Power System Quality and Reliability

ECEg-6312

WEEK 3

Origin and Classifications of Transients, Its Impact and Mitigation and Control Mechanism

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Topic Overview

This weeks discussion covers the following main topics:

- Origin of Transients
  - Capacitor switching transient
  - Lightning transient
  - Load or line switching transient
- Classification of Transients
- Impact of Transients
- Mitigation and Control Mechanisms of Transients

Learning Outcomes

After this lesson, students should be able to:

- **Identify & Classify Transients** – Understand the origin and types of transients, including switching, lightning, and fault-induced events.
- **Analyze Impacts** – On voltage stability, insulation, equipment, and protection systems.
- **Understand Mitigation Techniques** – Describe methods such as surge arresters, filters, and DSTATCOM.
- **Explain Control Mechanisms** – Explain theoretical principles of transient control and compensation to maintain power quality and system reliability.

1. Origin of Transients

- **Transients** are short-duration, high-frequency disturbances caused by sudden changes in system conditions.
- **Major sources include:**
  - Lightning strikes
  - Switching operations of capacitor bank, line, and transformer energization
  - Fault initiation and clearing
  - Electrostatic discharge (ESD)
  - Power electronic switching (inverters, converters)

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- As shown in **Figure 1**, transient refers to a high amplitude, short duration, and a high frequency electrical spike.
- Why transients are Critical?
  - Stress on insulation → premature ageing
  - Flashover in lines, cables, bushings
  - Circuit breaker failure
  - Transformer winding damage
  - Resonance instability in networks

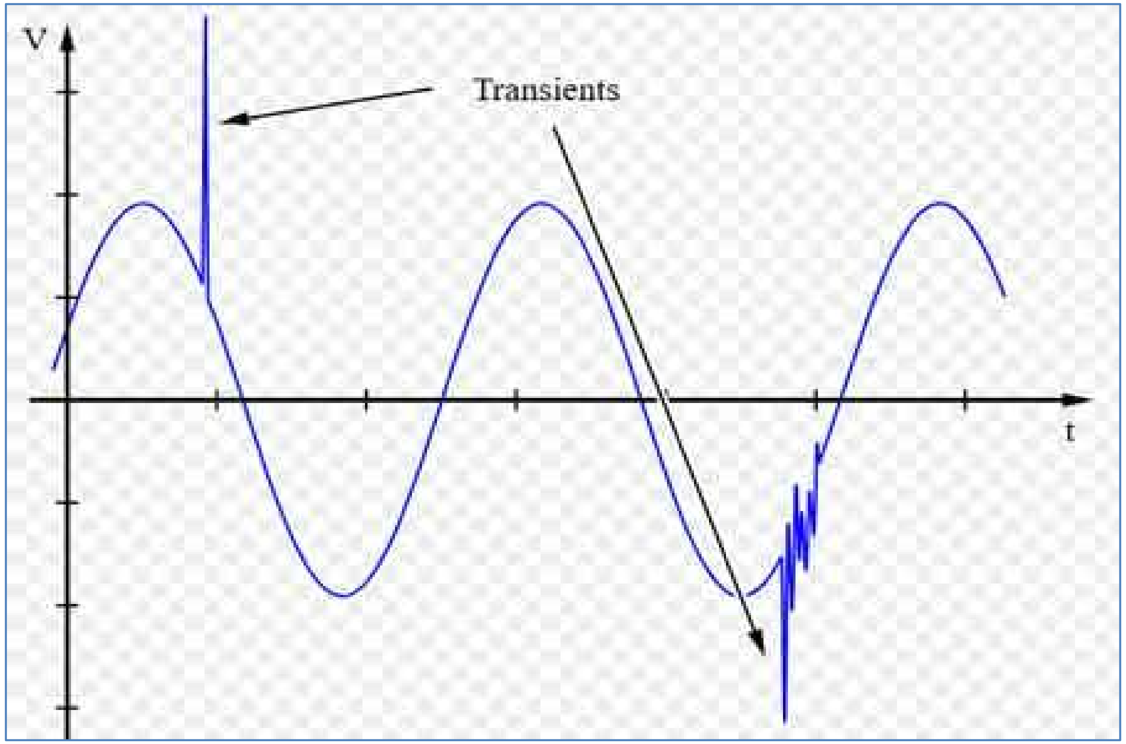

Figure 1: Transient Phenomanea.

1.1. Sources of Transient

1. Transients Due to Internal Sources: This event happen within the power system components and have a direct relation within the system voltage due to:

- Capacitor Switching
- Current Interuption (motors, etc.),
- Power Electronic operation
- Arc welding, Copy Machine,
- Faulty clearance or CB operation
- Transformer energization, Load Startup and disconnect

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2. Transients Due to External Sources

- **Lightning Strike:** Occur when lightning directly hits:
  - Transmission lines
  - Distribution feeders
  - Substations
- **Electrostatic Discharge (ESD):**
  - Transfer of charge between bodies with different potentials
- It takes the forms of a surge and has no direct relationship with the operating voltage.

1.2. Classifications of Transient

- According to IEEE standards, transients are broadly classified into:

1. Impulsive Transients

- Sudden, non-power frequency changes
- Unidirectional (positive or negative polarity)
- Very fast rise time (nanoseconds to microseconds)

2. Oscillatory Transients

- Characterized by oscillations that decay over time
- Caused by interaction of system inductance and capacitance

