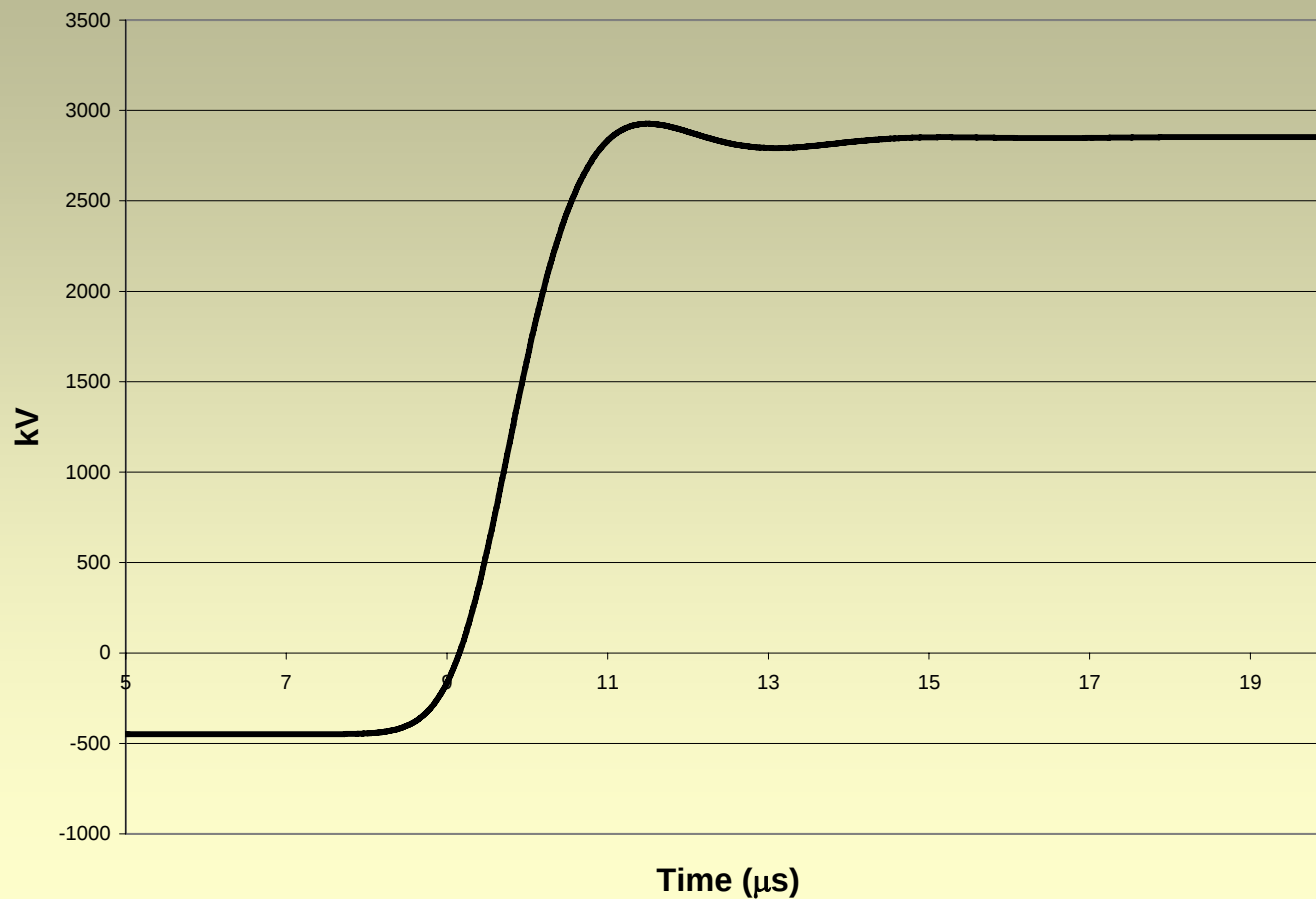
- $Z_{ph} 400 \Omega$
- $I_s = 10 \text{ kA}$
- $V_{ph} = 2 \text{ MV}$



