Faults

- Failure of the insulation around an electric cable
- Creates a “short circuit”
  - An easier path for the current
- A large fault current flows through this short circuit
- This fault current must be interrupted quickly because:
  - It is dangerous
  - It could destroy the equipment
  - It could make the power system unstable



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Types of insulating materials

- Air
  - Must have sufficient distance (clearance) between conductors and between conductors and ground (or earth)
- Gas (SF_6)
  - Better insulator than air
    - Need smaller clearances than in air
    - Needs to be contained
    - Contributes to global warming
- Oil (in transformers and cables)
- Paper (in transformers and older cables)
- Polymers (in newer cables)

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What causes faults?

- Lightning
- Contact between bare conductors
  - Branches, animals (e.g. squirrels, snakes, large birds)
- Movement of conductors
  - Wind, sagging due to too much current
- Defects in insulating material
  - Ageing of solid insulation, contamination of oil, pollution
- Damage to solid insulator
  - Rats, ants, vandalism, construction (i.e., digging up the street)
- Pollution on the insulators
  - Particularly in maritime areas

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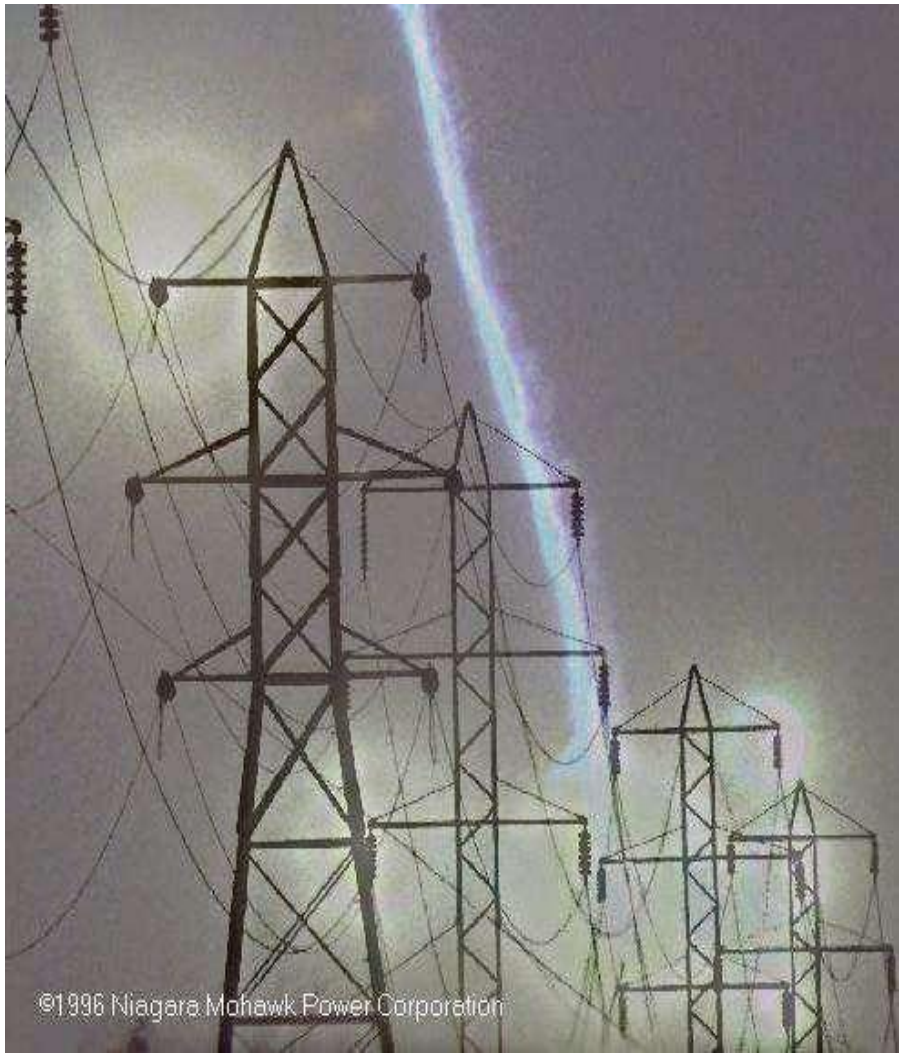
Lightning

- Lighting creates an ionized path
  - 30 million lightning strikes per year in US!
  - A single typical stroke might have 25,000 amps, with a rise time of 10 μs, dissipated in 200 μs.
  - Multiple strokes can occur in a single flash, causing the lightning to appear to flicker, with the total event lasting up to a second.
- Conduction path is maintained in ionized air by the fault current

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What causes faults?

Lightning…





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What causes faults?



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What causes faults?



Careless driving…



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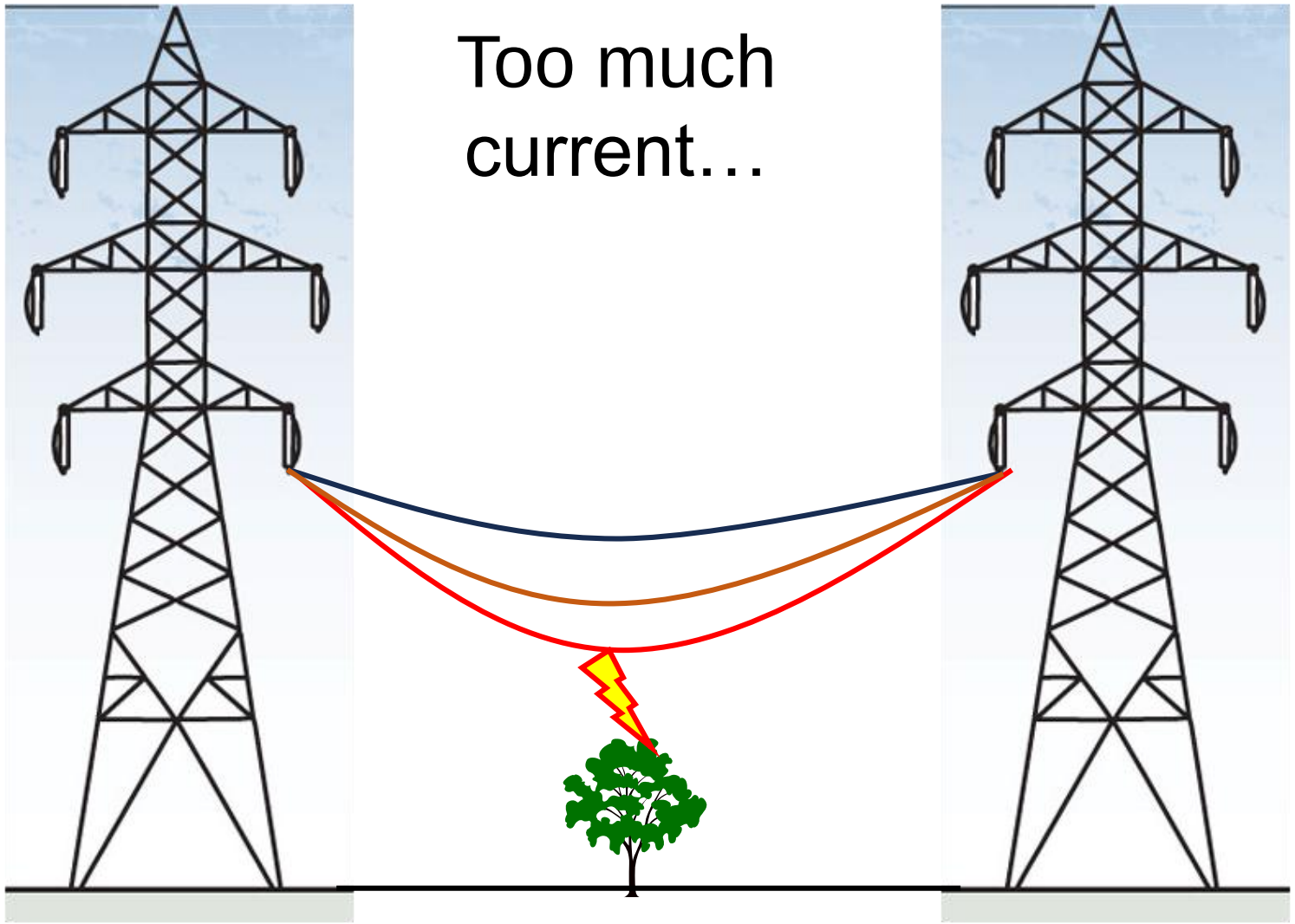
What causes faults?



Snow and ice…

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What causes faults?



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Effects of faults

- Sustained interruptions (outages)
- Momentary interruptions (equipment reset)
- Fires
- Equipment damage
- Electrocution
- Voltage dips
- System perturbation
  - Instability and blackouts

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Effects of faults - Outages

- Customer outages quantized by frequency and duration

- IEEE Standard reliability measures
  - System Average Interruption Frequency Index (**SAIFI**)
  - System Average Interruption Duration Index (**SAIDI**)

- Reported annually to Public Utilities Commissions

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Effects of faults - Outages

$$SAIFI = \frac{\#\ Sustained\ Interruptions}{\#\ of\ Customers}$$

$$SAIDI = \frac{Total\ Duration\ of\ all\ Sustained\ Interruptions}{\#\ of\ Customers}$$

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Effects of faults - Fires

- Forest fires
  - Recent major concern
  - Detailed discussion follows
- Manhole explosions
  - Different mechanisms
  - https://www.youtube.com/watch?v=1I6qAyQJLaA
- House fires
  - More deaths/year than electrocution

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Effects of faults – Forest Fires

- Several major fires in Western US due to faults on power lines
  - Faults on the transmission and distribution networks
  - Widespread death and destruction
    - 100 dead
    - Billions of dollars in damage
- Inadequate maintenance a factor
- In California, utilities responsible for all costs of fires started by their lines
  - PG&E bankrupt from 2017 fires
  - PG&E pleaded guilty to manslaughter – paid ~$85M fine

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Washington: Malden Fire - 2020



- Strong winds
- Large branch fell on a line
- 67 homes destroyed
- No loss of life

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California: Camp Fire - November 2018

- 115 kV Transposition tower – ca. 1920
  - Structure slightly different from actual failed tower
  - Conductor routing the same
- Failure of hook holding up lower insulator
- Conductor swung into (grounded) tower
- Shower of sparks (molten aluminum)
- Fault interrupted normally



NBC news

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California: Camp Fire - November 2018

- Closeup of similar hook
- Note worn hole in back
- Note “new” flange



Tubetimus twitter

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California: Camp Fire - November 2018

- Worn hook, for scale
- Not failed
- Possibly the hook on the previous slide



Tubetimus twitter

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California: Camp Fire - November 2018

- Close up of surface of actual failed hook
- Taken in situ, hanging upside down
- Red lines – wear marks
- Blue circle – point of failure
- Black circle - rust

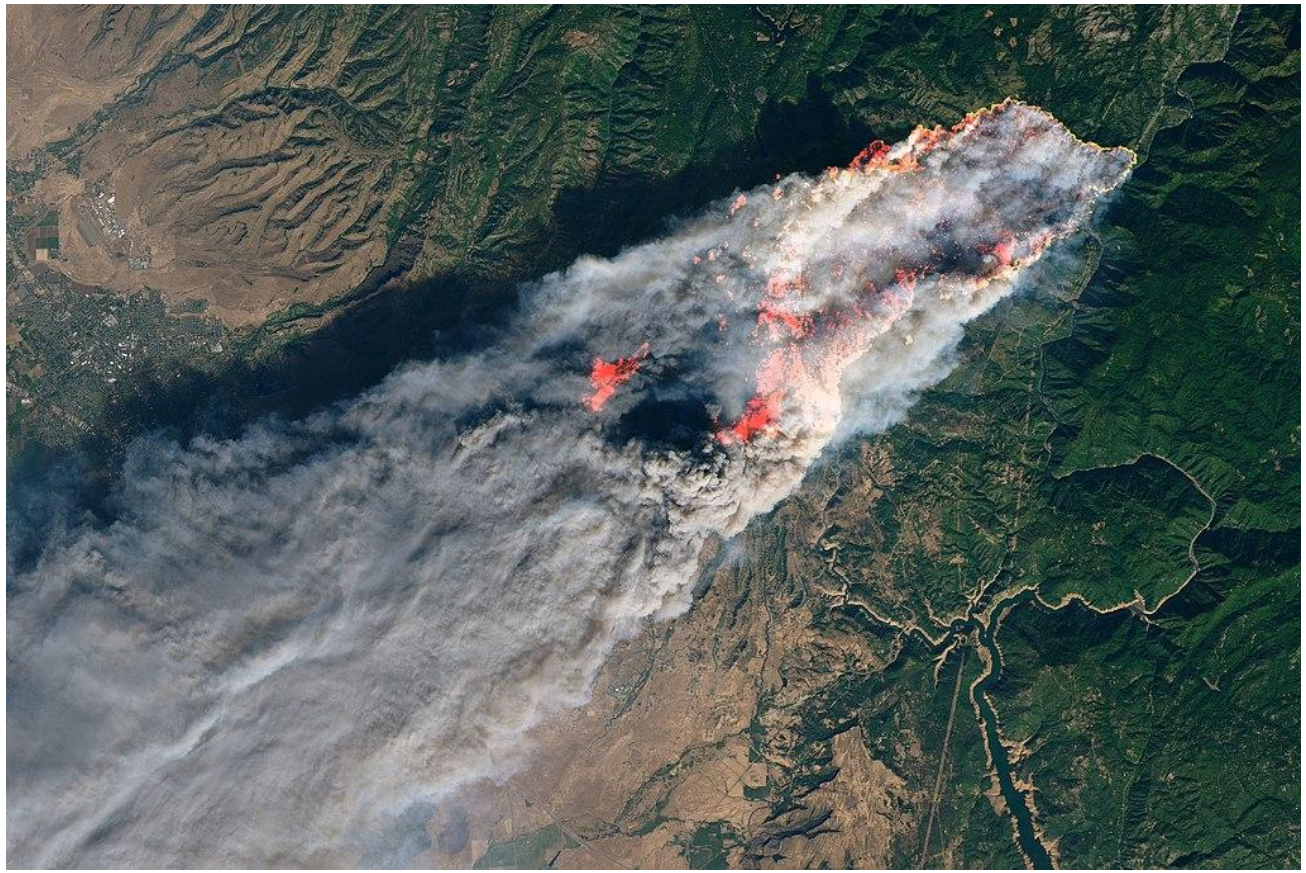


Tubetimus twitter

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California: Camp Fire - November 2018

- Satellite view of Camp Fire, November 8, 2018
- Burned 153,336 acres
  - 16th largest in California
- Destroyed 18,804 structures
- Killed 85
  - Worst in California



Wikipedia

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California: Camp Fire - November 2018

- Paradise, California, post-fire
- Why so large?
  - Santa Ana winds
  - Stress power lines
  - Dry underbrush
  - Fan flames
  - Poor forest management
- Why so destructive?
  - Build and live in fire zone
  - Poor fire precautions



Gannett-cdn.com

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Preventing faults from causing fires

- Preventive de-energization
  - Based on risk of wildfire (temperature, humidity, wind)
  - Must balance risk against inconvenience of outages
- Protection (relays, breakers) not fast enough to prevent arcing
  - Still better than letting arc
- Reduce fault probability
  - Undergrounding – 3 to 10 times the cost of overhead lines
  - Wider rights of way & fire retardant
  - More maintenance
  - Can reduce but not prevent

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Effect of faults - Fires

- Prediction
  - Present approach unsustainable
    - Bankrupt utilities
    - Prolonged de-energization
  - Rational balance of protection vs. cost of fires unlikely
  - Expect overreaction to continue

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What happens when a fault is not cleared?

http://www.youtube.com/watch?v=fzbQjd_Oo4Q



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Sagging transmission line

- https://nos.nl/video/2443017-explosies-en-rokende-kabels-bij-verdeelstation-in-dronten
- 300,000 customers without power for an hour
- Cables and other equipment had to be replaced
- Train line was damaged
- Causes of the problem:
  - Work was underway at the substation
  - Worked grounded the line for safety not realizing that it was energized
  - Protection system did not function properly

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Damage to the train tracks



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How can we prevent faults?