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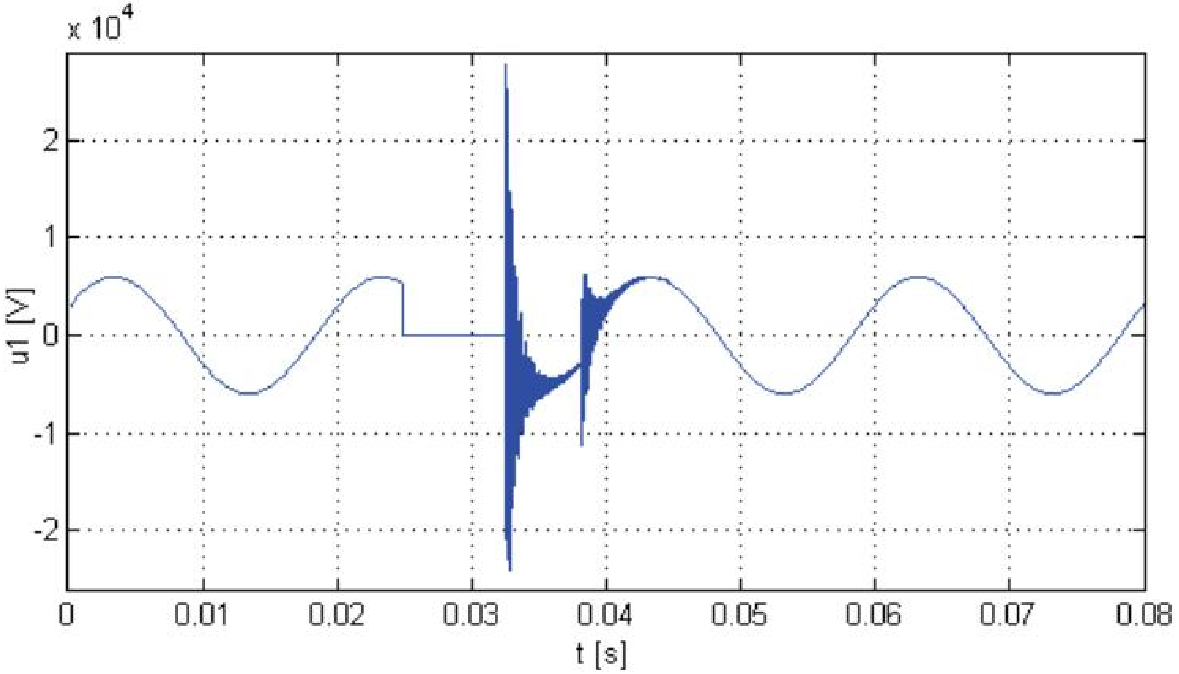
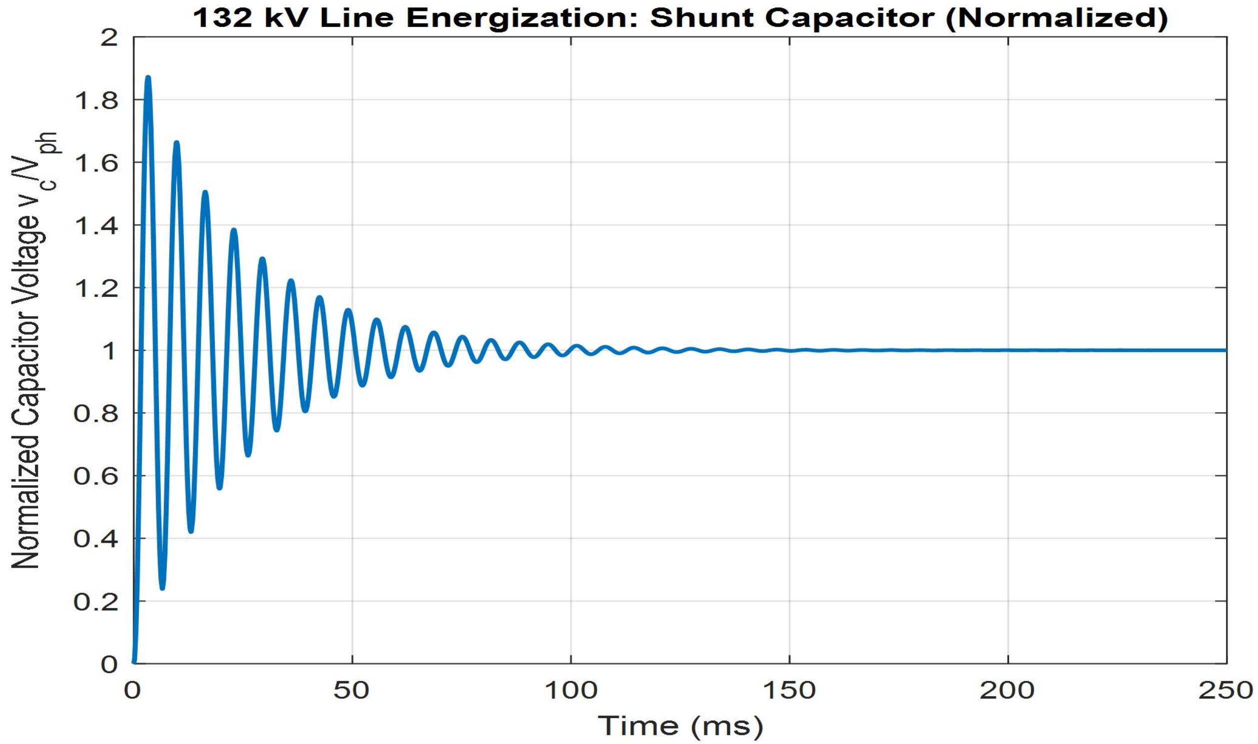


a). Impulsive (lightining) Type



b). Oscilatory (switching) Type

Figure 2: Voltage Transient [1].

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Depending on the magnitude and duration of the transient in power system it can be also catagoriezed as:

1. **Fast-front transients**
   - Examples: lightning impulses, switching of capacitors
   - Typical rise time: 0.1–1.2μs
2. **Slow-front transients**
   - Examples: switching of transmission lines, transformer energization
   - Typical rise time: 20–500 μs

1.3. Lightning Transient

- **Lightning phenomenon** is a natural electrostatic discharge that occurs between two electrically charged regions in the atmosphere.
- **Lightning discharges** are broadly classified into two main categories [2]:
  - **Intra-cloud (IC) discharges** (including cloud-to-cloud), which account for approximately 70–90% of all lightning events, and
  - **Cloud-to-ground (CG) discharges**, representing about 10–30%, which pose the greatest threat to humans and electrical infrastructure.

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- Focusing on **cloud-to-ground lightning**, different types of lightning discharges occur with varying directions and polarities.
- In scientific literature and lightning protection studies, the most common reference is downward negative lightning, as it constitutes around 90% of CG events [2].
- This simplification is practical because upward flashes generally occur on structures taller than 60 meters and are often of lower intensity, comparable to subsequent strokes in a flash.