# *EXAMPLE*



# *SHIELDING FAILURE PHASE TO GROUND SURGE @ OPEN BREAKER*



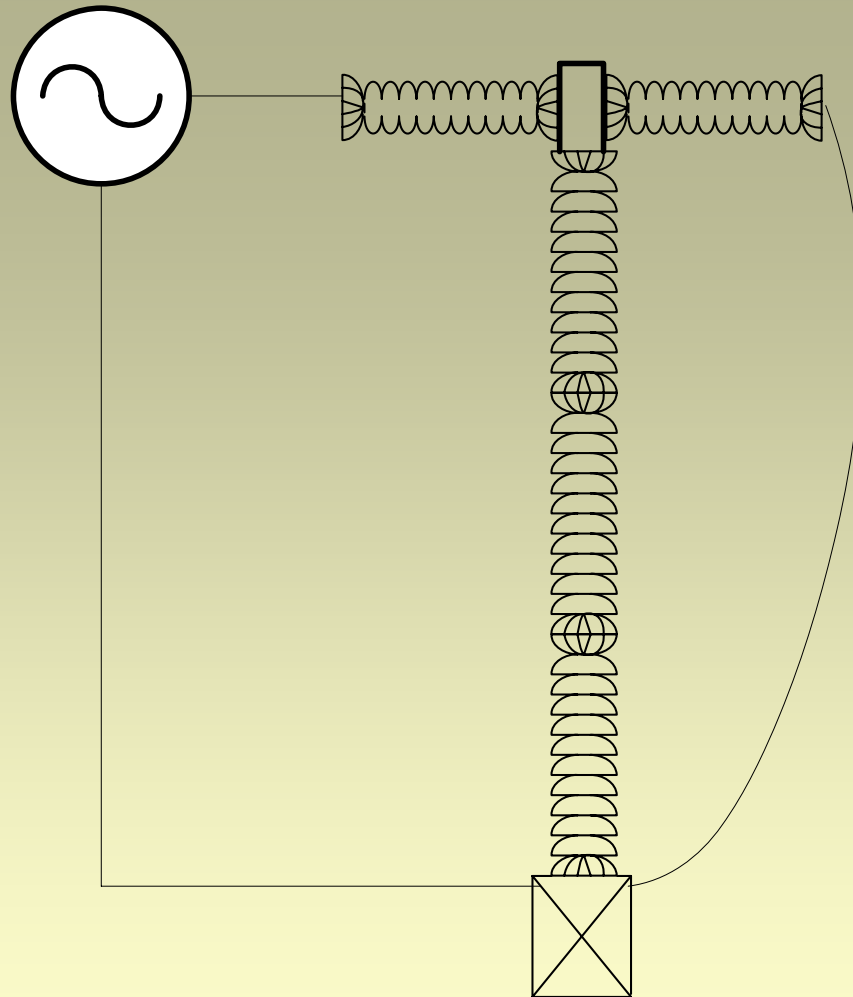
# *INSULATION CAPABILITY & TESTING*

- EARLY 1900's
- 60 Hz TESTING ONLY
- TEST LEVEL:  
2.25 x RATED VOLTAGE + 2000 V
- 1 MINUTE DRY – 10 SECONDS WET

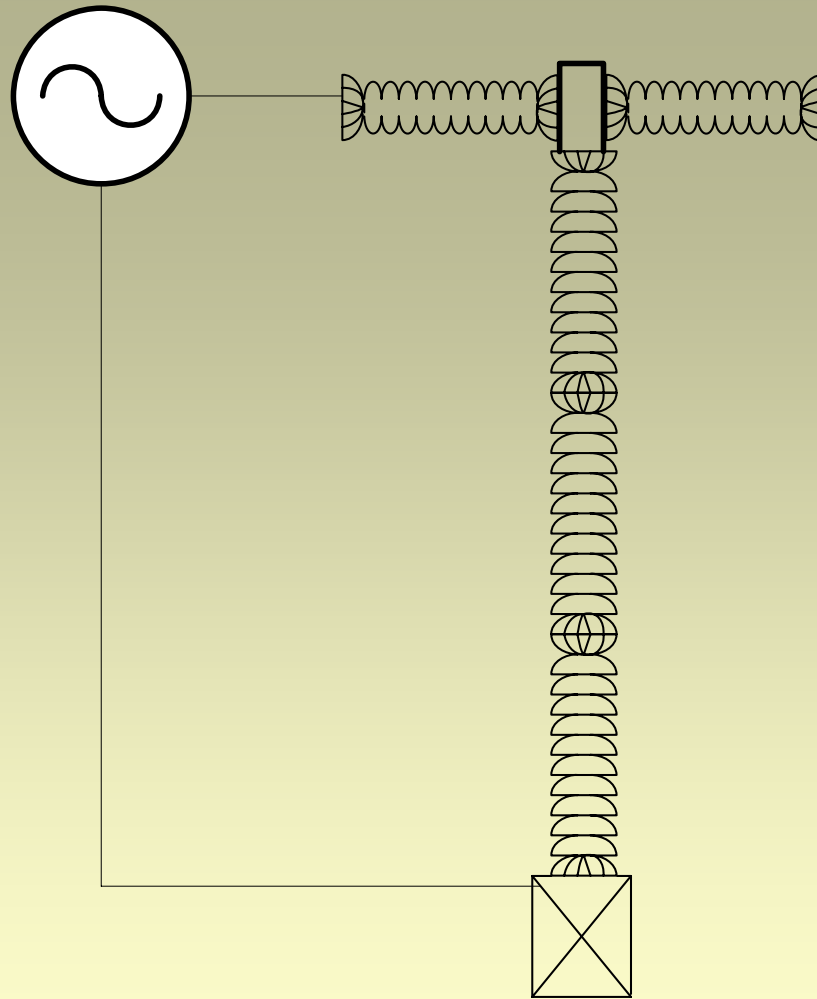
# *POWER FREQUENCY TEST LEVELS*

|                                 | Power Frequency Test   |                         |
|---------------------------------|------------------------|-------------------------|
| Rated Maximum Voltage (kV, rms) | 1 Minute Dry (kV, rms) | 10 Second Wet (kV, rms) |
| 15.5                            | 50                     | 45                      |
| 25.8                            | 60                     | 50                      |
| 38                              | 80                     | 75                      |
| 72.5                            | 160                    | 140                     |
| 123                             | 260                    | 230                     |
| 145                             | 310                    | 275                     |
| 170                             | 365                    | 315                     |
| 245                             | 425                    | 350                     |
| 362                             | 555                    | -                       |
| 550                             | 860                    | -                       |
| 800                             | 960                    | -                       |

# *CONTACTS OPEN*



# *CONTACTS CLOSED*



# *RATIO TEST VOLTAGE TO RATED MAXIMUM VOLTAGE*

|                                 | Power Frequency Test   |                            |
|---------------------------------|------------------------|----------------------------|
| Rated Maximum Voltage (kV, rms) | 1 Minute Dry (kV, rms) | In pu of Rated L-G Voltage |
| 15.5                            | 50                     | 5.59                       |
| 25.8                            | 60                     | 4.03                       |
| 38                              | 80                     | 3.65                       |
| 72.5                            | 160                    | 3.82                       |
| 123                             | 260                    | 3.66                       |
| 145                             | 310                    | 3.70                       |
| 170                             | 365                    | 3.72                       |
| 245                             | 425                    | 3.00                       |
| 362                             | 555                    | 2.66                       |
| 550                             | 860                    | 2.71                       |
| 800                             | 960                    | 2.08                       |