- Tree pruning
- Animal guards
- Shield wires
- Circulating current to de-ice
- Washing insulators
- Voltage and load limits
- Incipient failure monitoring

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Types of faults

- Transient faults
  - Fault disappears once the fault current has been interrupted
    - Faults caused by lightning
  - Component can be put back in service very quickly
    - Auto-reclosure
- Permanent faults
  - Insulation is permanently damaged
  - Component must be repaired or replaced before being put back in service

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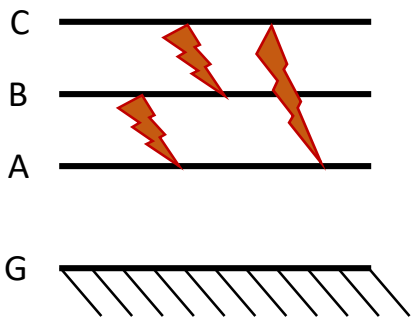
Types of faults

- Balanced faults (a.k.a. symmetrical faults)
  - All three phases affected in the same way
  - Symmetry between the phases is unaffected
  - Can be studied using single phase model

- Unbalanced faults (a.k.a. asymmetrical faults)
  - Not all phases are affected in the same way
  - Behaviour in all three phases is no longer symmetrical
  - Calculating the fault current requires special techniques
    - Symmetrical components

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Types of faults: balanced fault

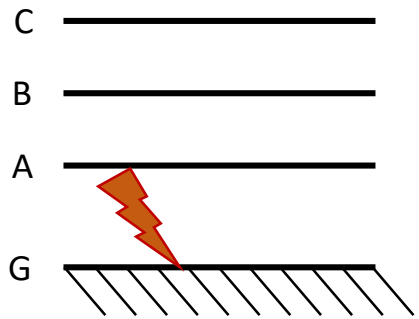


Balanced three-phase fault
(L-L-L)

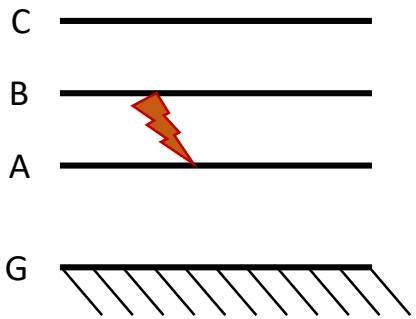
Affects all three phases equally
Does not break the three-phase symmetry

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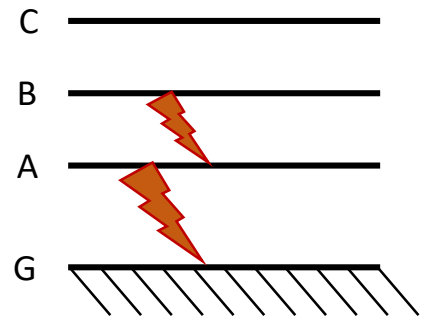
Types of faults: unbalanced or asymmetrical faults



Phase-to-ground
Line-to-ground (L-G)



Phase-to-phase
Line-to-line (L-L)



Two-phase-to-ground
Line-ot-line-to ground (L-L-G)

Do not affect all three phases equally
Break the three-phase symmetry

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Which type of fault is more frequent?

1. Single-line-to-ground ~ 70%
2. Line-to-line ~ 15%
3. Line-to-line-to-ground ~ 10%
4. Balanced three-phase ~ 5%

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Which type of fault is more severe?

- A more severe fault is one with a larger fault current
- Balanced three phase faults are usually the most severe
- In some cases, a single line to ground fault can be more severe than a balanced fault
- Other types of faults are less severe

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Fault resistance R_f

- Bolted fault or solid fault
  - Short circuit has zero resistance
  - $R_f = 0$
- Non-zero impedance fault
  - Arc has a non-zero impedance
  - $R_f \neq 0$
- Can't predict R_f
- R_f reduces the fault current
- But makes it more difficult to detect the fault!



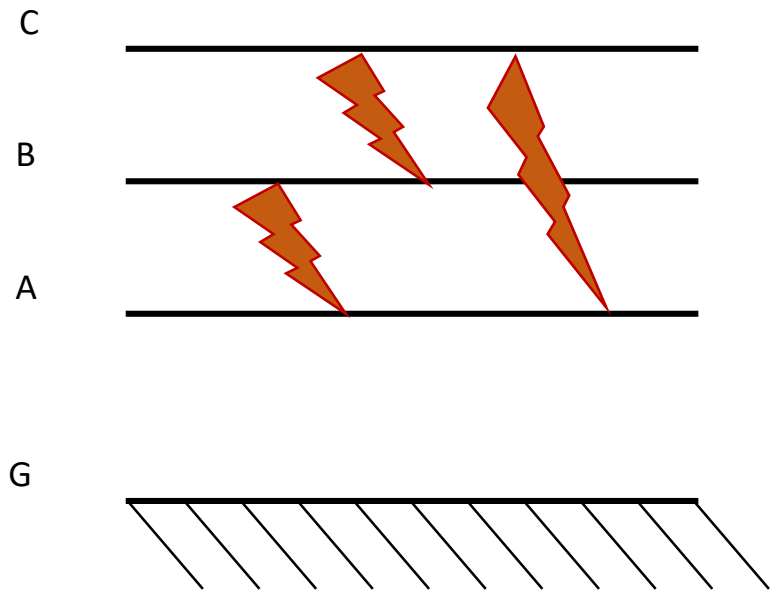
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Handling faults

1. Detect the fault
   - Must be done quickly before it becomes a bigger problem: 10’s ms – 100’s ms
2. Locate the fault
   - Which piece of equipment is faulted and must be isolated?
   - Done using various types of relays
3. Clear the fault
   - Interrupt the fault current using a circuit breaker or a fuse
4. Remove the cause of the fault or repair the faulted component
   - Only if fault is not a transient fault
5. Re-energize the circuit

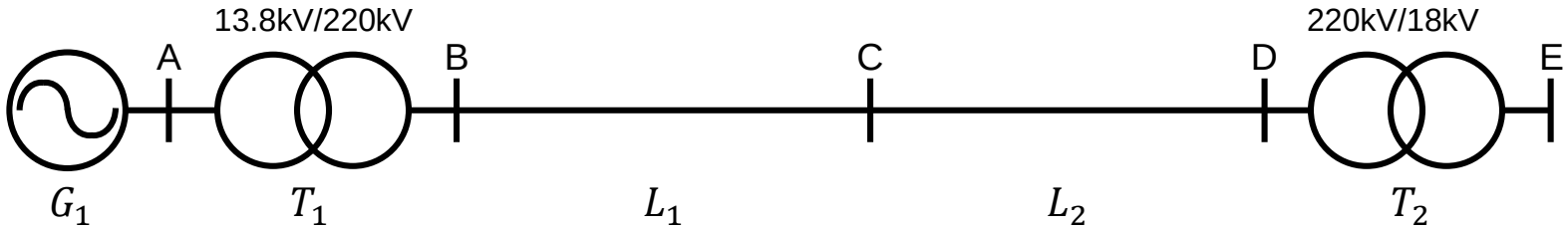
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Balanced three phase fault analysis



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Example 9.1: System with one source

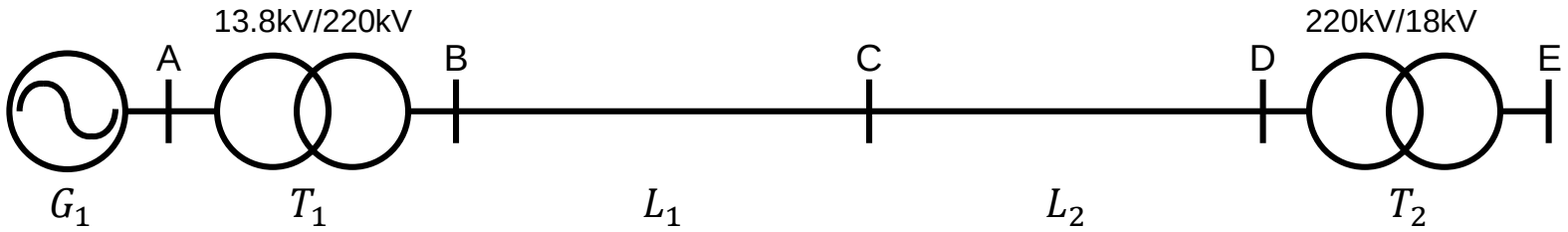


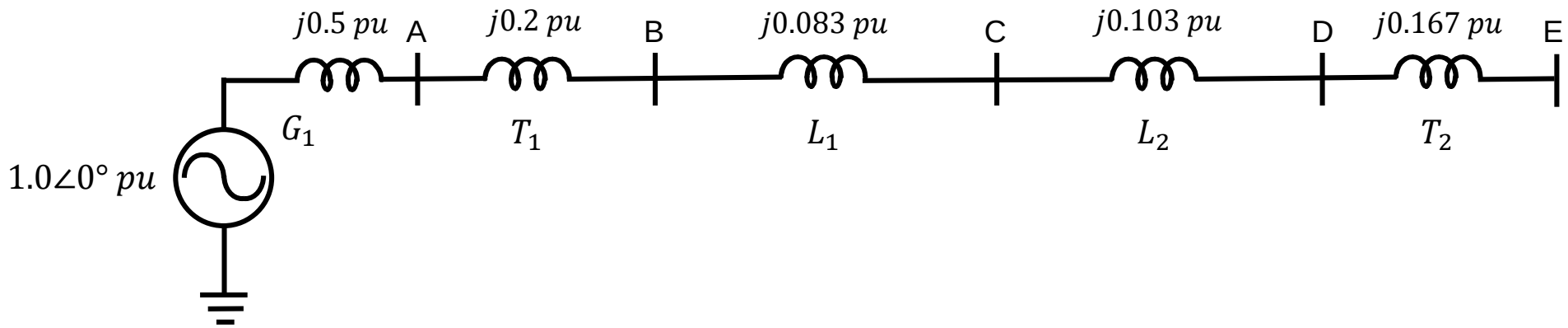
Component	Reactance (pu)
G_1	0.5
T_1	0.2
L_1	0.083
L_2	0.103
T_2	0.167

- All impedances are in per unit on a 50 MVA basis
- Resistances and shunt admittances are neglected
- No loads on the system
- All voltages are at nominal value

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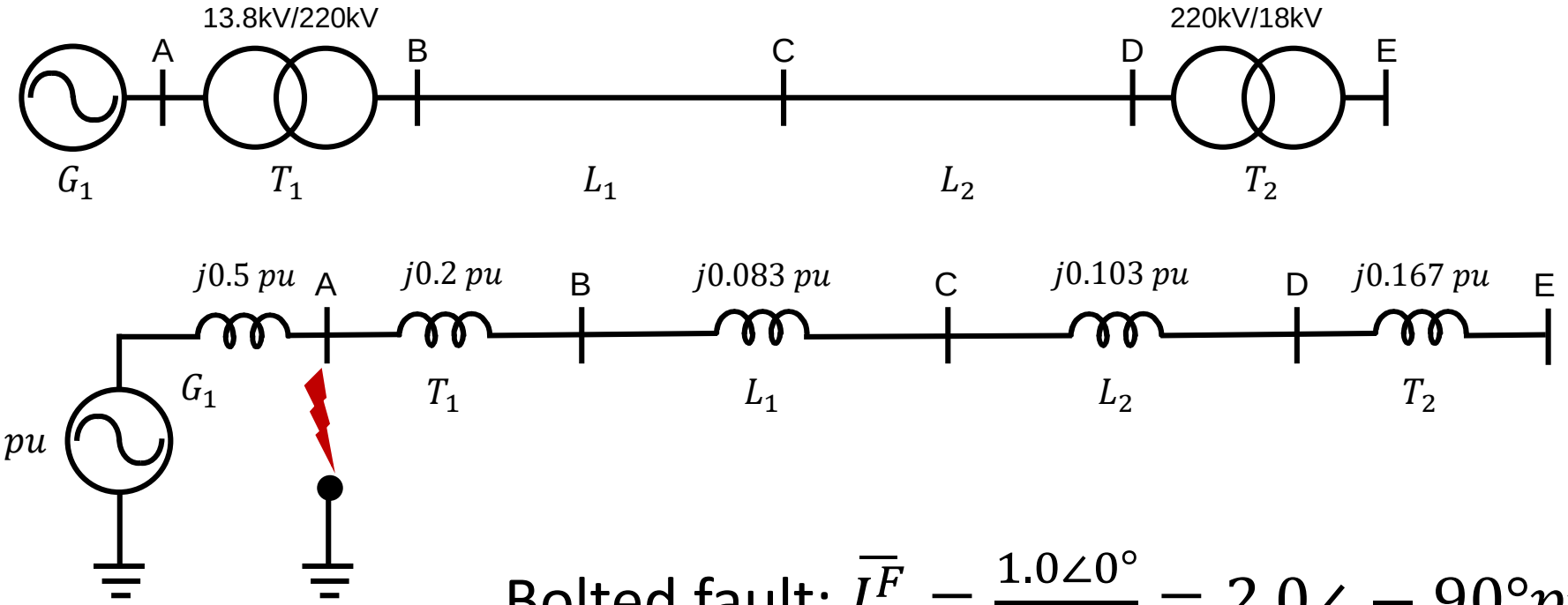
Example 9.1: System with one source