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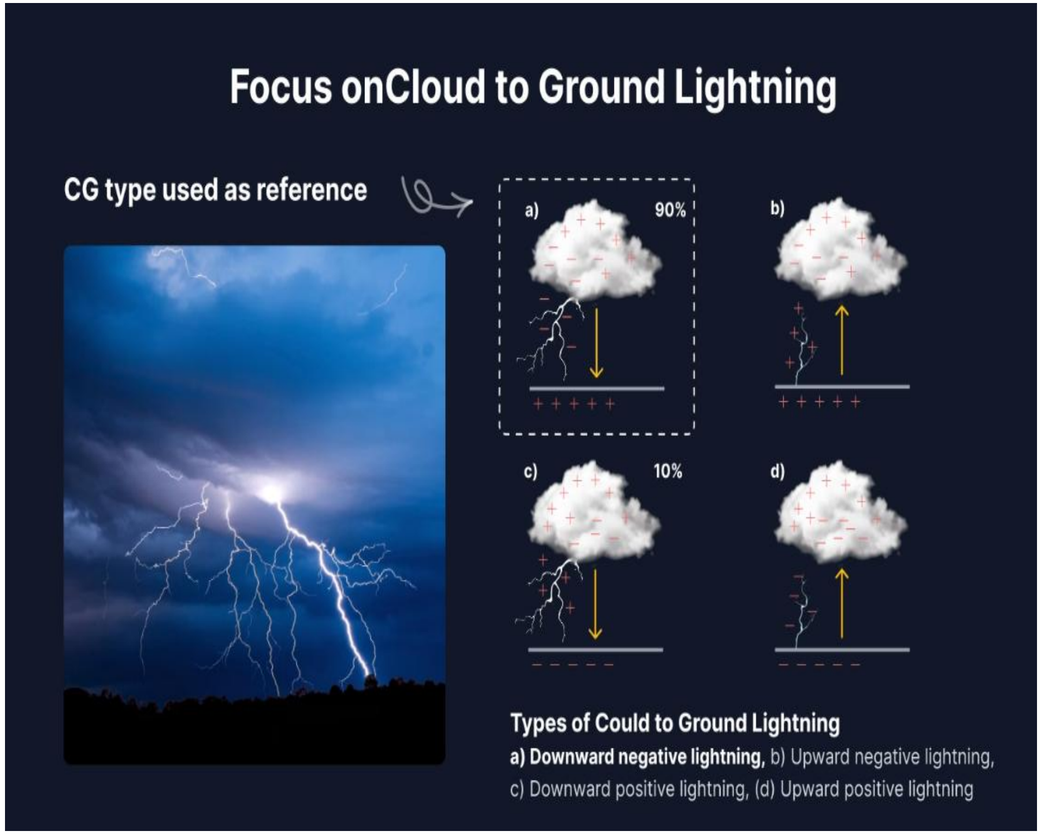

Figure 3: Lightining Phenomenon [2].

A. Origin of Lightning Transient

- **Lightning transient** refers to a **fast-front**, **high-magnitude transient overvoltage** produced by **direct** or **indirect** lightning events.

a) Direct Lightning Strikes

- The lightning channel makes physical contact with a phase conductor or shield wire.
- Results in very high current injection (10–200 kA typical) and produces steep-front transient voltages.

b) Indirect Lightning Strikes (Induced): Lightning strikes the ground or nearby objects.

- Rapidly changing electromagnetic fields induce overvoltages on conductors.
- Typically lower magnitude but still dangerous for distribution networks.

B. Waveform Characteristics

- Lightning-generated surges are modeled using the standard lightning impulse waveform:
  - Front time: 1.2 μs
  - Time to half-value: 50 μs
  - Hence, the waveform is referred to as 1.2/50 μs impulse.
- This represents a fast-front transient with:
  - Very high dv/dt
  - Magnitudes from hundreds of kV up to several MV on exposed lines
- Lightning transient propagates as traveling waves: Velocity: ~3×10^8 m/s (approx. speed of light)

Lightning Mathematical Model

- A lightning event is mathematically modeled using both **current** and **voltage surge** representations.
- The standard lightning voltage and current waveform recommended by the IEC is represented using a double-exponential function:

$$i(t) = I_o(e^{-\alpha t} - e^{-\beta t})$$

$$V(t) = Z_c i(t)$$

- where, α,β → waveform constants (front and tail shaping parameters respectively) and Z_c is the surge impedance of the power system components (line).

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- The characteristic parameters of lightning transient waveforms, including both current and voltage signals, are summarized in Table 1.

Table 1: Lightning Transient Parameters Based on IEC Standard.

Standard	Type	Rise Time	Tail Time	α (s^{-1})	β (s^{-1})
1.2/50	Voltage	1.2	50	4.9×10^4	1.4×10^6
8/20	Current	8	20	3.2×10^4	1.0×10^5
10/350	Current	10	350	2.0×10^3	2.0×10^4

Example

- A 160 kA lightning surge with a 1.2/50 μs waveform strikes a 765 kV transmission line with a surge impedance of 40 Ω.
- The resulting current and voltage transient waveforms are plotted using MATLAB.