## *MINIMUM CREEPAGE DIST.*

- CONTAMINATION ISSUES
- LIGHT CONTAMINATION
- MINIMUM CREEP AT  $27.7 \text{ mm/kV}_{\text{rms, p-g}}$
- SALT FOG, INDUSTRIAL  
CONTAMINATION MAY NEED MORE  
CREEP

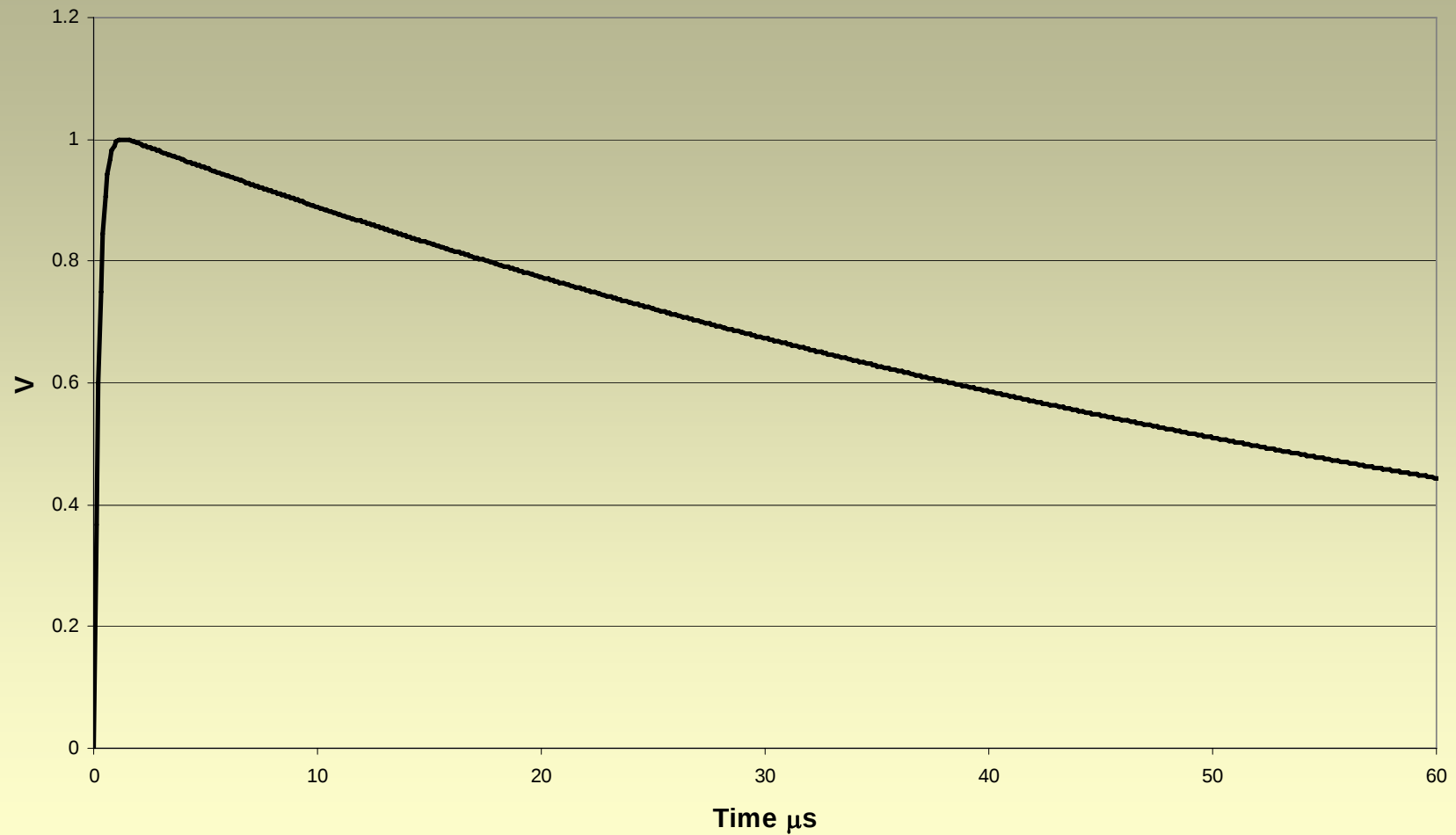
# ***CREEPAGE REQUIREMENTS***

| <b>Rated Maximum Voltage (kV,<br/>rms)</b> | <b>Minimum Creepage to<br/>Ground,(mm)</b> |
|--------------------------------------------|--------------------------------------------|
| <b>15.5</b>                                | <b>250</b>                                 |
| <b>25.8</b>                                | <b>420</b>                                 |
| <b>38</b>                                  | <b>610</b>                                 |
| <b>72.5</b>                                | <b>1170</b>                                |
| <b>123</b>                                 | <b>1990</b>                                |
| <b>145</b>                                 | <b>2340</b>                                |
| <b>170</b>                                 | <b>2750</b>                                |
| <b>245</b>                                 | <b>3960</b>                                |
| <b>362</b>                                 | <b>5850</b>                                |
| <b>550</b>                                 | <b>8890</b>                                |
| <b>800</b>                                 | <b>12900</b>                               |