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Example 9.1: Fault at bus A

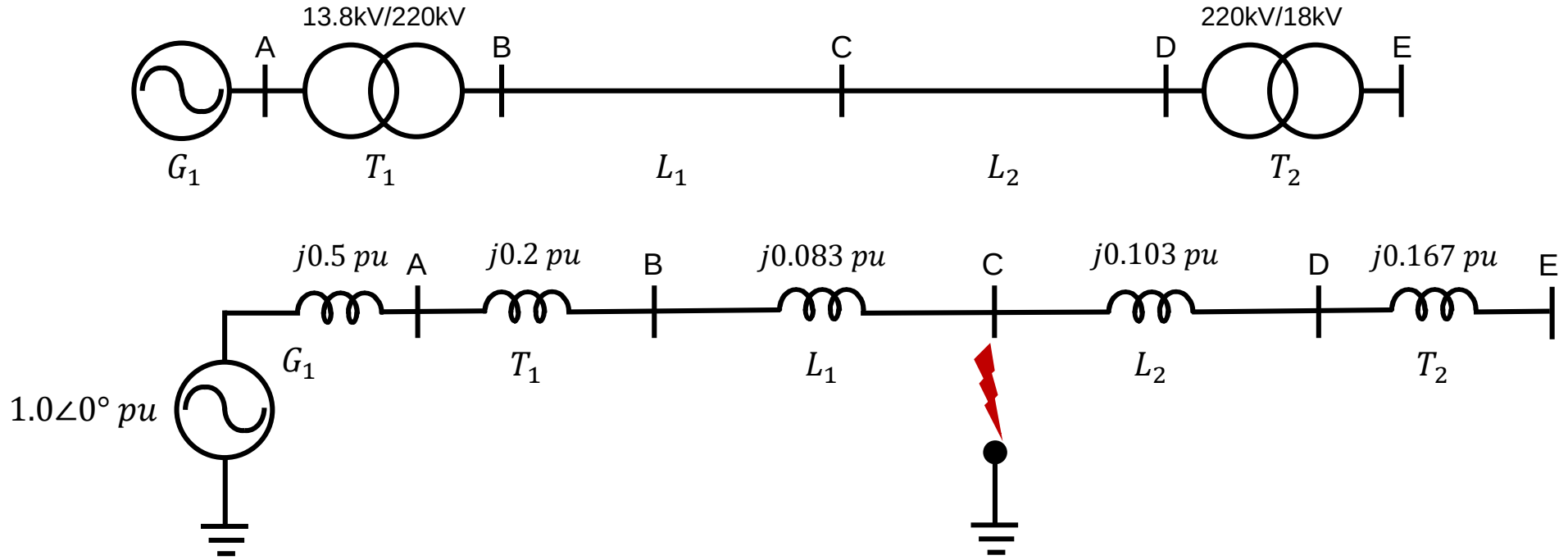


Bolted fault: $\overline{I_A^F} = \frac{1.0\angle 0°}{j0.5} = 2.0\angle -90°pu$

Fault with arc resistance R_f: $\overline{I_A^F} = \frac{1.0\angle 0°}{R_f + j0.5}$

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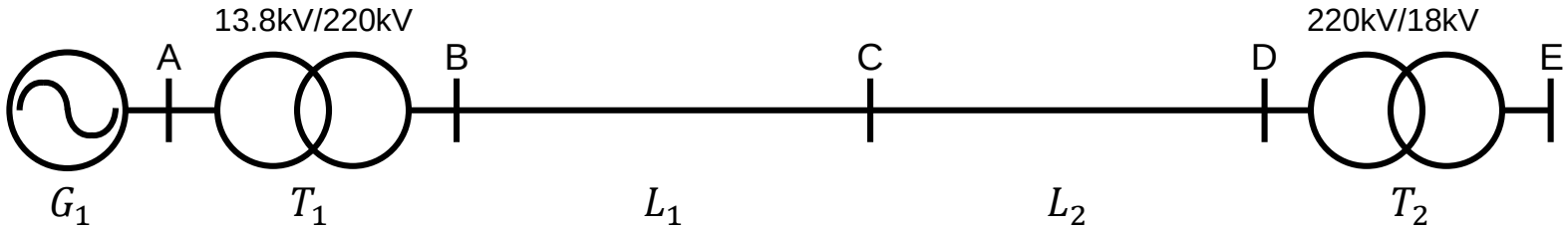
Example 9.1: Bolted fault at bus C



$$\overline{I_C^F} = \frac{1.0\angle 0°}{j0.5 + j0.2 + j0.083} = 1.28\angle -90° pu$$

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Example 9.1: Fault currents in amperes



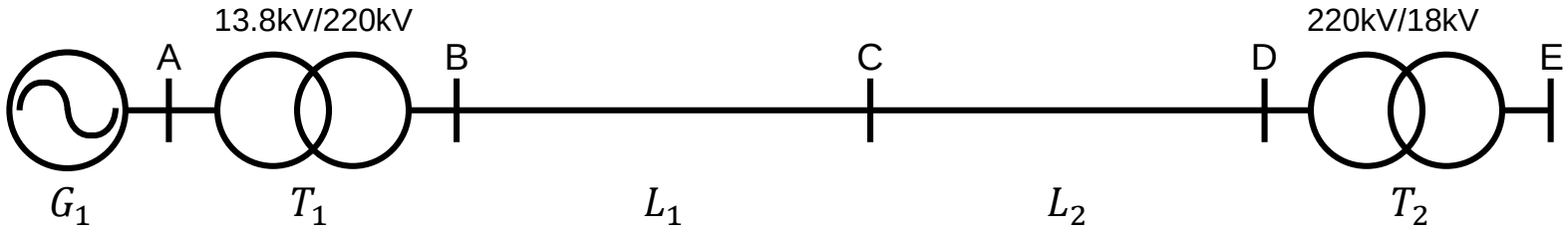
$$I_B = \frac{S_B}{\sqrt{3}V_B^{LL}}$$

Bus	A	B	C	D	E
$\lvert I_F \rvert$ (pu)	2.0	1.43	1.28	1.13	0.95
V_B (kV)	13.8	220	220	220	18
I_B (A)	2,092	131.2	131.2	131.2	1,604
$\lvert I_F \rvert$ (A)	4,184	188	168	148	1524

Fault current in Amps depends on the nominal voltage at the location of the fault

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Example 9.1: Short circuit level



$$SC = \sqrt{3} V_B I_F$$

Bus	A	B	C	D	E
$\lvert I_F \rvert$ (pu)	2.0	1.43	1.28	1.13	0.95
V_B (kV)	13.8	220	220	220	18
I_B (A)	2,092	131.2	131.2	131.2	1,604
$\lvert I_F \rvert$ (A)	4,184	188	168	148	1524
SC (MVA)	100	71.5	64	56.5	47.5

Convenient way of comparing the severity of faults at different voltage levels

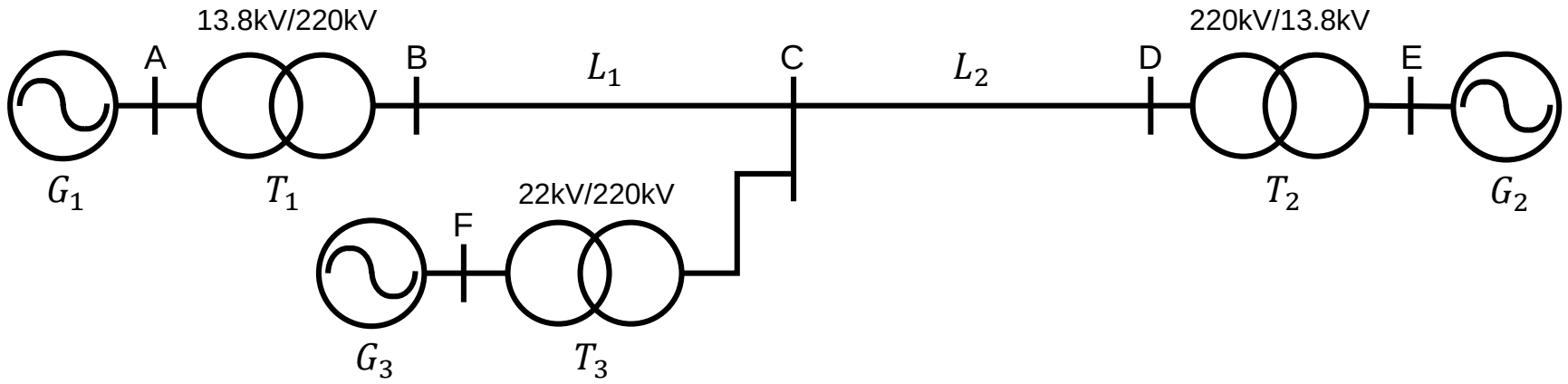
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Short circuit level

- Units of SC is MVA
- Does NOT represent the power dissipated in a fault
- Power dissipate in a fault is zero if $R_f = 0$
- Large SC level:
  - Small impedance between source and fault location
  - Large fault current
  - Normal load current causes a small voltage drop
- Small SC level
  - Large impedance between source and fault location
  - Small fault current
  - Normal load current causes a large voltage drop
- Good power system design requires balancing these requirements

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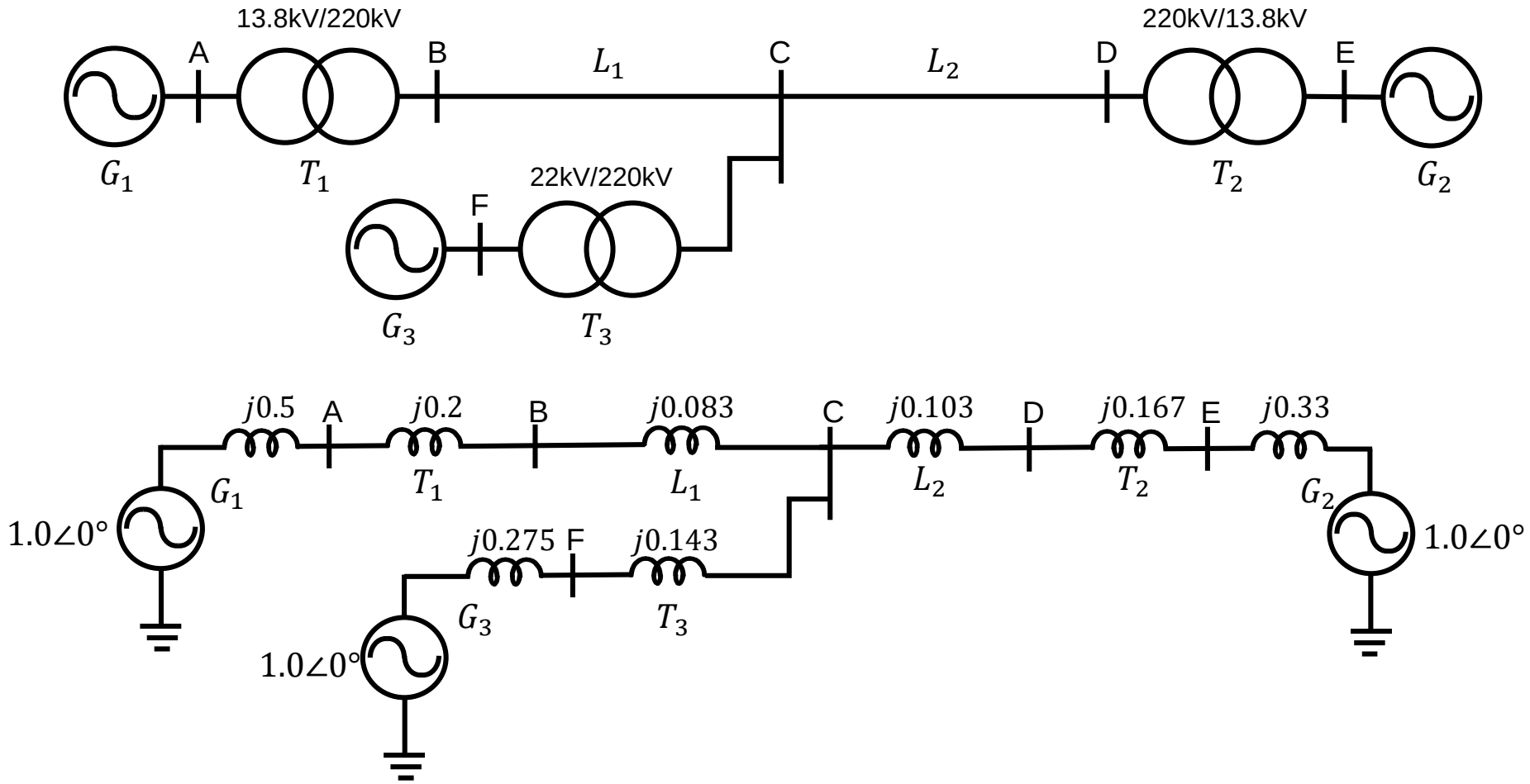
Example 9.2: System with multiple sources



- Assumptions:
  - No loads in the system
  - No currents flowing before the fault
  - All voltages (including internal emfs) at nominal value (1.0 pu)