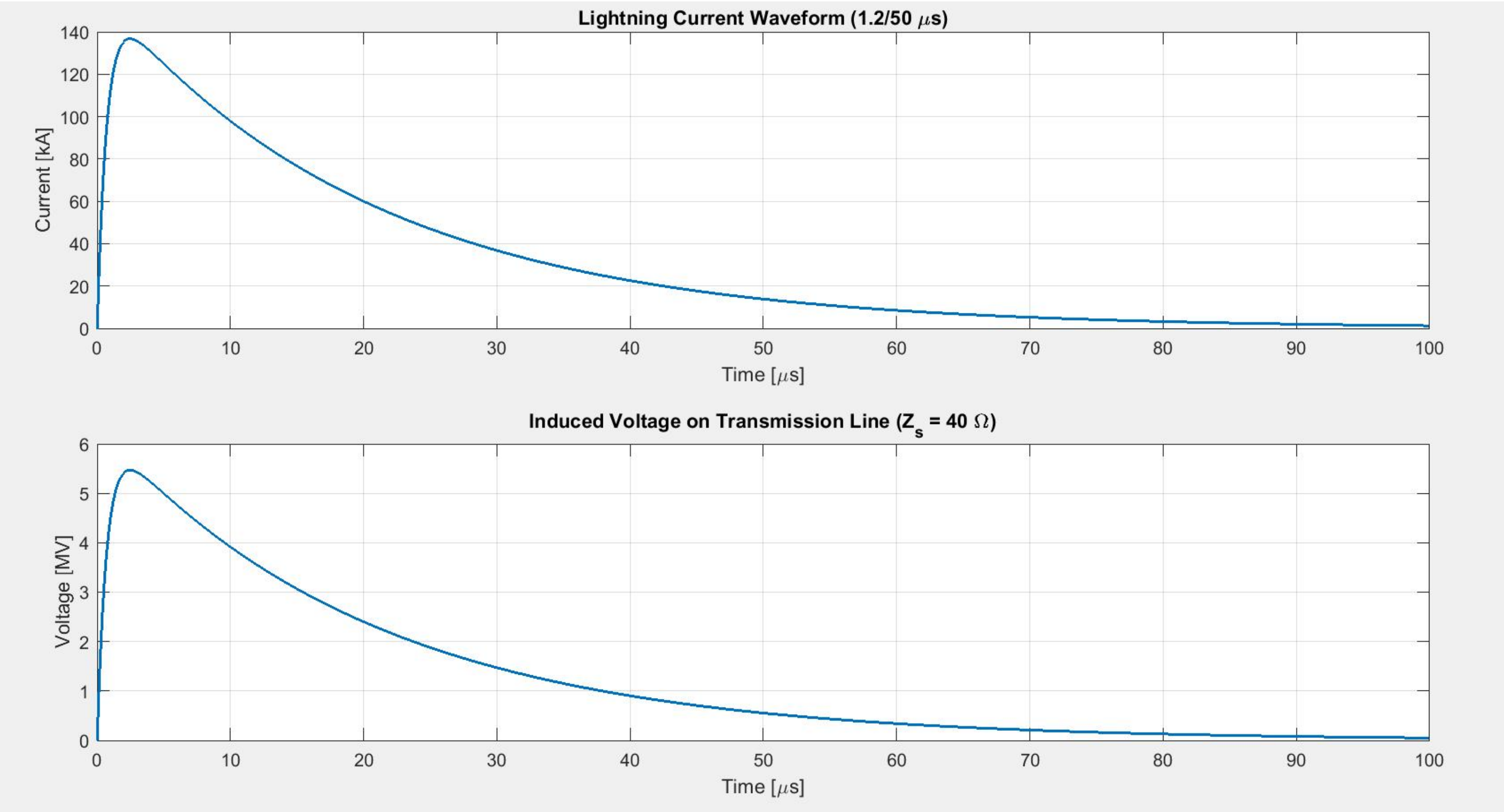

Figure 4: Current and Voltage Lightning Transient 1.2/50 μs Matlab Plot.

C. Impacts of Lightning Transient

a) Insulation Flashover

- Air-insulated equipment: insulators, bushings, switches
- Flashover may occur if protective level < surge magnitude

b) Breakdowns on Distribution Lines

- Pole-mounted transformers
- Service drops
- Customer equipment

c) Transformer Winding Stress

- High dv/dt causes winding inter-turn insulation failure.

D. Protection of Lightning Transients

- Lightning transients can cause insulation failure, equipment damage, and service interruptions.
- Protection techniques aim to limit transient voltages and currents to safe levels using:
  - Lightning Arresters (Surge Arresters)
  - Shielding and Grounding
  - Insulation Coordination
  - Surge Protection Devices (SPDs)
  - Line Design Measures: Optimal spacing, grounding, and surge impedance considerations.

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a) **Shield (Earth) Wires:** Installed above transmission conductors to intercept direct strokes.

- Shielding effectiveness is determined by the shielding angle.

$$\theta = \tan^{-1}\left(\frac{h - h_c}{d}\right)$$

- where, h=height of shield wire, hc is height of conductor and d is distance between them.

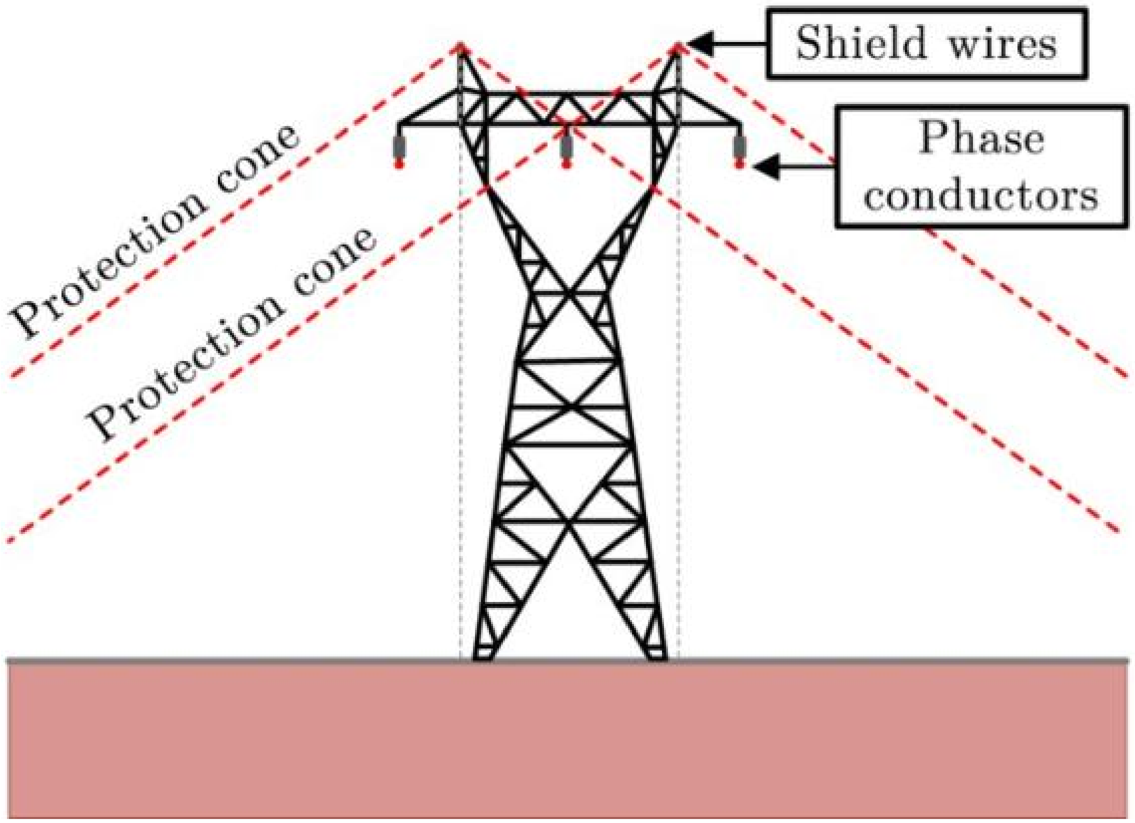

Figure 5: Line Sheild Wire Protection [3].

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b) **Lightning Arrester:** It is a protective device installed in power systems to safely divert lightning-induced surge currents to ground.

- **Key features include:**
  - Surge Current Handling
  - Voltage Limiting: Restricts transient voltages to levels below equipment insulation withstand.
  - Automatic Recovery: Returns to a high-resistance state after the surge passes.