# *LIGHTNING IMPULSE TEST*

- INTRODUCED IN 1930's
- TEST LEVEL – 2 x LF TEST + 40 kV
- 1.5 x 40  $\mu$ s WAVE SHAPE
- NOW – 1.2 x 50  $\mu$ s
- FULL WAVE & 2  $\mu$ s CHOPPED WAVE
- 10 % PROB. OF FLASHOVER OR LESS

# *LIGHTNING IMPULSE WAVESHAPE*



# *LIGHTNING IMPULSE TEST LEVELS*

|                                 | Lightning Impulse |                    |
|---------------------------------|-------------------|--------------------|
| Rated Maximum Voltage (kV, rms) | Full Wave         | Chopped Wave (2μs) |
| 15.5                            | 110               | 142                |
| 25.8                            | 150               | 194                |
| 38                              | 200               | 258                |
| 72.5                            | 350               | 452                |
| 123                             | 550               | 710                |
| 145                             | 650               | 838                |
| 170                             | 750               | 968                |
| 245                             | 900               | 1160               |
| 362                             | 1300              | 1680               |
| 550                             | 1800              | 2320               |
| 800                             | 2050              | 2640               |

# *TEST PROCEDURE*

- CONTACTS OPEN – ALL OTHER TERMINALS GROUNDED
- CONTACTS CLOSED – ALL OTHER PHASES GROUNDED
- APPLY THREE IMPULSES (NEG AND POS)
- IF ZERO FLASHOVERS – PASS
- IF ONE FLASHOVER IN FIRST THREE, THEN 9 MORE TESTS WITH NO FLASHOVERS

# *RATIO OF FULL WAVE IMPULSE TO RATED MAXIMUM VOLTAGE*

|                                 | Lightning Impulse |                                  |
|---------------------------------|-------------------|----------------------------------|
| Rated Maximum Voltage (kV, rms) | Full Wave         | In pu of Rated L-G Crest Voltage |
| 15.5                            | 110               | 8.69                             |
| 25.8                            | 150               | 7.12                             |
| 38                              | 200               | 6.45                             |
| 72.5                            | 350               | 5.91                             |
| 123                             | 550               | 5.48                             |
| 145                             | 650               | 5.49                             |
| 170                             | 750               | 5.40                             |
| 245                             | 900               | 4.50                             |
| 362                             | 1300              | 4.40                             |
| 550                             | 1800              | 4.01                             |
| 800                             | 2050              | 3.14                             |

# *SWITCHING IMPULSE TESTING*

- INCREASE IN SYSTEM VOLTAGE TO EHV LEVELS - 345 AND 500 kV
- BEGUN IN EARLY 1960'S
- TEST WAVESHAPE -  $250 \times 2500 \mu\text{s}$

# *TEST PROCEDURE*

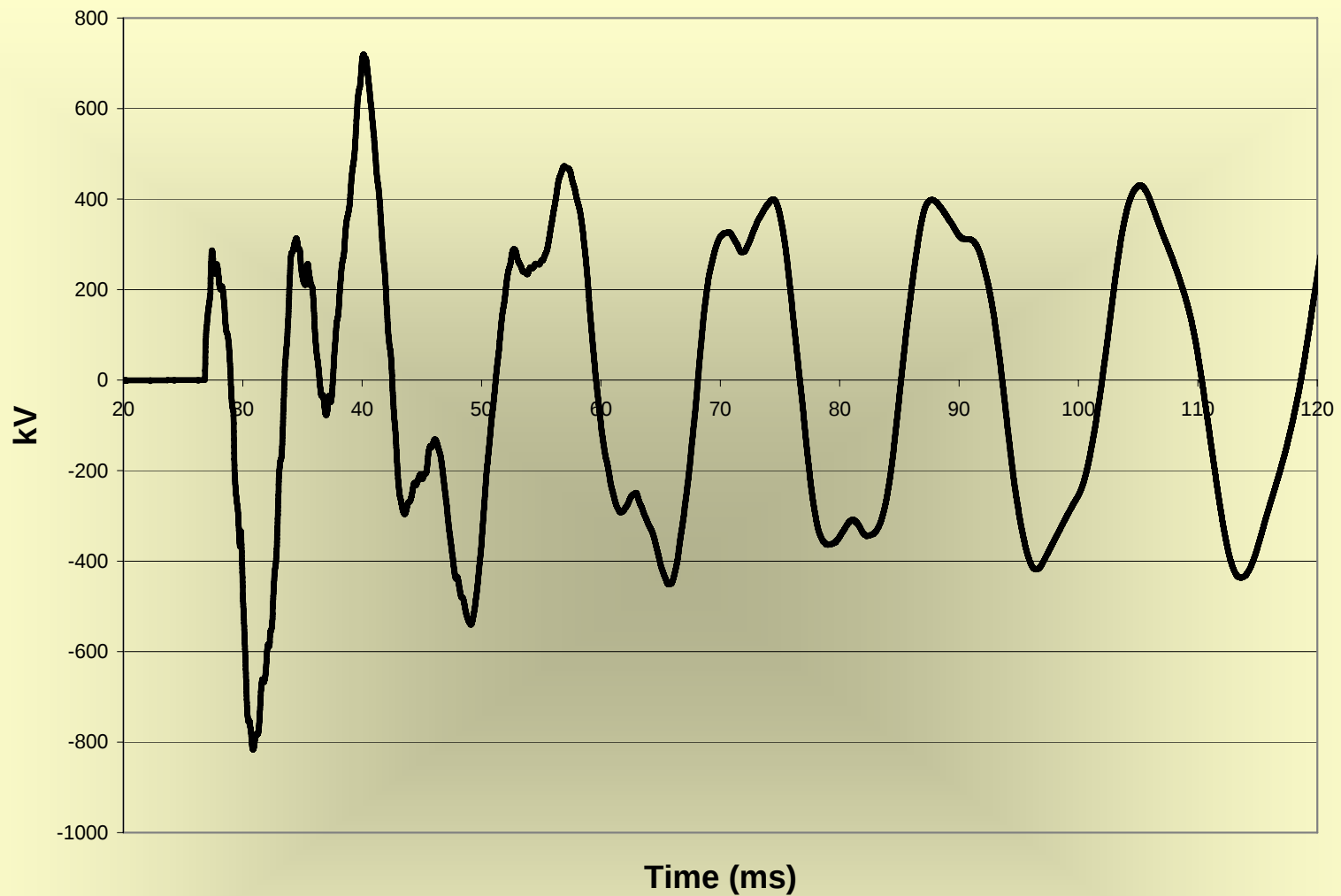
- POSITIVE AND NEGATIVE POLARITIES
- SAME 3 – 9 TEST SERIES
- WET AND DRY TESTS REQUIRED
- OPEN AND CLOSED TEST VALUES DIFFERENT
- 10 % PFO OR LESS