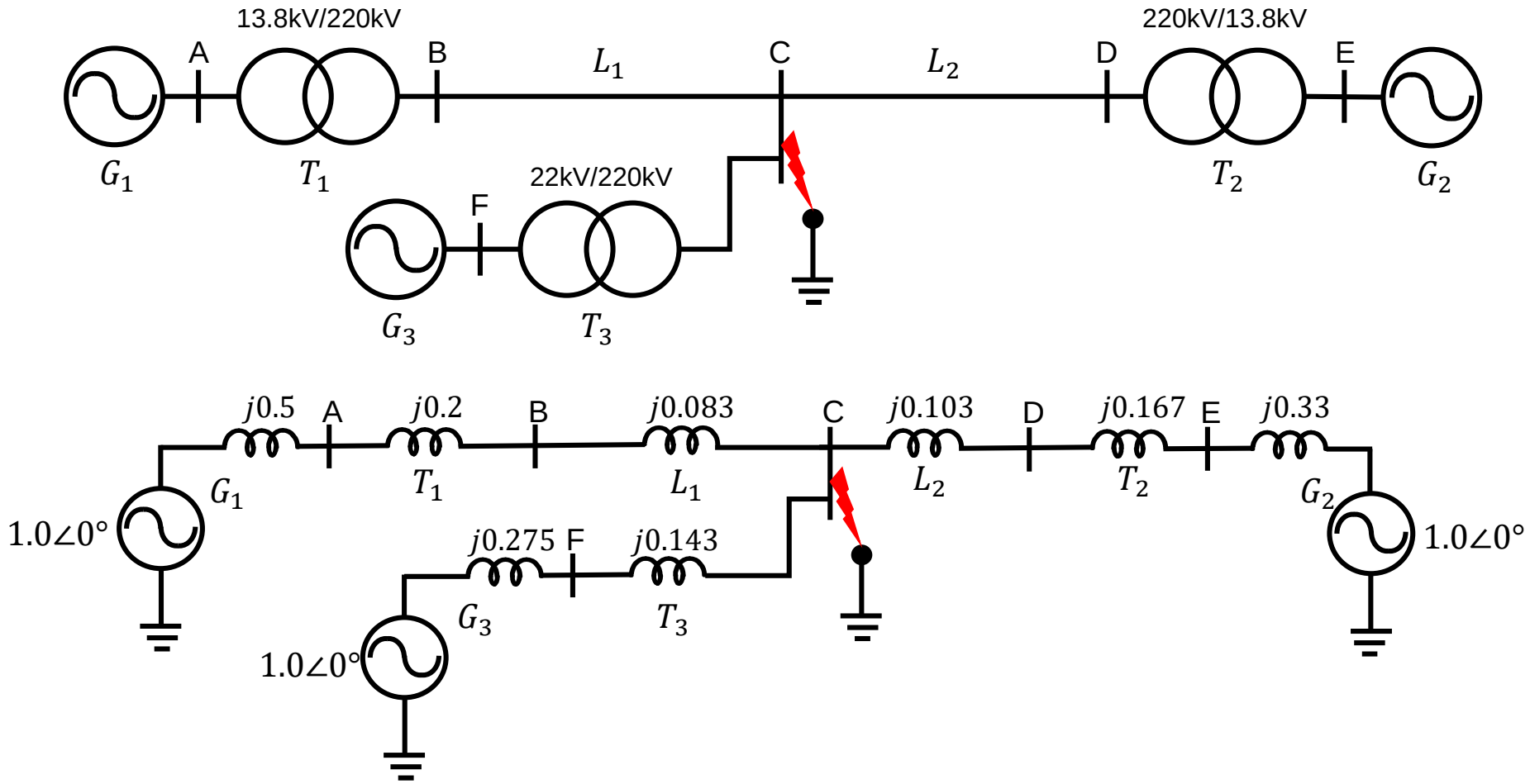
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Example 9.2: System with multiple sources



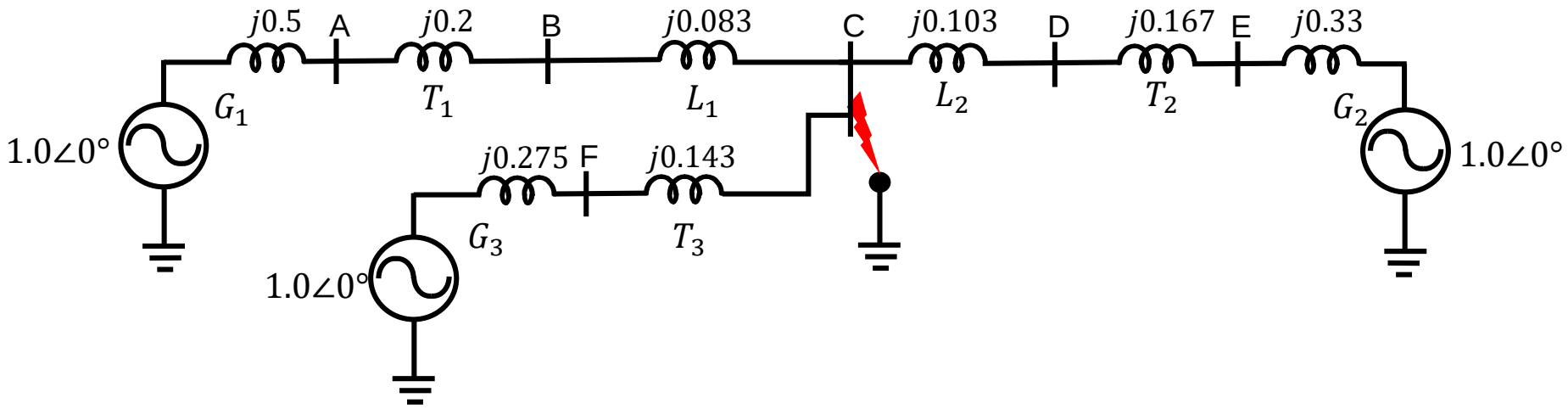
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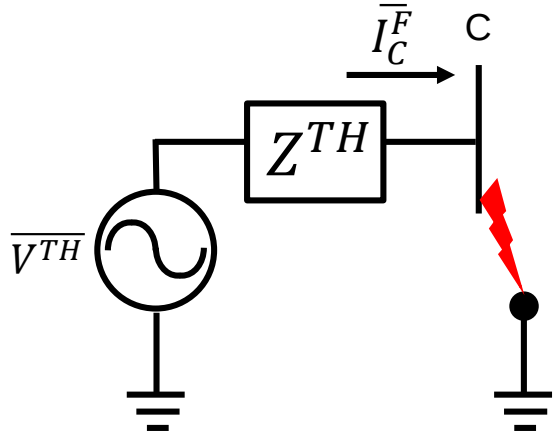
Example 9.2: Fault at bus C



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Example 9.2: Fault at bus C



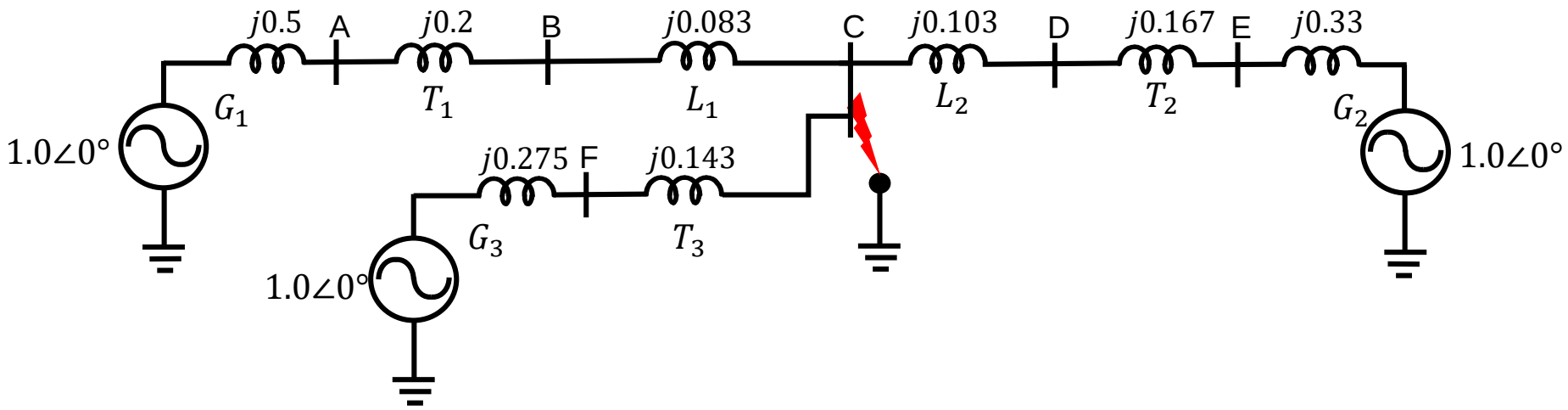


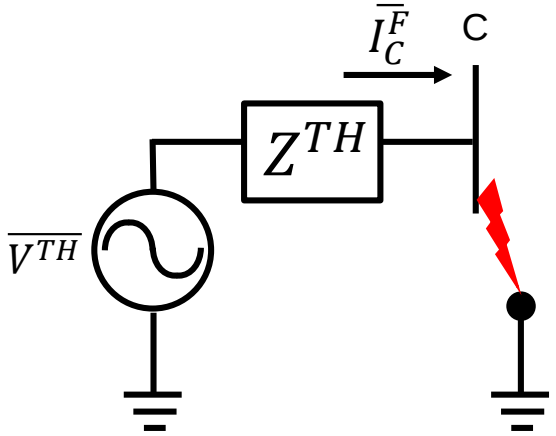
$$\overline{V_C^{TH}} = 1.0\angle 0° p.u.$$

$$Z_C^{TH} = ?$$

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Example 9.2: Fault at bus C





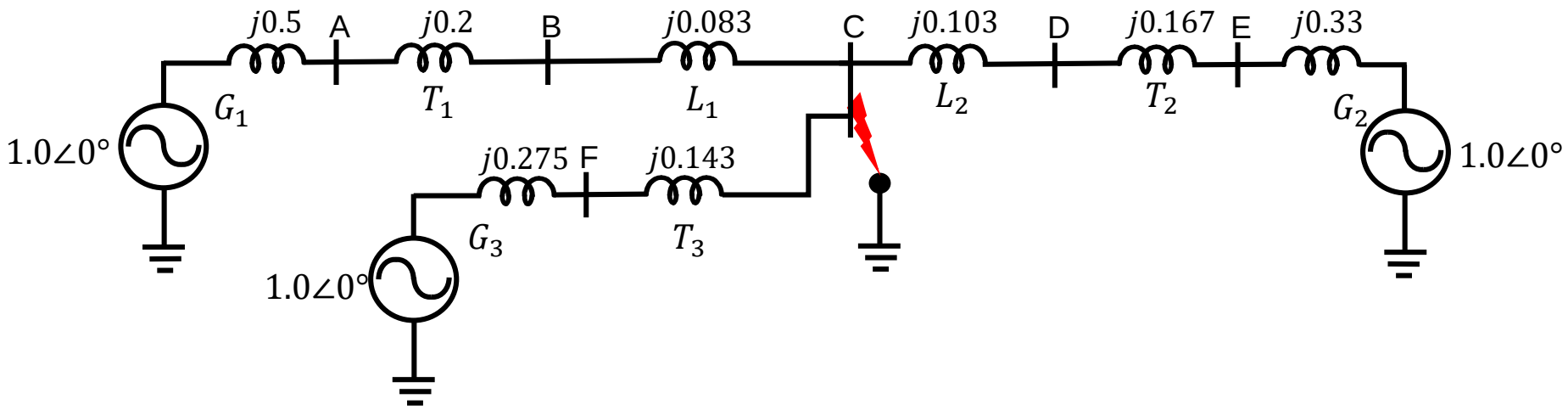
$$\overline{V_C^{TH}} = 1.0\angle 0° p.u.$$

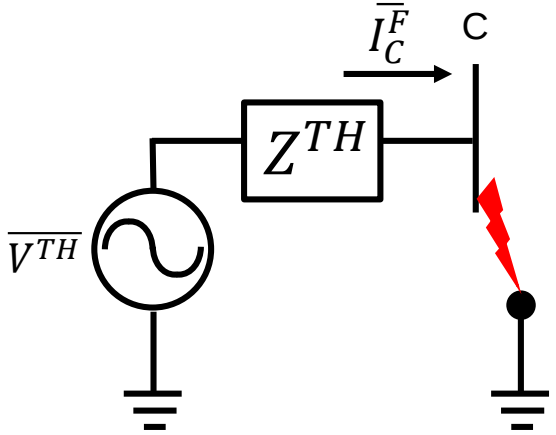
$$Z_C^{TH} = j(0.33 + 0.167 + 0.103) \parallel j(0.5 + 0.2 + 0.083) \parallel j(0.275 + 0.143)$$

$$= j0.187\ p.u.$$

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Example 9.2: Fault at bus C





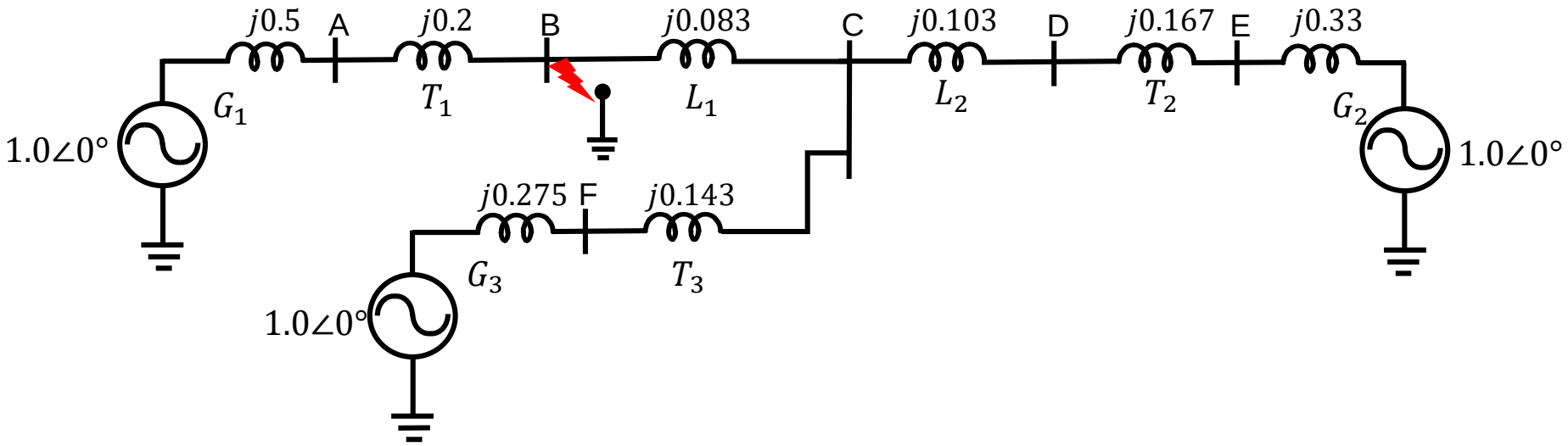
$$\overline{V_C^{TH}} = 1.0\angle 0° p.u.$$