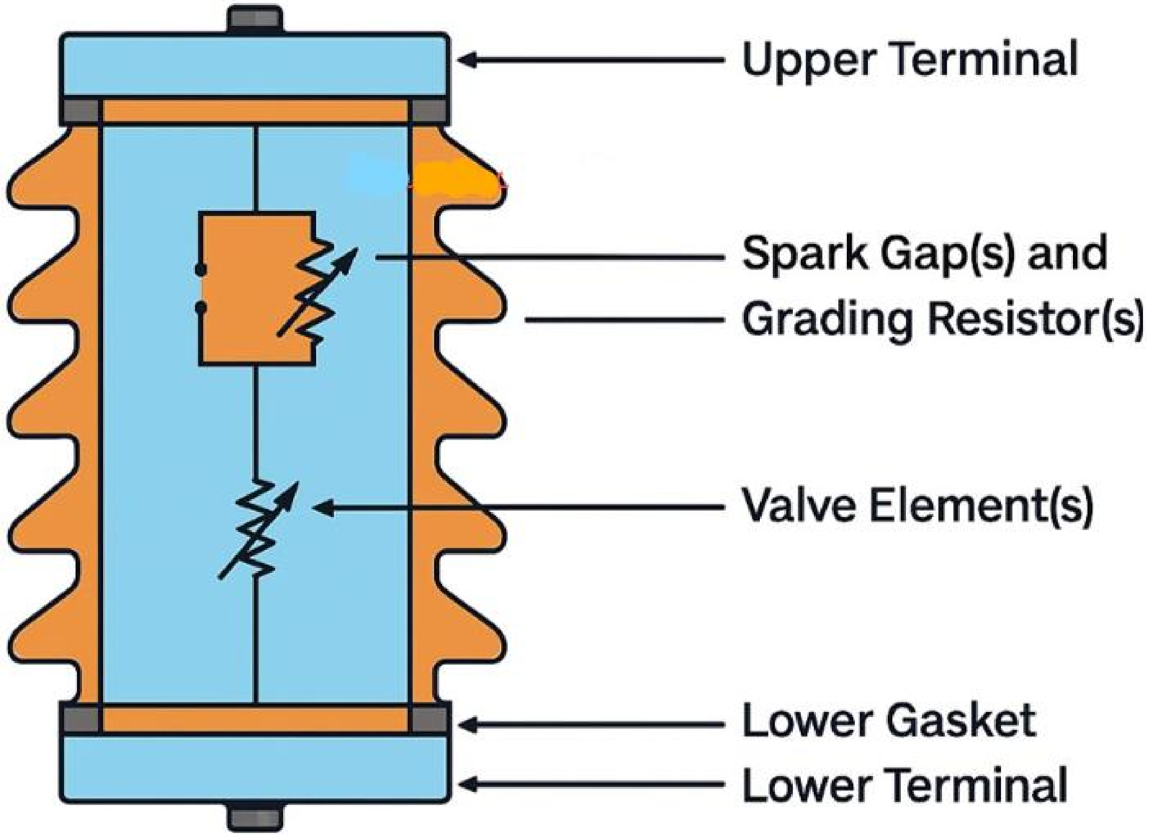

Figure 6: Lightning Arresters Substation Protection [4].

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c) Insulation Coordination:

- It is a design methodology used to ensure that electrical equipment can withstand expected overvoltages caused by lightning and switching events.
- It is a critical solution for protecting power systems against lightning transients.
- **Applications:**
  - Transmission lines,
  - substations,
  - transformers, and
  - sensitive equipment in high-voltage networks.

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Key Principles of Insulation Coordination:

1. **Selection of Insulation Levels:** Equipment insulation is rated to tolerate expected lightning transients.
2. **Coordination with Surge Arresters:** Surge arresters are installed to limit transient voltages below the equipment’s insulation withstand level.
3. **Statistical Design:** Uses lightning statistics (peak currents, flash density) to determine insulation requirements.
4. **System Reliability:** Proper coordination reduces failure probability and ensures continuity of service.

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d) **Surge Protection Devices (SPDs):** are installed in electrical systems to limit transient overvoltages caused by lightning by diverting surge currents to ground and clamping the voltage to safe levels.

Key Functions:

1. **Voltage Clamping:** Limits overvoltage to protect insulation and equipment.
2. **Energy Dissipation:** Safely conducts high surge energy to ground.
3. **Fast Response:** Operates within microseconds during lightning events.
4. **System Protection:** Safeguards sensitive loads and power electronics.

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e) **Line Design Measures:** Line design measures mitigate lightning effects through proper physical configuration and electrical parameters. These include:

- **Optimal Conductor Spacing:** Reduces electric field stress and minimizes flashover risk.
- **Effective Grounding:** Low tower footing resistance ensures efficient dissipation of lightning currents.
- **Surge Impedance Control:** Proper selection of conductor size and configuration to manage traveling wave behavior and limit overvoltages.

1.4. Switching Transients

- **Switching transients** are short-duration overvoltages or overcurrents generated in power systems due to switching operations such as:
  - Energization or de-energization of lines and transformers,
  - Switching operations of capacitors, and reactors.
- **Characteristics:**
  - Lower frequency compared to lightning transients
  - Higher energy content and longer duration
  - Significant impact on insulation stress

A. Transmission Line Energization

- Consider the series RLC circuit shown in **Figure 7** for analaysing a switching transient.

1. Series branch (R–L):

$$v(t) = Ri(t) + L\frac{di}{dt} + v_c(t)$$

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2. Capacitor current:

$$i(t) = C\frac{dv_c}{dt}$$

Substitute

$$v(t) = RC\frac{dv_c}{dt} + LC\frac{d^2v_c}{dt^2} + v_c(t)$$

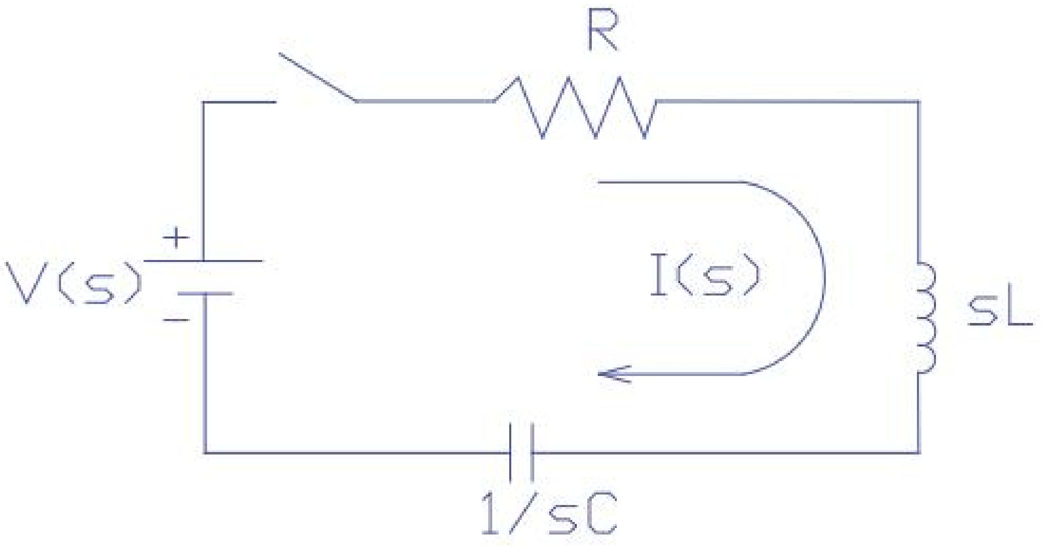

Figure 7: Transmission Line Energization.