# TEST LEVELS

|                                 | Switching Impulse Terminal to Terminal |                       |
|---------------------------------|----------------------------------------|-----------------------|
| Rated Maximum Voltage (kV, rms) | Breaker Closed (kV, cr)                | Breaker Open (kV, cr) |
| 15.5                            | -                                      | -                     |
| 25.8                            | -                                      | -                     |
| 38                              | -                                      | -                     |
| 72.5                            | -                                      | -                     |
| 123                             | -                                      | -                     |
| 145                             | -                                      | -                     |
| 170                             | -                                      | -                     |
| 245                             | -                                      | -                     |
| 362                             | 825                                    | 900                   |
| 550                             | 1175                                   | 1300                  |
| 800                             | 1425                                   | 1500                  |

# *RATIO OF TEST LEVELS TO RATED MAXIMUM VOLTAGE*

|                                    | Switching Impulse Terminal to<br>Terminal |                                     |
|------------------------------------|-------------------------------------------|-------------------------------------|
| Rated Maximum<br>Voltage (kV, rms) | Breaker Closed<br>(kV, cr)                | In pu of Rated L-G Crest<br>Voltage |
| 362                                | 825                                       | 2.79                                |
| 550                                | 1175                                      | 2.62                                |
| 800                                | 1425                                      | 2.18                                |



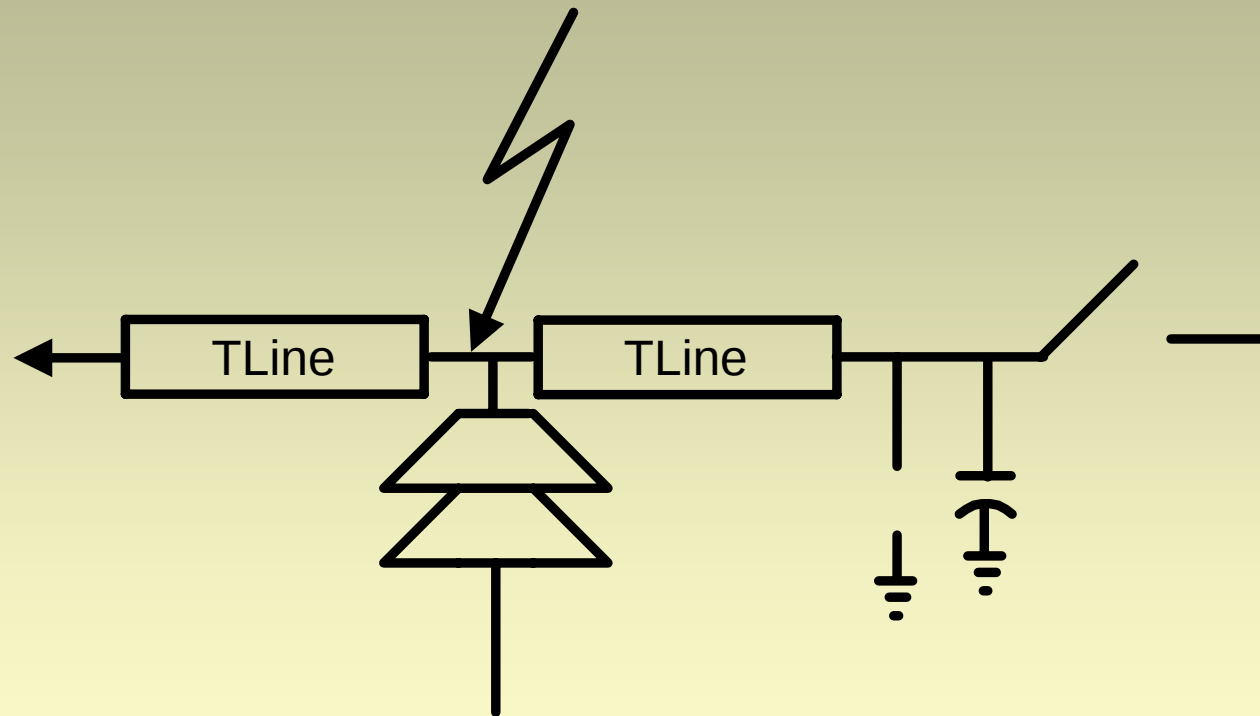
2.90 PU Phase to Ground Switching Surge  
345 kV System