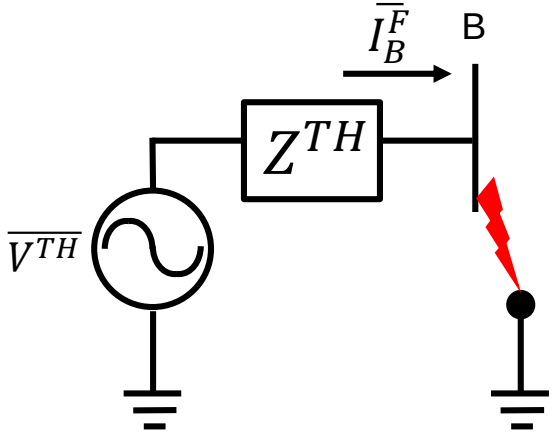
$$Z_C^{TH} = j0.187\ p.u.$$

$$\overline{I_C^F} = \frac{\overline{V_C^{TH}}}{Z_C^{TH}} = \frac{1.0\angle 0°}{j0.187} = 5.348\angle -90° p.u.$$

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Example 9.2: Fault at bus B



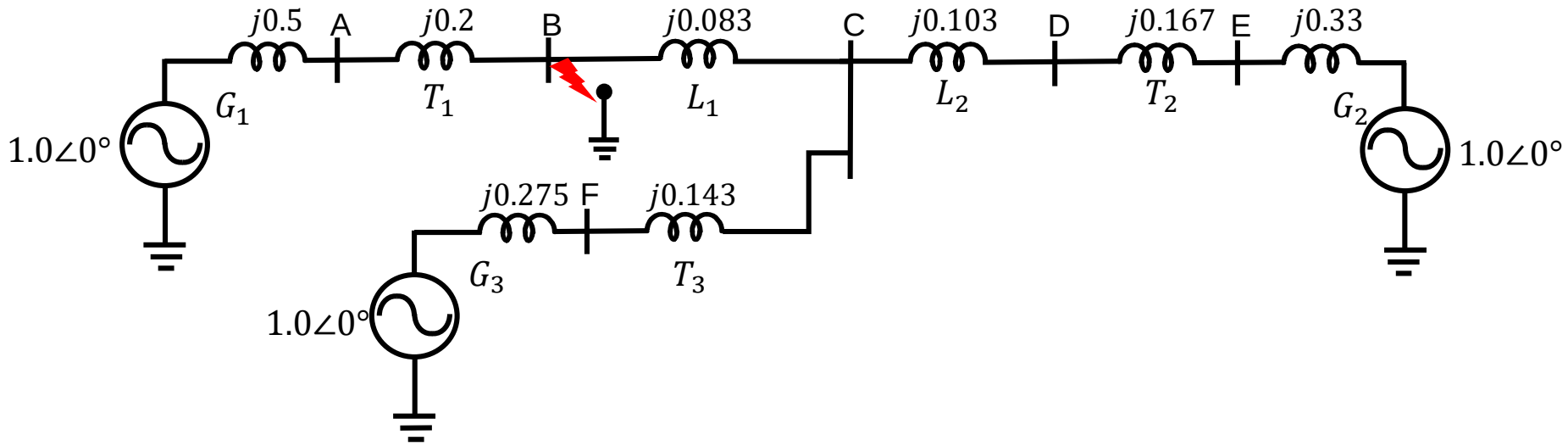


$$\overline{V_B^{TH}} = 1.0\angle 0° p.u.$$

$$Z_B^{TH} = ?$$

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Example 9.2: Fault at bus B



$$\overline{V_B^{TH}} = 1.0\angle 0°p.u.$$

$$Z_B^{TH} = j(0.5 + 0.2) \parallel \{j0.083 + [j(0.275 + 0.143) \parallel j(0.33 + 0.167 + 0.103)]\} = j0.224\,pu$$

$$\overline{I_B^F} = \frac{\overline{V_B^{TH}}}{Z_B^{TH}} = \frac{1.0\angle 0°}{j0.224} = 4.465\angle -90°p.u.$$

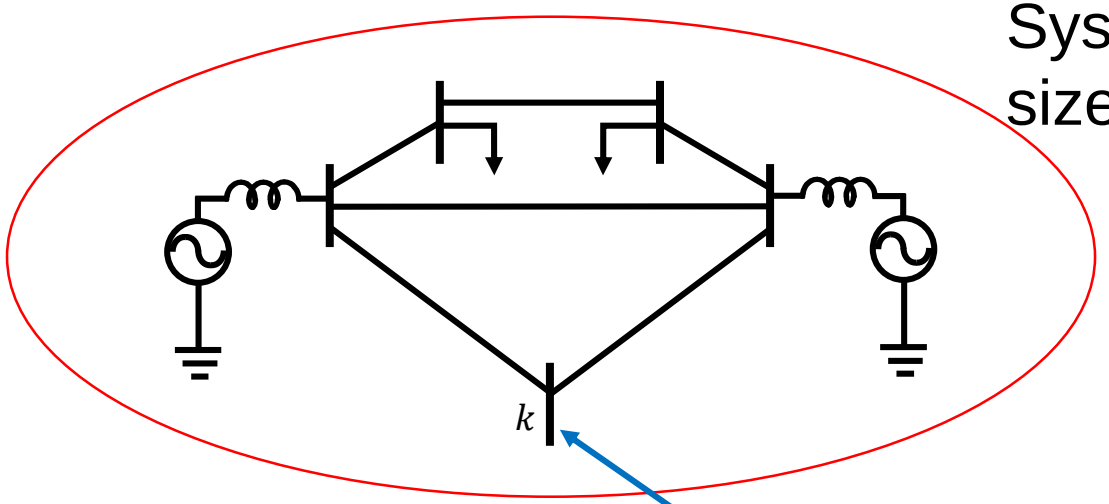
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Balanced fault calculations in large systems

- Goals:
  - Develop a systematic and scalable technique for computing fault currents
  - Remove simplifying assumptions
    - No loads in the system
    - All voltages are at nominal value
- Approach:
  - Thevenin equivalent
  - Superposition theorem

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Balanced fault calculations in large systems

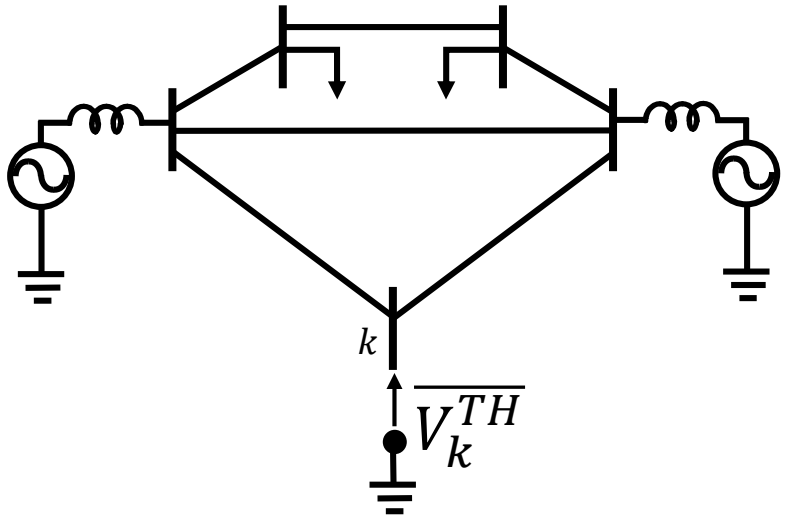


System of arbitrary size and complexity

Bus where we want to calculate the fault current

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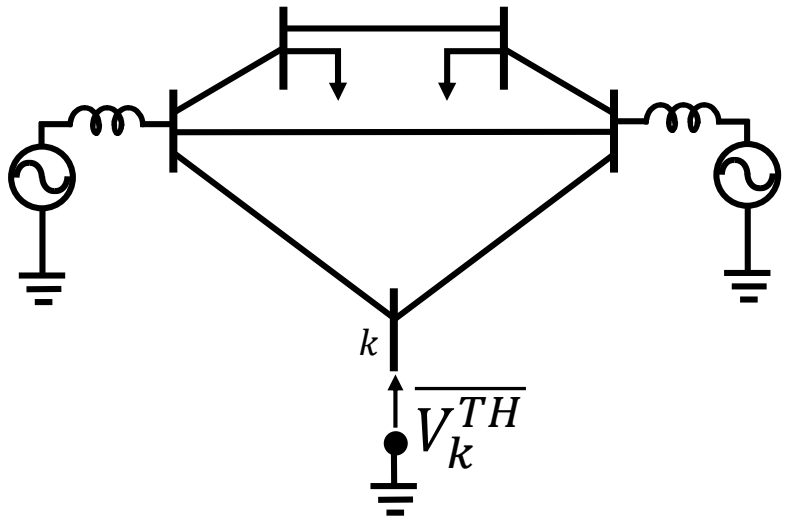
Pre-fault conditions

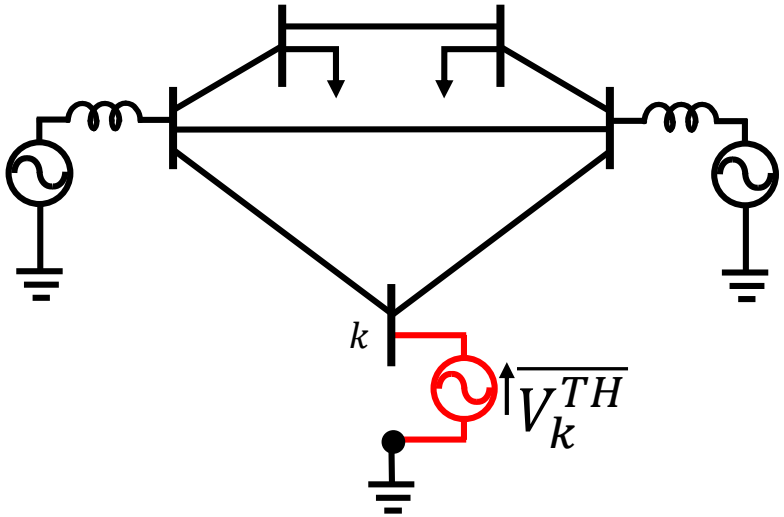


Run a power flow to calculate $\overline{V_k^{TH}}$

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Pre-fault conditions

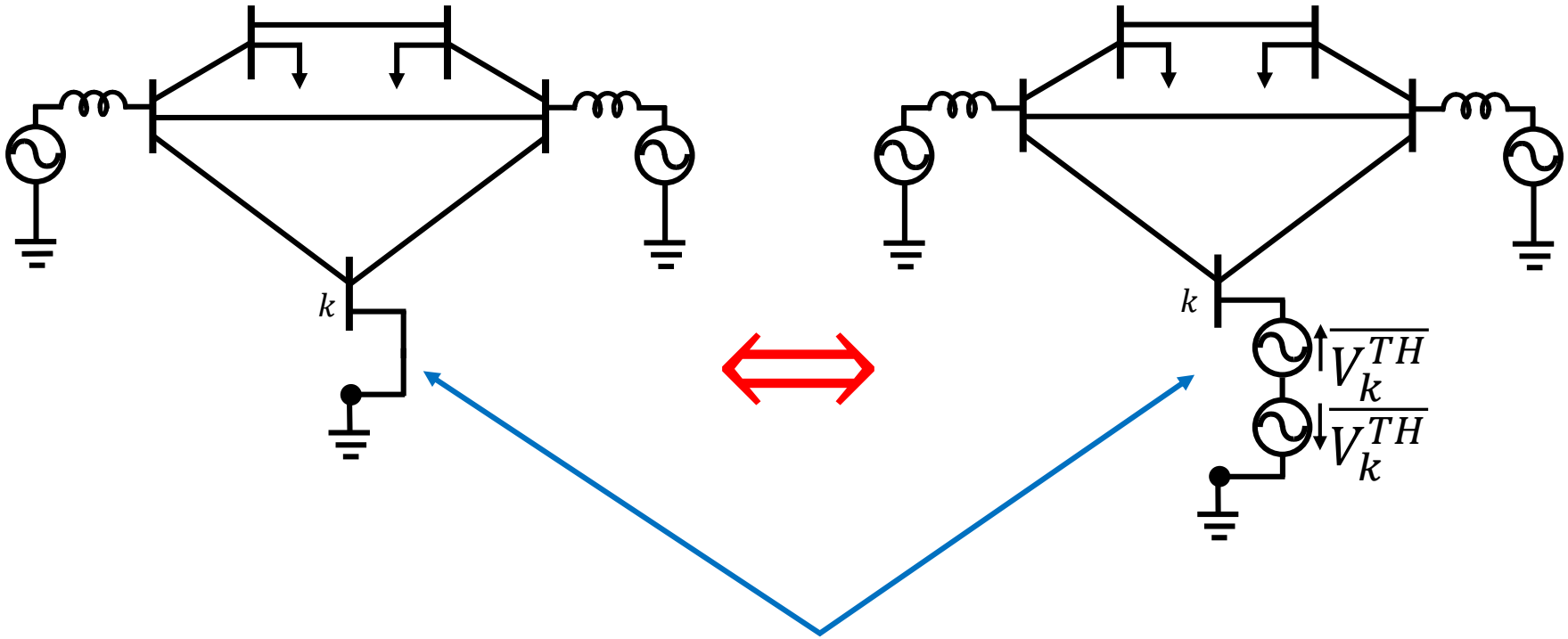




- Imagine that we add a voltage source of $\overline{V_k^{TH}}$ at bus k
- Adding this voltage source does not change the pre-fault flows or voltages in any way
- No current flows through the additional voltage source $\overline{V_k^{TH}}$

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Modeling a bolted balanced fault at bus k