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- The frequency domain analysis of a transmission line modeled with a series R-L-C circuit as in Figure 6:

$$V_C(t) = \frac{V(s)}{LC(s^2 + \frac{R}{L}s + \frac{1}{LC})} = V(s)\frac{\omega_o^2}{s^2 + 2\alpha s + \omega_o^2}$$

- Let's define:

$$\alpha = \frac{R}{2L}, \ \omega_o = \frac{1}{\sqrt{LC}}$$

- *So the denominator becomes:* $s^2 + 2\alpha s + \omega_o^2$

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- The transient voltage and current due to energization of transmission line are:

$$v_c(t) = \frac{V_0}{\omega_0^2}\left[1 - e^{-\alpha t}\left(\cos(\omega_d t) + \frac{\alpha}{\omega_d}\sin(\omega_d t)\right)\right]$$

- The line Current also expressed as:

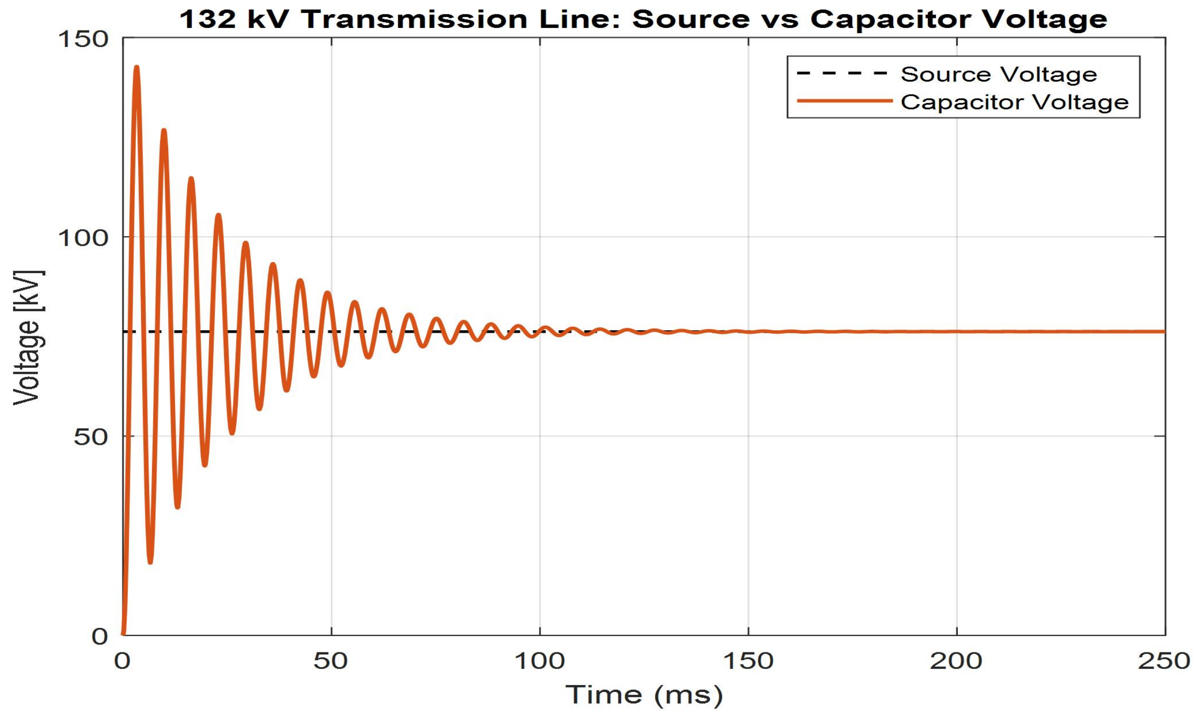
$$i(t) = C\frac{dV_C(t)}{dt} = C.V_o e^{-\alpha t}(\alpha\cos\omega_d t + \omega_d \sin\omega_d t)$$

- $where, \omega_d = \sqrt{\omega_o^2 - \alpha^2}$

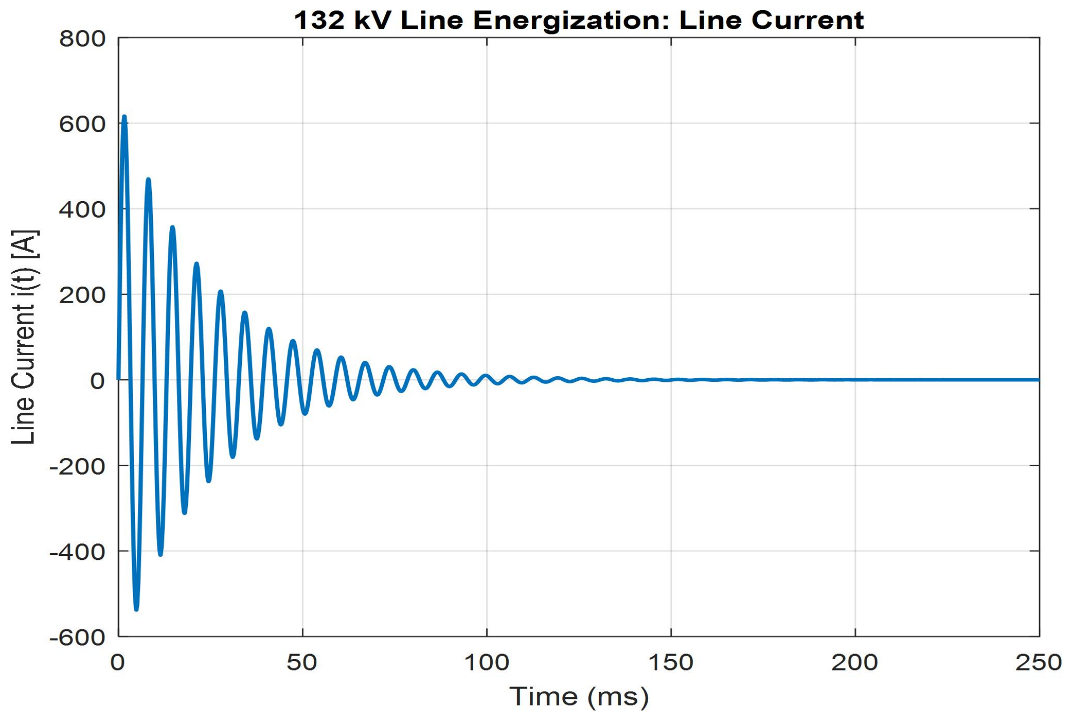
Example

- **A 132 kV (76.2 kV phase voltage) transmission line**, 100km long, is energized by a transformer when a circuit breaker closes.
- **The transmission line has the following lumbed parameters:** Series resistance, R=15Ω, Series inductance, L=0.12H, and shunt capacitance of C=9μF.
- **Using Matlab:**
  1. Determine the capacitor voltage $V_c(t)$, over the first 250 ms after switching.
  2. Determine the line current i(t) over the same interval.
  3. Find the peak voltage and peak current due to the switching transient.