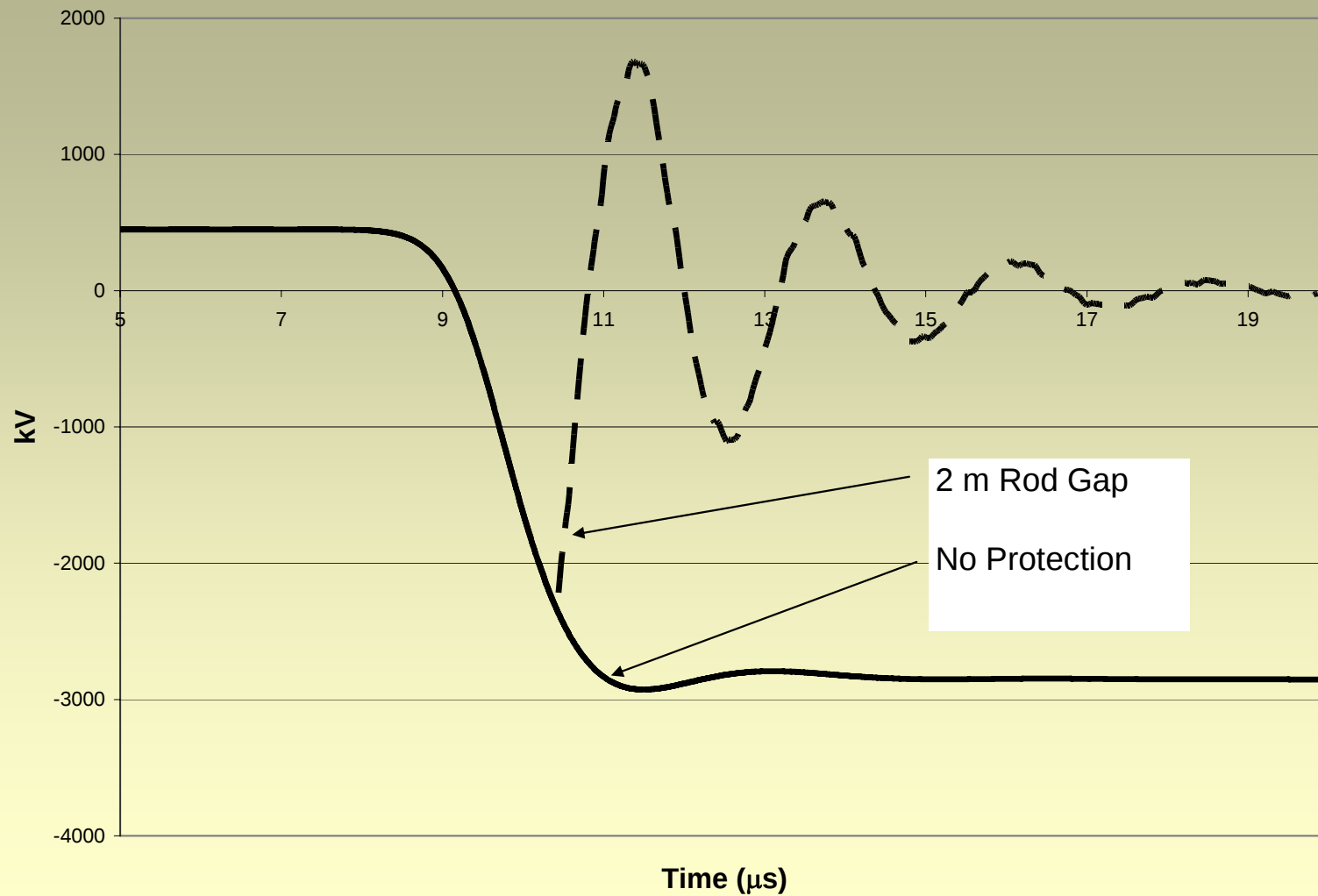
Application of 276 kV Surge Arrester  
1.83 PU