Voltage at bus k is zero

The two representation of the fault are equivalent

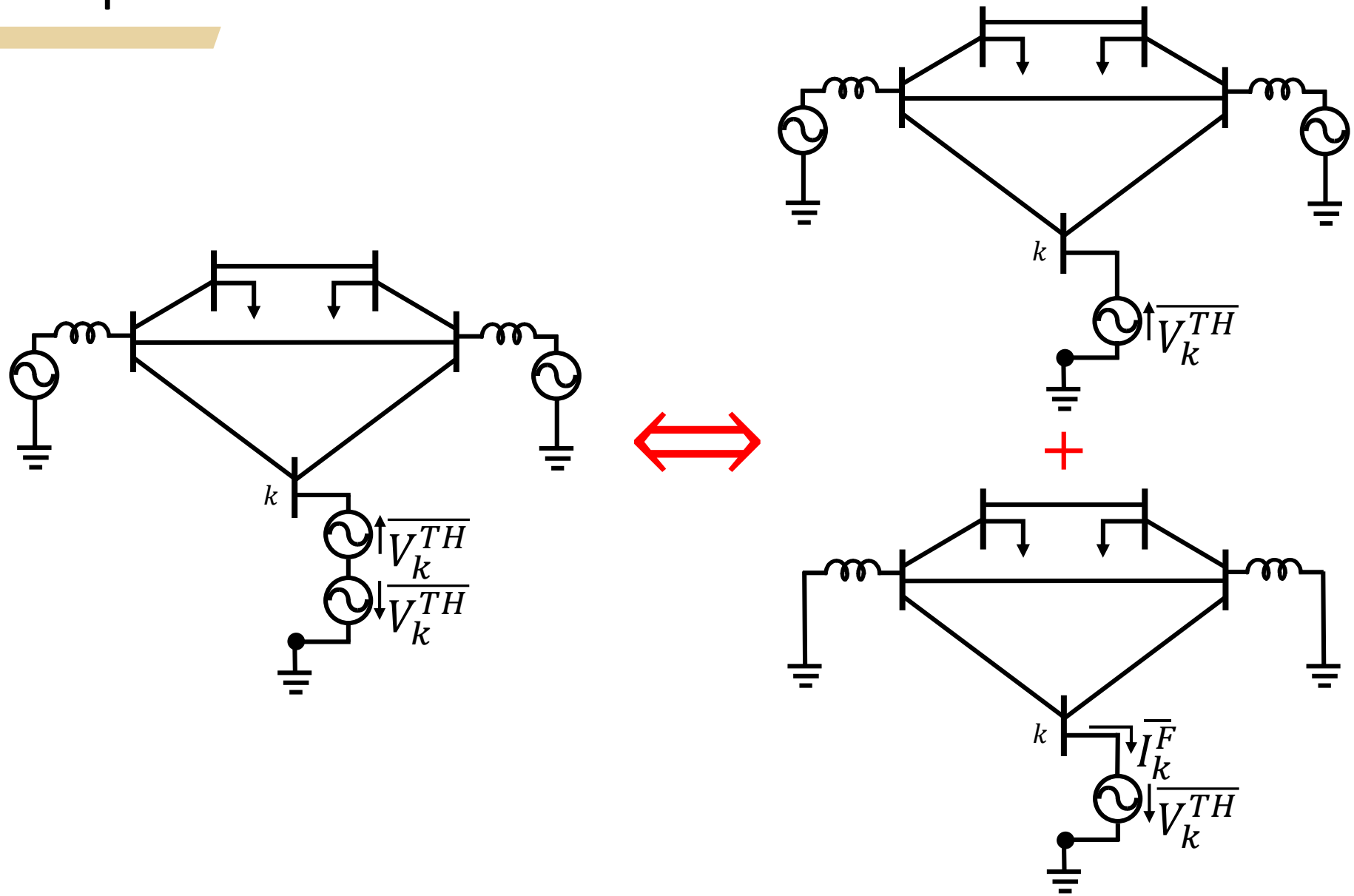
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Superposition theorem

- From circuit theory:
- A linear circuit with multiple sources can be analyzed by calculating the voltages and currents resulting from each source acting separately
- The combined effects of all the sources can then be calculated by adding the voltages and currents produced by each sources taken separately

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Superposition theorem

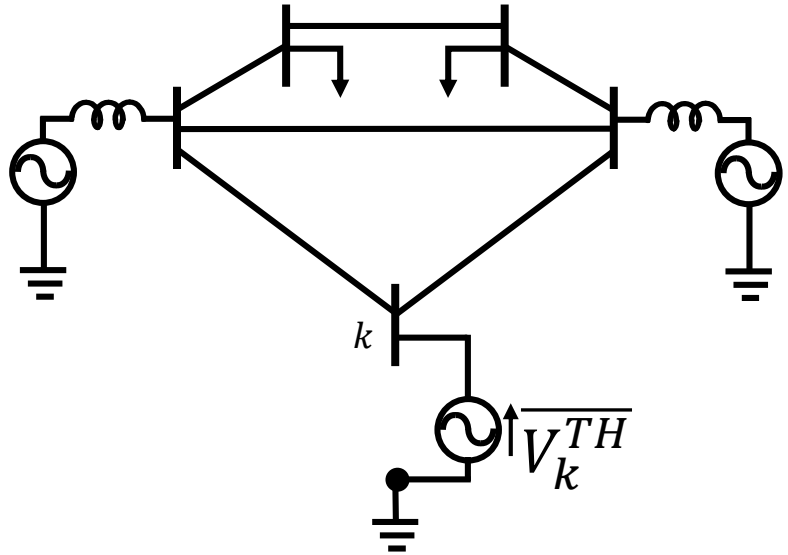


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Superposition theorem

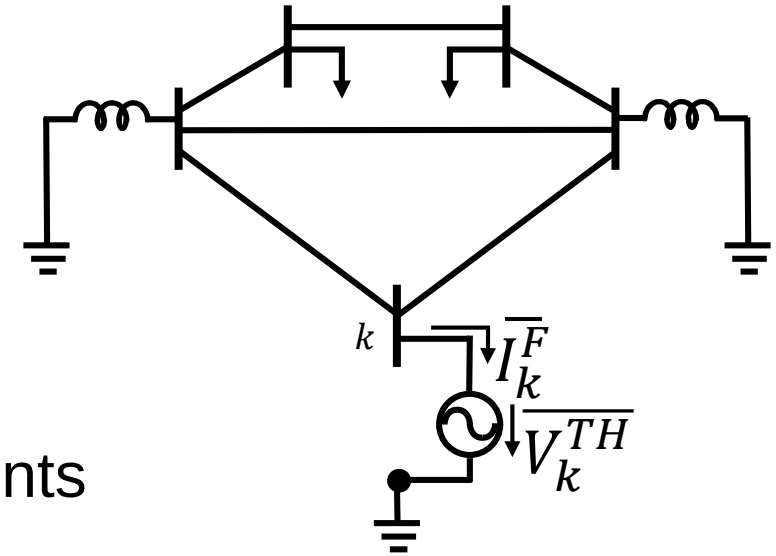
Pre-fault conditions:

No current flows through the additional voltage source $\overline{V_k^{TH}}$.
Normal load currents in the rest of the network.



Fault conditions:

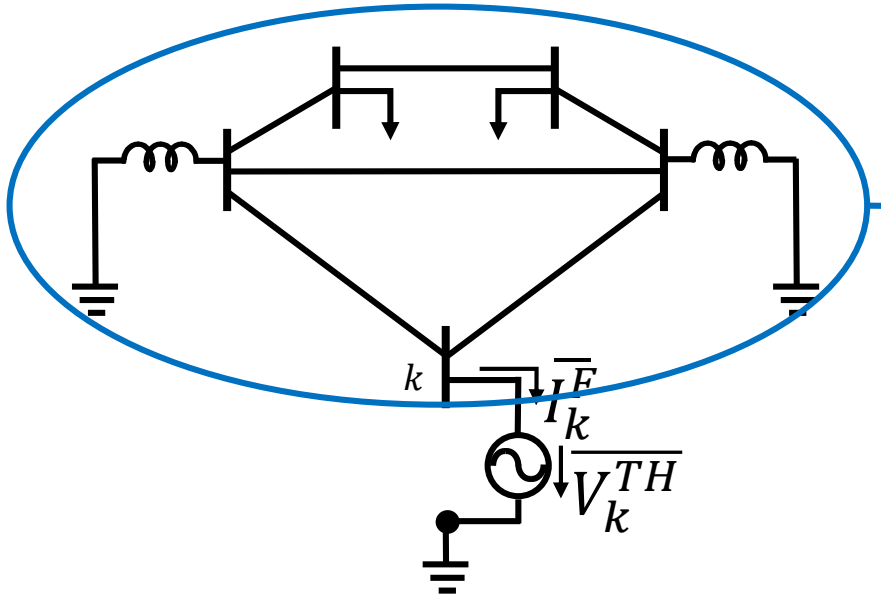
Fault current $\overline{I_k^F}$ flows driven by voltage source $-\overline{V_k^{TH}}$ at bus k.



Fault currents usually >> load currents

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Calculating the fault currents



Replace by an equivalent (i.e., Thevenin) impedance

Need a technique that scales up to any size network

Nodal analysis

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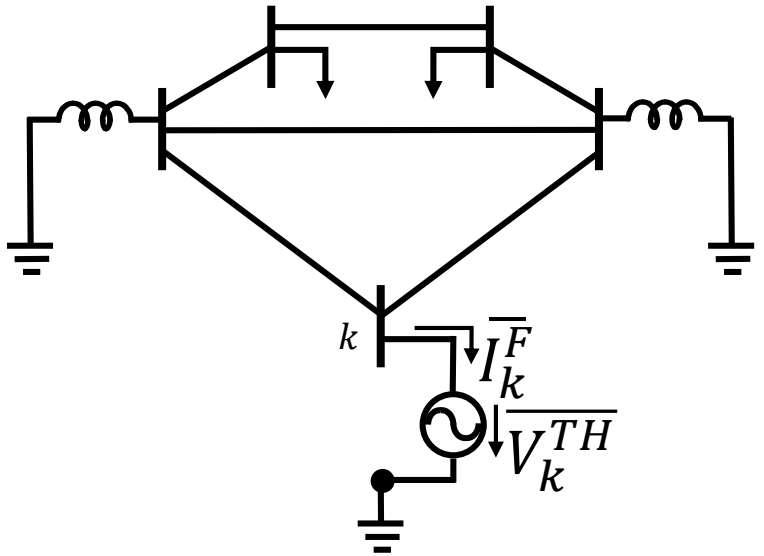
Calculating the fault currents

$$YV = I$$

Y: Admittance matrix

V: Vector of nodal voltages

I: Vector of injected currents



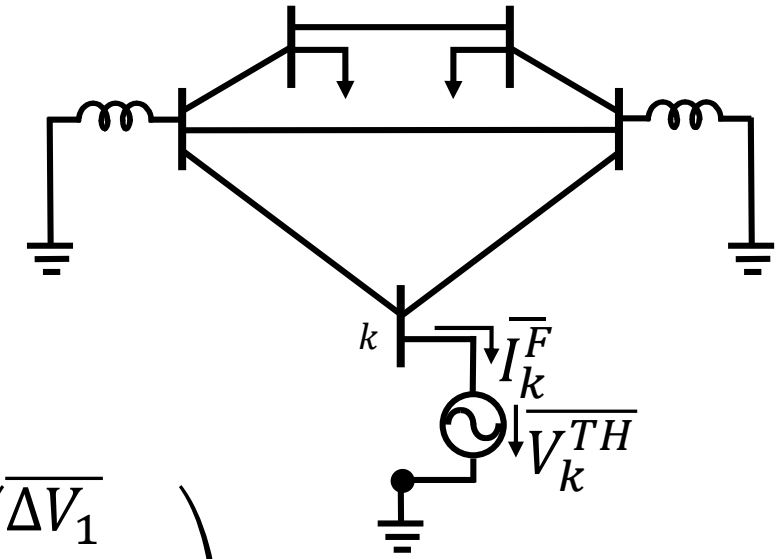
$$Y.\begin{pmatrix} \overline{\Delta V_1} \\ \vdots \\ -\overline{V_k^{TH}} \\ \vdots \\ \overline{\Delta V_n} \end{pmatrix} = \begin{pmatrix} 0 \\ \vdots \\ -\overline{I_k^F} \\ \vdots \\ 0 \end{pmatrix}$$

$-\overline{I_k^F}$ is the only injected current

$\overline{\Delta V_j}$: change in voltage at bus j due to fault current

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Calculating the fault currents



$$Y.\begin{pmatrix} \overline{\Delta V_1} \\ \vdots \\ -\overline{V_k^{TH}} \\ \vdots \\ \overline{\Delta V_n} \end{pmatrix} = \begin{pmatrix} 0 \\ \vdots \\ -\overline{I_k^F} \\ \vdots \\ 0 \end{pmatrix} \qquad Z = Y^{-1} \Rightarrow \qquad Z.\begin{pmatrix} 0 \\ \vdots \\ -\overline{I_k^F} \\ \vdots \\ 0 \end{pmatrix} = \begin{pmatrix} \overline{\Delta V_1} \\ \vdots \\ -\overline{V_k^{TH}} \\ \vdots \\ \overline{\Delta V_n} \end{pmatrix}$$

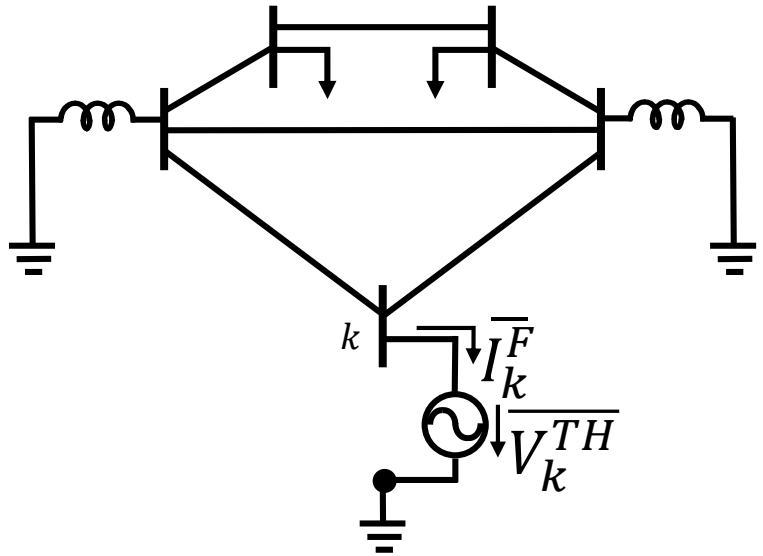
Z: impedance matrix of the circuit

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Calculating the fault currents