Example



a). Voltage Transient



b). Current Transient

Figure 8: Line Energization Transient Voltage and Current for 132kV (76.2kV phase) Transmission Line.

B. Capacitor Bank Switching

- At the **instant of switching**, the capacitor voltage **cannot change suddenly**; the capacitor current can be large (inrush) to force the capacitor voltage to its nominal value.
- When the network has inductance and resistance, the connection produces a **damped oscillation**) between L and C.

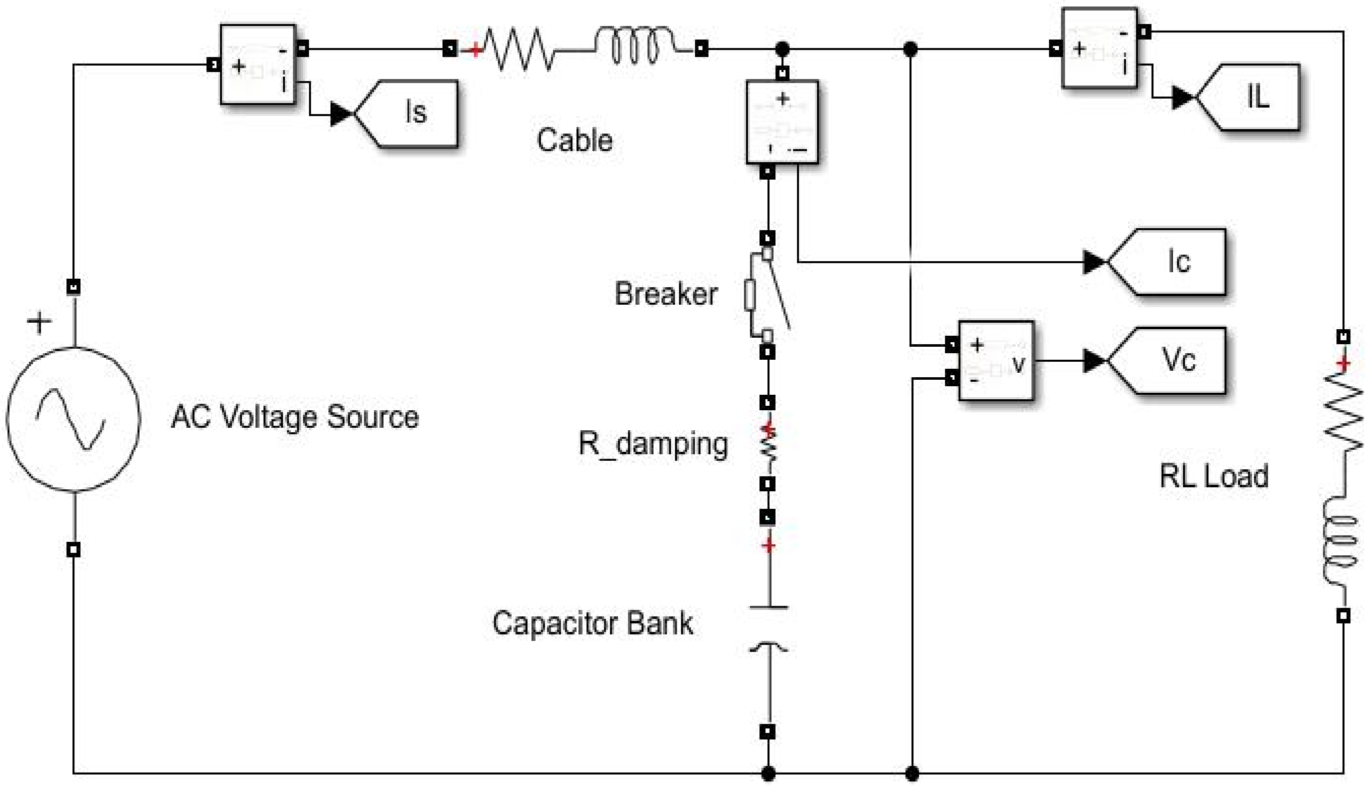


Figure 9: Capacitor Bank Switching

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- Resonance (low damping) can produce large overcurrents/overvoltages during capacitor bank switching.
- Include a **surge resistor** or **pre-insertion resistor**/thyristor control to limit inrush current.
- The insertion and rejection of the Capacitor-bank into or from the network have different surge magnitude.
- Capacitor-bank disconnection is **more terrible**.

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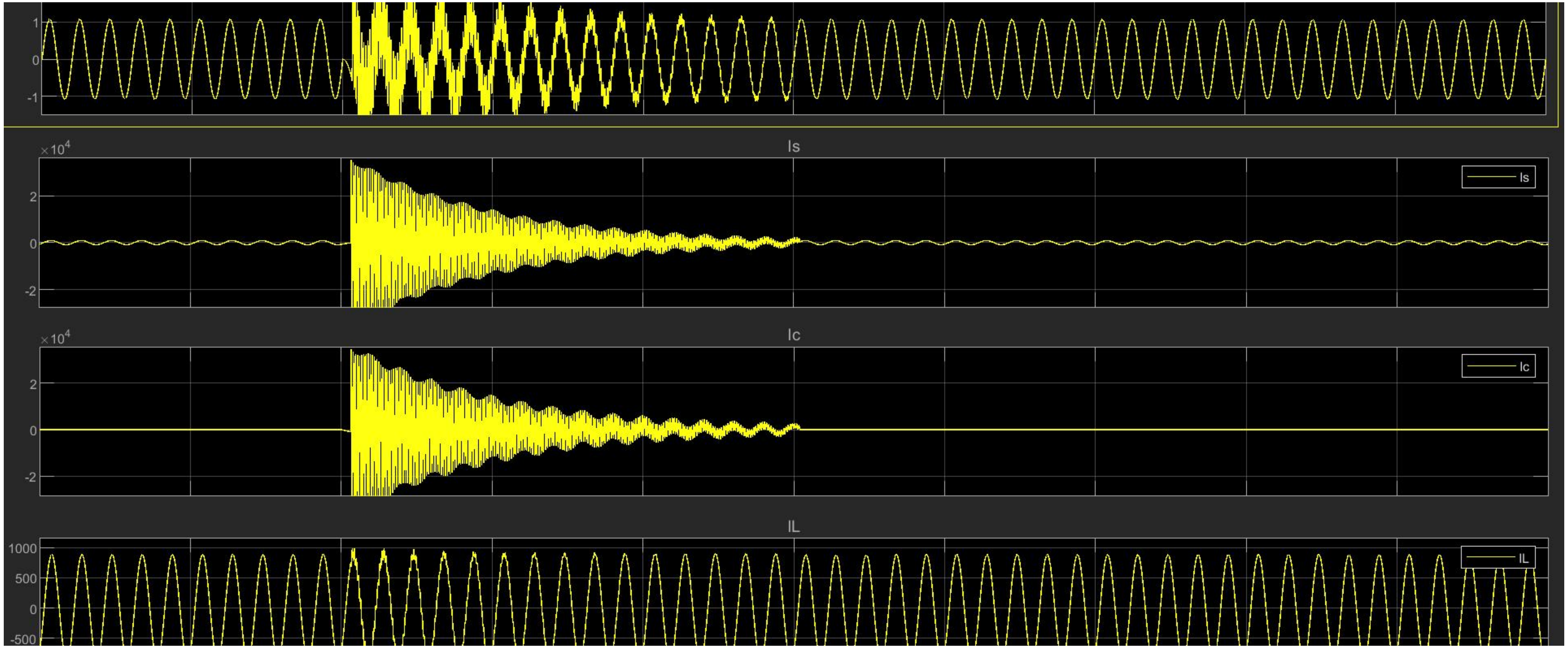