# *LIGHTNING SURGE PROTECTION*

## *USE OF GAP*

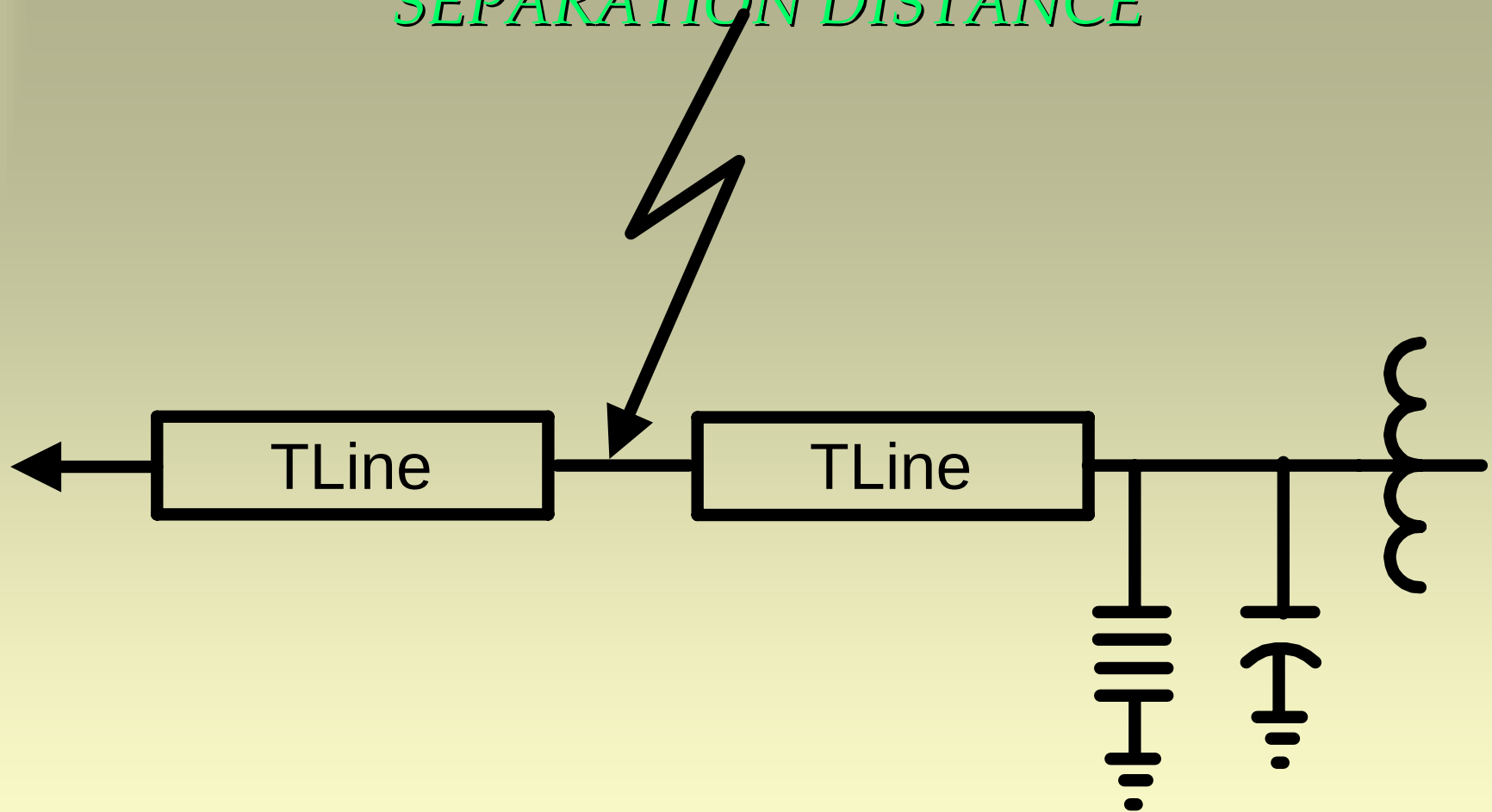


# *LIGHTNING SURGE PROTECTION - GAPS*

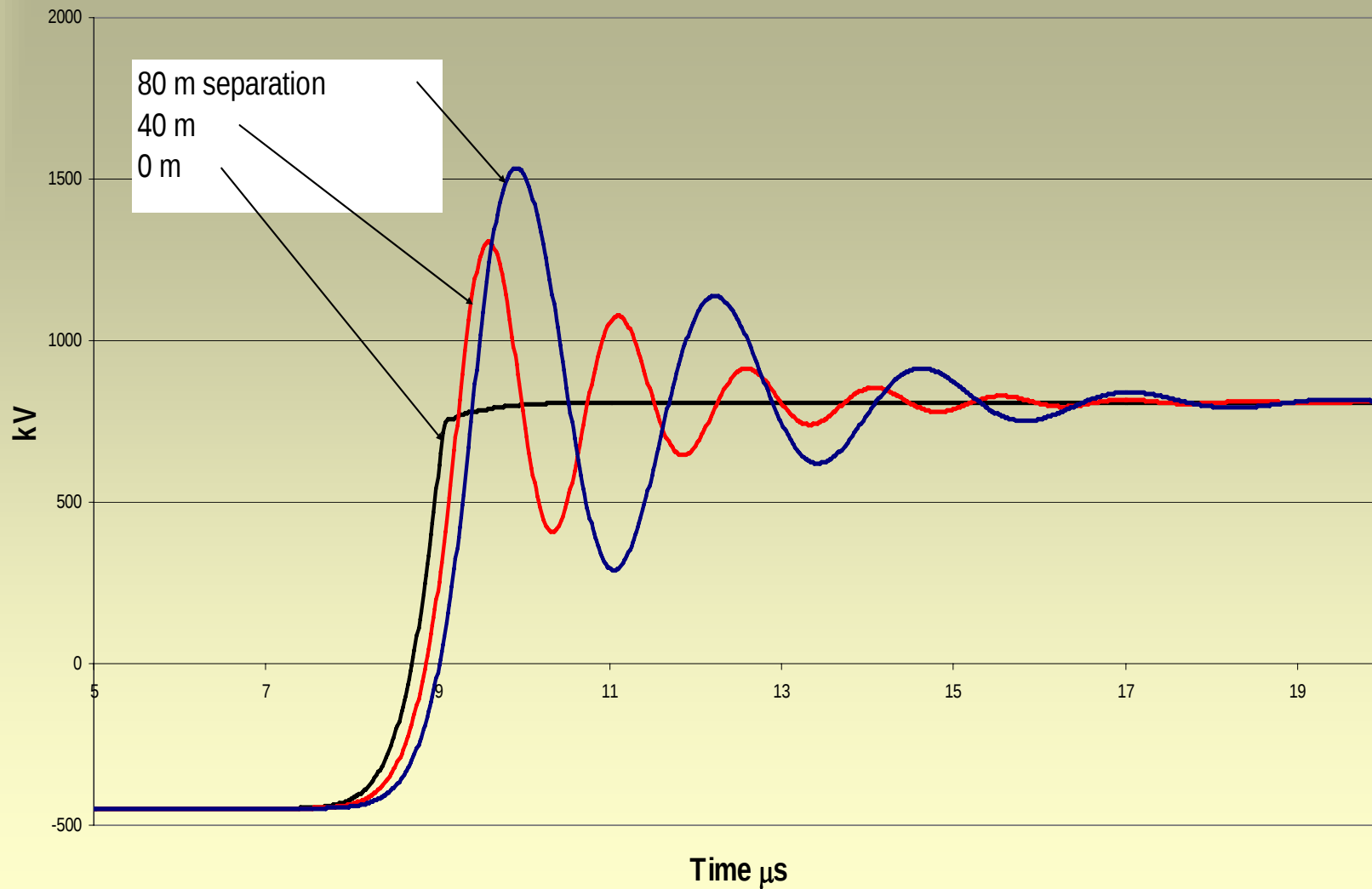


# *APPLICATION OF ARRESTER*

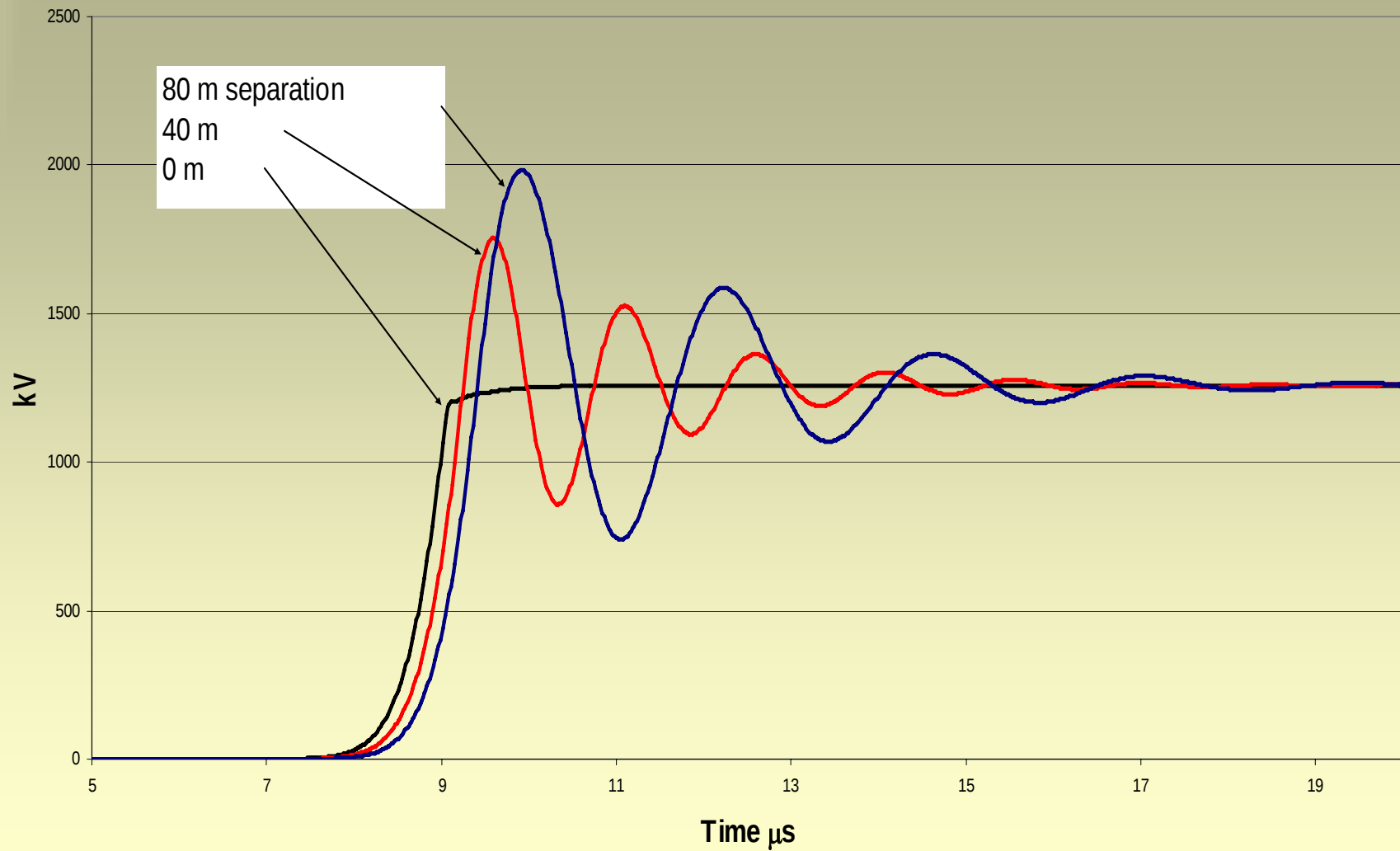
## *SEPARATION DISTANCE*



# *APPLICATION OF ARRESTER PHASE TO GROUND AT OPEN BREAKER*



# *APPLICATION OF ARRESTER ACROSS OPEN BREAKER*



# *EFFECT OF ALTITUDE*

- TESTED AT NTP (normal temperature and pressure)
- REDUCTION IN EXTERNAL INSULATION WITH INCREASING ALTITUDE

# *ALTITUDE CORRECTION FACTOR*

$$k_d = e^{-m\left(\frac{H}{8150}\right)}$$

- H – ALTITUDE IN METERS
- m – GAP FACTOR
  - ♦ 1 FOR POWER FREQUENCY, LIGHTNING AND PHASE TO PHASE SWITCHING SURGES
  - ♦ 0.9 FOR INSULATION ACROSS OPEN GAP
  - ♦ 0.75 FOR PHASE TO GROUND SWITCHING SURGES

# *ALTITUDE CORRECTION*