Consider row k of this equation:

$$Z.\begin{pmatrix} 0 \\ \vdots \\ -\overline{I_k^F} \\ \vdots \\ 0 \end{pmatrix} = \begin{pmatrix} \overline{\Delta V_1} \\ \vdots \\ -\overline{V_k^{TH}} \\ \vdots \\ \overline{\Delta V_n} \end{pmatrix}$$



$$Z_{kk}\,(-\overline{I_k^F}) = -\overline{V_k^{TH}}$$

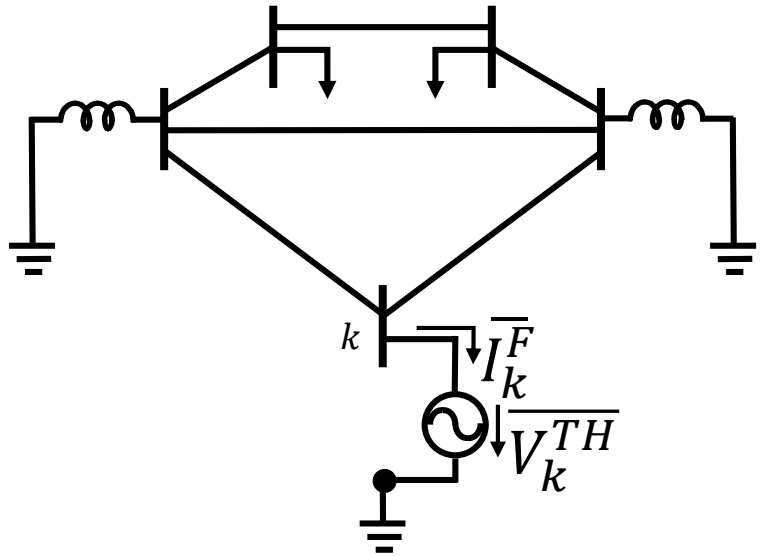
Z_{kk}: diagonal element (k,k) of Z

$$\overline{I_k^F} = \frac{\overline{V_k^{TH}}}{Z_{kk}}$$

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What happens to the voltage at the other buses?

$$Z.\begin{pmatrix} 0 \\ \vdots \\ -\overline{I_k^F} \\ \vdots \\ 0 \end{pmatrix} = \begin{pmatrix} \overline{\Delta V_1} \\ \vdots \\ -\overline{V_k^{TH}} \\ \vdots \\ \overline{\Delta V_n} \end{pmatrix} \qquad \overline{I_k^F} = \frac{\overline{V_k^{TH}}}{Z_{kk}}$$



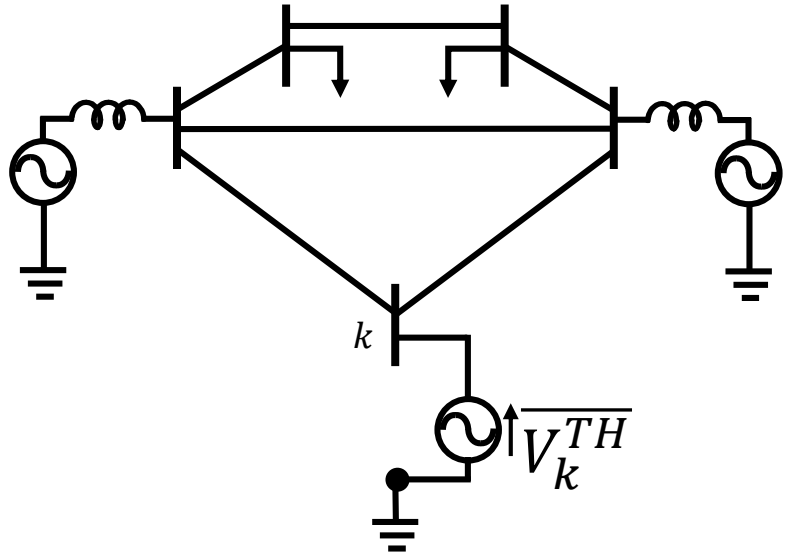
Other rows of this equation:

$$\overline{\Delta V_i} = -Z_{ik}\overline{I_k^F} = -\frac{Z_{ik}}{Z_{kk}}\overline{V_k^{TH}} \qquad i = 1, \cdots n \quad i \neq k$$

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What happens to the voltage at the other buses?

$\overline{V_i^{pre}}$

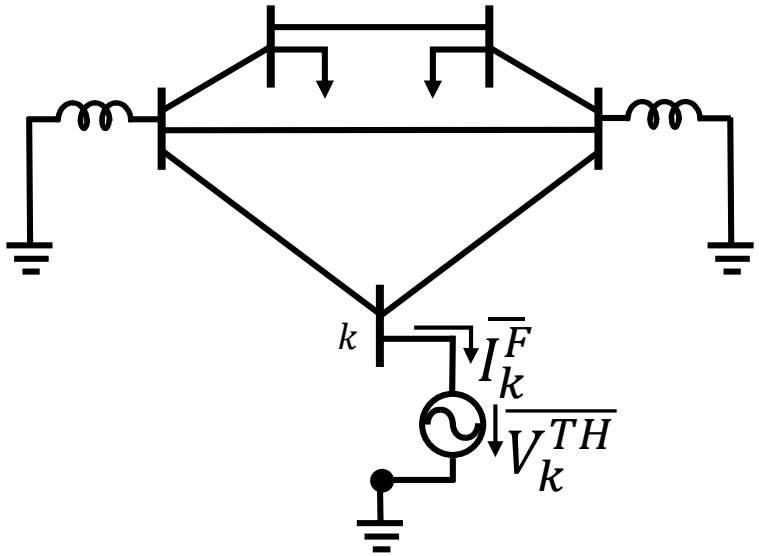


$$\overline{V_i^F} = \overline{V_i^{pre}} + \overline{\Delta V_i} = \overline{V_i^{pre}} - \frac{Z_{ik}}{Z_{kk}}\overline{V_k^{TH}}$$

$$i = 1, \cdots n$$

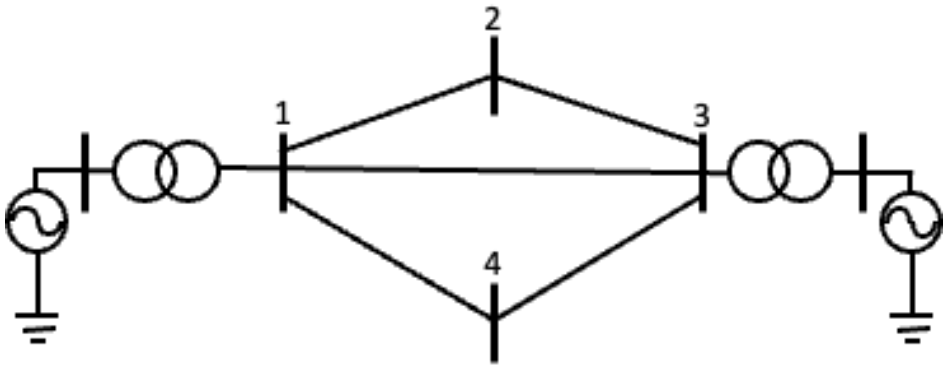
+

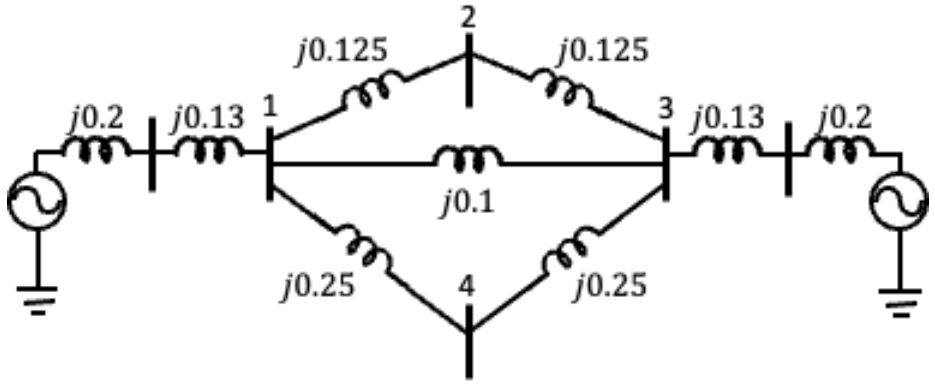
$\overline{\Delta V_i}$



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Example 9.3: Fault calculation using the impedance matrix



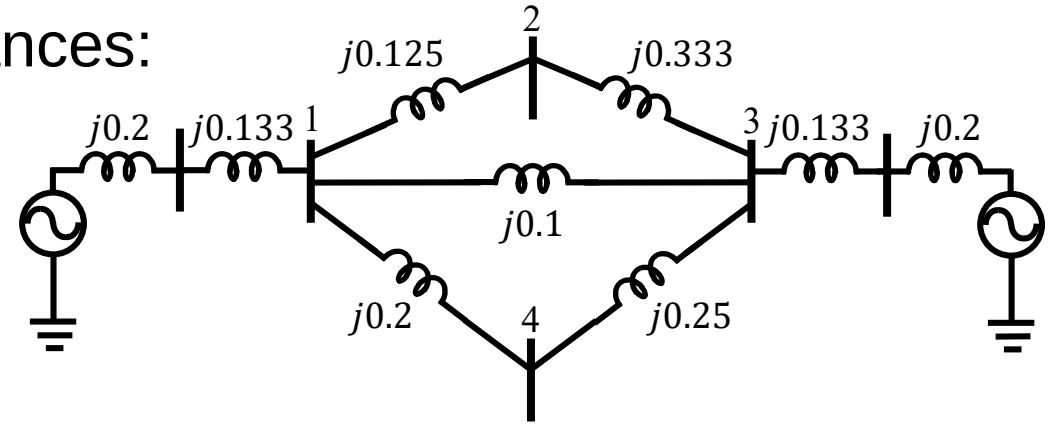


Calculate the fault current for a bolted, three-phase fault at bus 2. Neglect loads and assume nominal voltage at all buses.

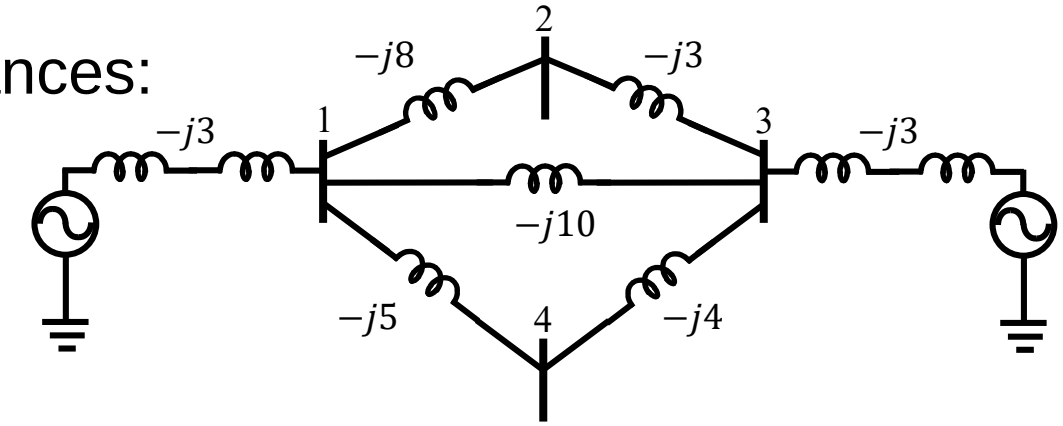
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Example 9.3 : Fault calculation using the impedance matrix

Impedances:



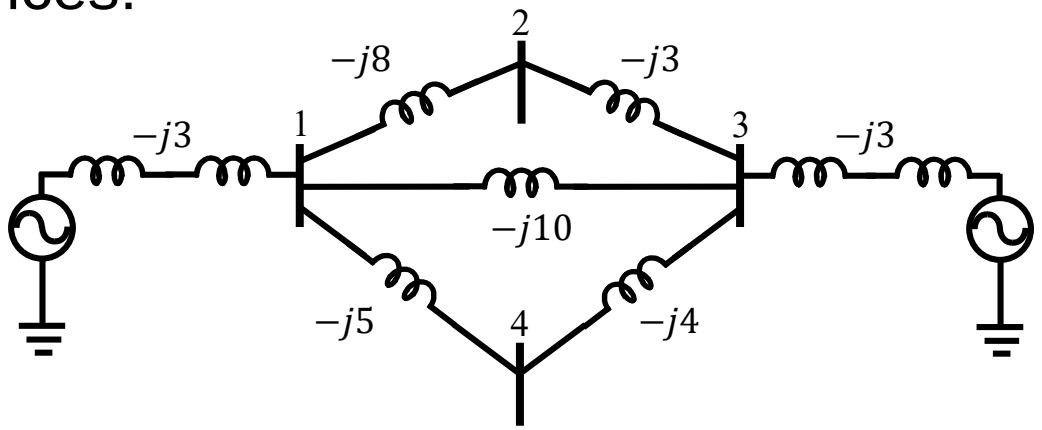
Admittances:



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Example 9.3 : Fault calculation using the impedance matrix

Admittances:



$$Y = \begin{pmatrix} -j26 & j8 & j10 & j5 \\ j8 & -j11 & j3 & 0 \\ j10 & j3 & -j20 & j4 \\ j5 & 0 & j4 & -j9 \end{pmatrix}$$

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Example 9.3

$$Y = \begin{pmatrix} -j26 & j8 & j10 & j5 \\ j8 & -j11 & j3 & 0 \\ j10 & j3 & -j20 & j4 \\ j5 & 0 & j4 & -j9 \end{pmatrix} = j\begin{pmatrix} -26 & 8 & 10 & 5 \\ 8 & -11 & 3 & 0 \\ 10 & 3 & -20 & 4 \\ 5 & 0 & 4 & -9 \end{pmatrix}$$

$$Z = Y^{-1} = j\begin{pmatrix} 0.182 & 0.174 & 0.151 & 0.168 \\ 0.174 & 0.261 & 0.160 & 0.167 \\ 0.151 & 0.160 & 0.182 & 0.165 \\ 0.168 & 0.167 & 0.165 & 0.278 \end{pmatrix}$$

Bolted, three-phase fault at bus 2:

$$\bar{I}_2^F = \frac{\overline{V_2^{TH}}}{Z_{22}} = \frac{1.0\angle 0°}{j0.261} = 3.83\angle -90° p.u.$$

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Example 9.3 : Fault calculation using the impedance matrix

$$Z = j\begin{pmatrix} 0.182 & 0.174 & 0.151 & 0.168 \\ 0.174 & 0.261 & 0.160 & 0.167 \\ 0.151 & 0.160 & 0.182 & 0.165 \\ 0.168 & 0.167 & 0.165 & 0.278 \end{pmatrix}$$

$$\overline{V_i^F} = \overline{V_i^{pre}} + \overline{\Delta V_i} = \overline{V_i^{pre}} - \frac{Z_{ik}}{Z_{kk}}\overline{V_k^{TH}}$$

$$\overline{V_i^{pre}} = 1.0\angle 0°\ p.u. \quad i = 1, \cdots 4$$

$$\overline{V_1^F} = 1.0\angle 0° - \frac{j0.174}{j0.261}1.0\angle 0° = 0.334\angle 0° p.u.$$

$$\overline{V_3^F} = 1.0\angle 0° - \frac{j0.160}{j0.261}1.0\angle 0° = 0.388\angle 0° p.u.$$

$$\overline{V_4^F} = 1.0\angle 0° - \frac{j0.167}{j0.261}1.0\angle 0° = 0.358\angle 0° p.u.$$