Figure 10: Without a surge resistor **a).** Capacitor Voltage. **b).** Source Current. **c).** Capacitor Current. **d.** Load Current

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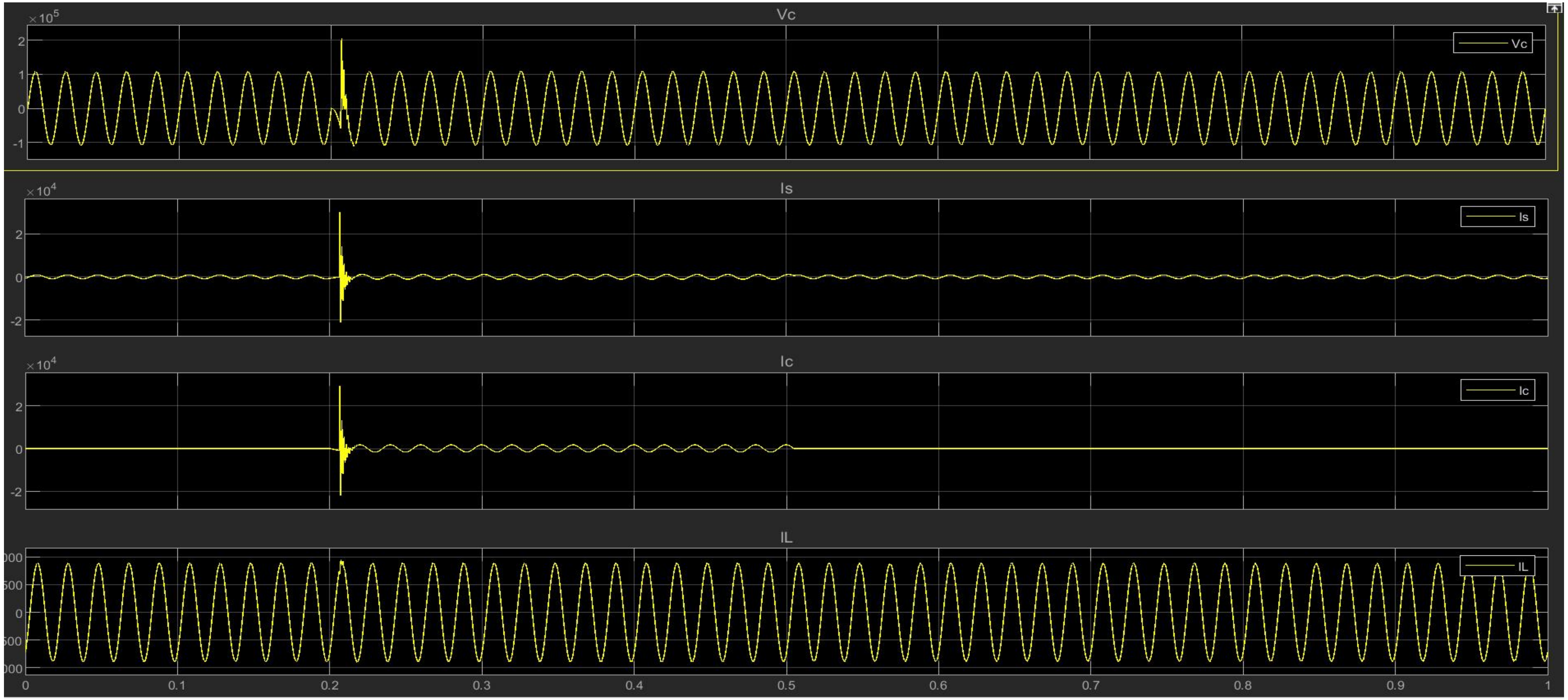

Figure 11: With a surge resistor of **1 ohm** **a).** Capacitor Voltage. **b).** Source Current. **c).** Capacitor Current. **d.** Load Current

2. Impact of Switching Transients

- **Key Impacts:**
  - **Overvoltages:** May exceed insulation limits → equipment damage.
  - **Overcurrents:** Can trigger protection devices unnecessarily.
  - **Oscillations & Resonance:** High-frequency transients → component stress.
  - **Voltage Sags & Swells:** Affect sensitive loads (computers, drives).
  - **Equipment Aging:** Repeated stresses degrade insulation, shorten transformer/switchgear life.
  - **Protection Maloperation:** False tripping of relays due to transient signals.

3. Mitigation of Switching Transients

Key Mitigation Techniques include:

1. Use of Surge Arresters
   – Absorb and divert transient overvoltages.
2. Pre-insertion Resistors (PIRs)
   – Inserted during capacitor switching to limit surge currents.
3. Damping Circuits / Snubbers
   – RC or RLC snubber networks across switching devices..
4. Proper System Design & Line Termination

- Optimize line length, spacing, and grounding.

References

[1] M. Hoger, P. Bracinik, and P. Rafajdus, "The specification of data needed for fault location in medium voltage distribution networks based on triangulation principle," Przegląd Elektrotechniczny, vol. 87, no. 1, pp. 242–245, 2011.

[2] V. A. Rakov and M. A. Uman, Lightning: Physics and Effects. Cambridge, U.K.: Cambridge University Press, 2003.

[3] M. Hoger, P. Bracinik, and P. Rafajdus, "Shield wires on the top of a power line," in Przegląd Elektrotechniczny, vol. 93, no. 2, pp. 124-130, 2013.

[4] V. K. Mehta and R. Mehta, Principles of Power System, 4th ed. New Delhi, India: S. Chand Publishing, 2005, pp. 542–545.

Thank You!