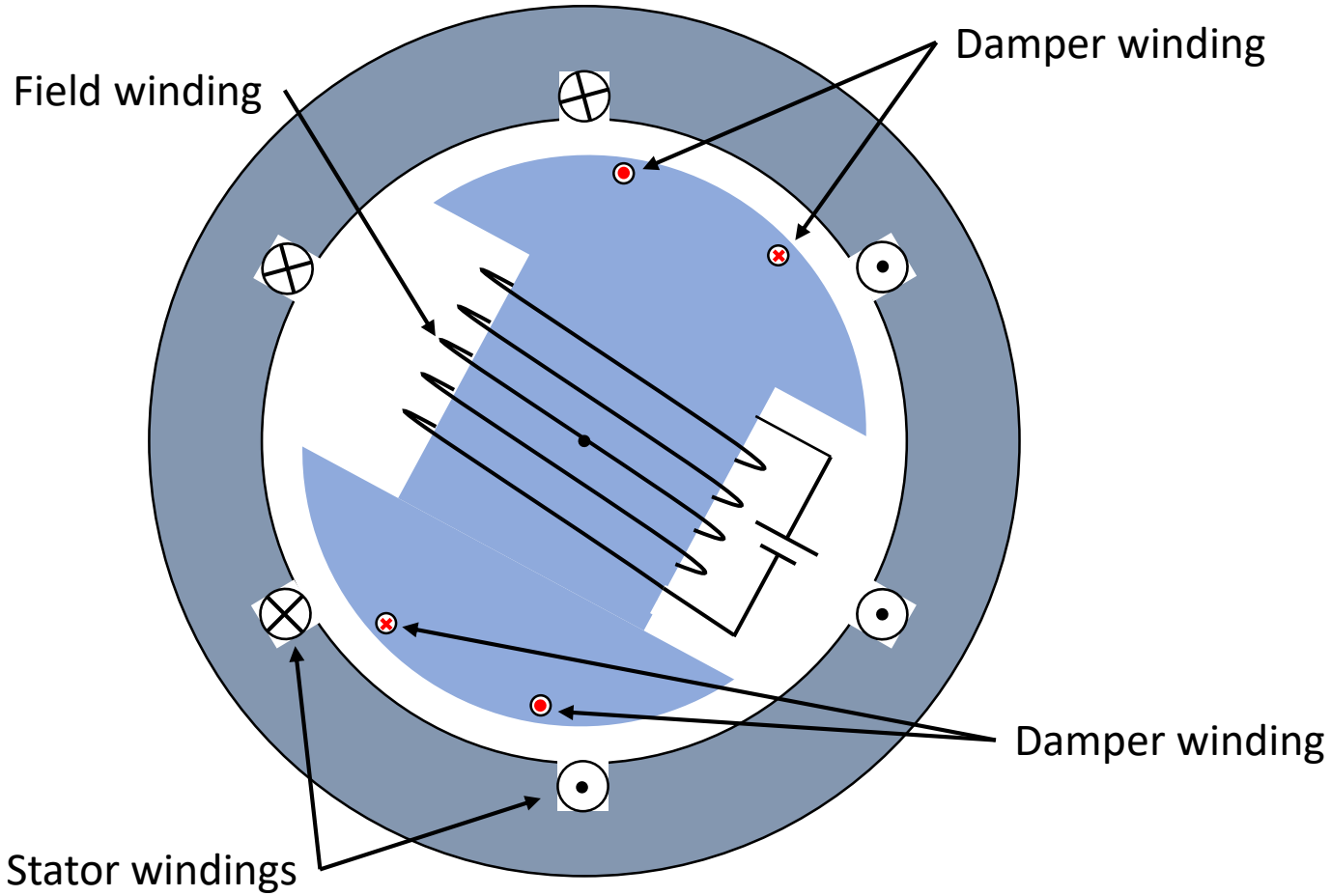
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Modeling generators for fault calculations

- So far, we have assumed that generators behaved like ideal voltage sources
- Need to enhance our generator model to reflect what happens when the stator current changes rapidly due to a fault
- Model what happens to the magnetic flux inside the generator

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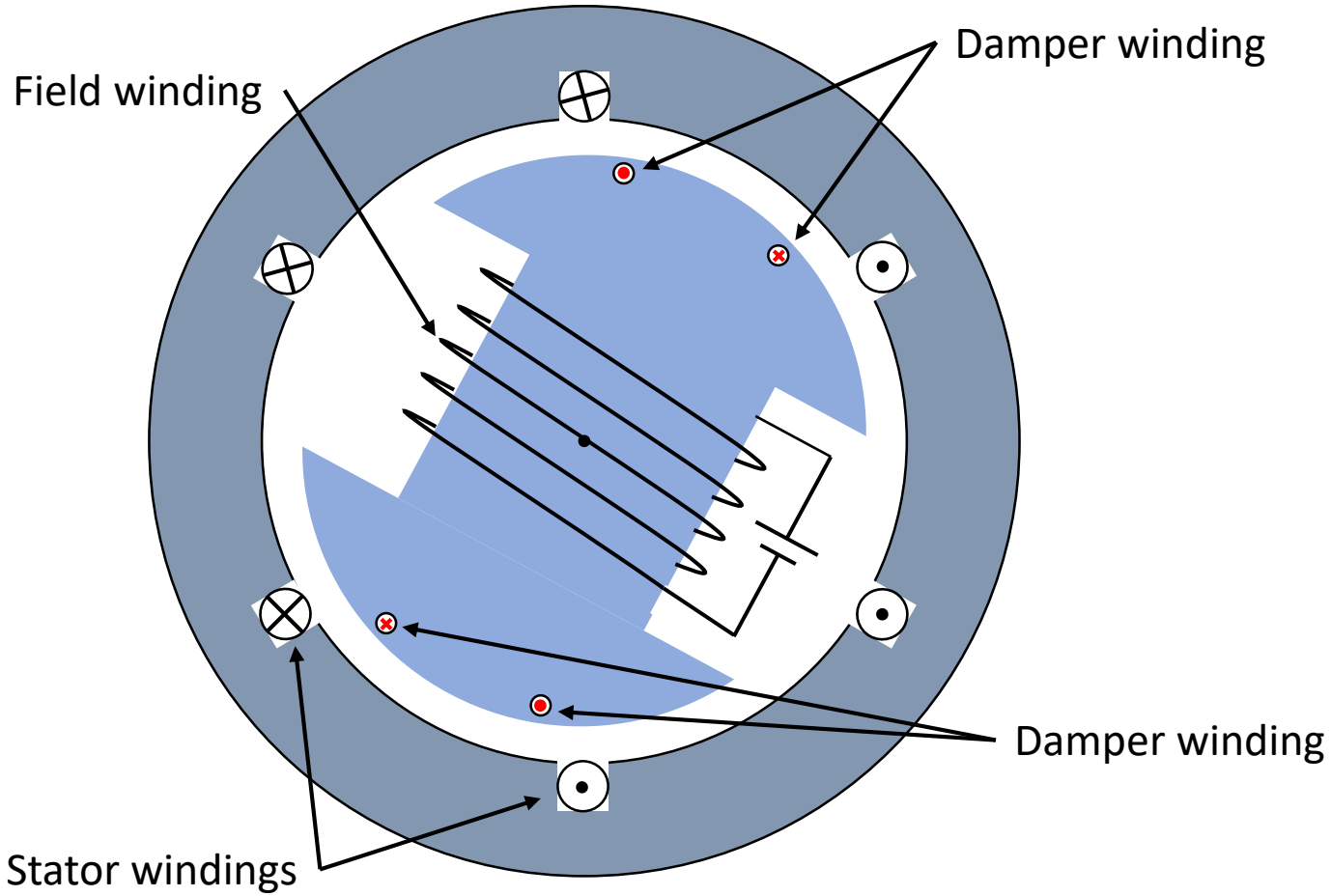
Damper windings



- Short circuit windings in the pole face
- No effect in the steady state
- Designed to dampen mechanical oscillations of the rotor

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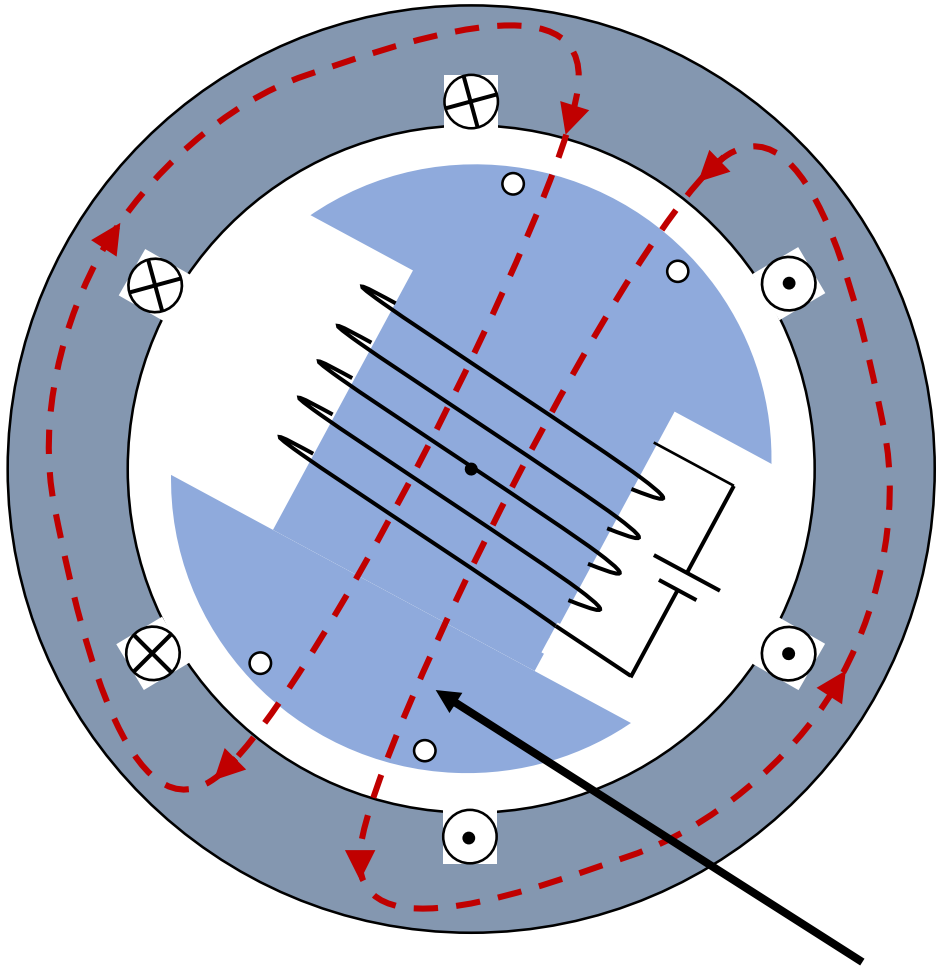
Magnetic coupling



- Stator, field, and damper windings are magnetically coupled
- Current flowing in each of these windings affects the magnetic flux in the other windings

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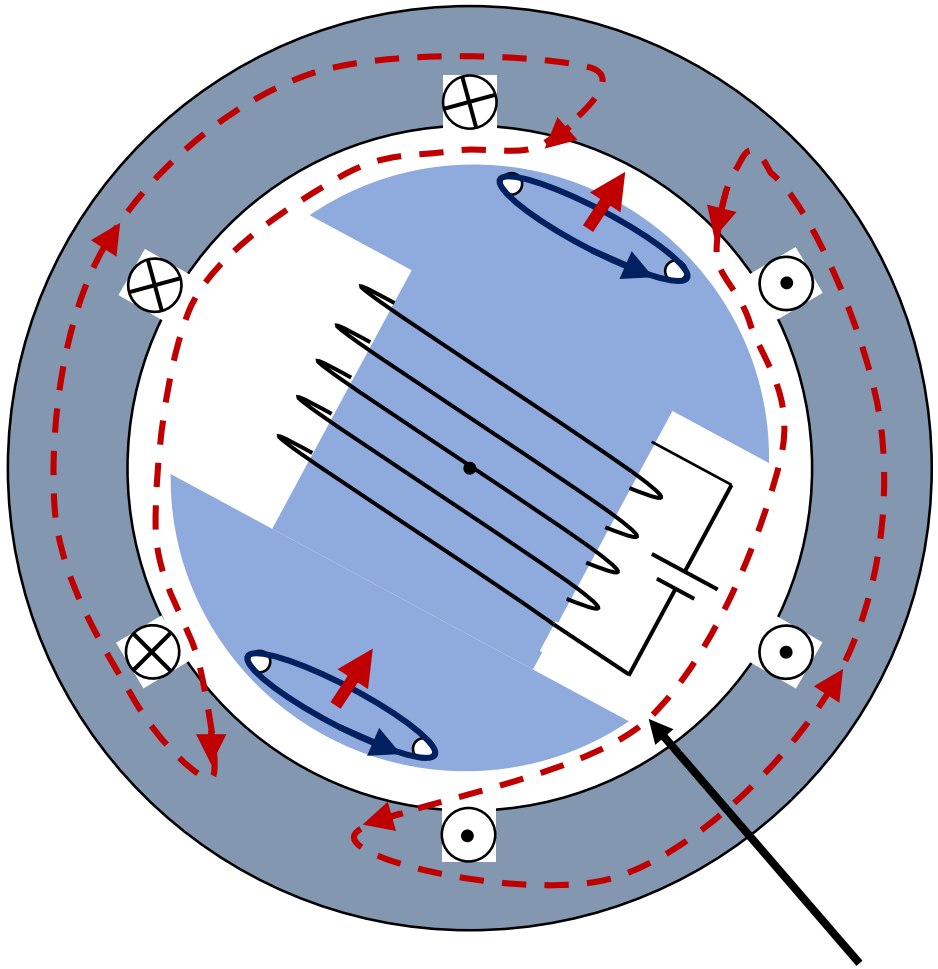
Steady state



- Field current creates rotor flux
- Three-phase stator current creates stator flux
- Stator flux rotates in synchronism with the rotor
- Stator flux linking the field and damper windings is constant
- Stator flux path is mostly through iron → low reluctance path
- Self inductance of stator winding L_S and synchronous reactance $X_S = \omega L_S$ are large

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Sudden increase in stator current

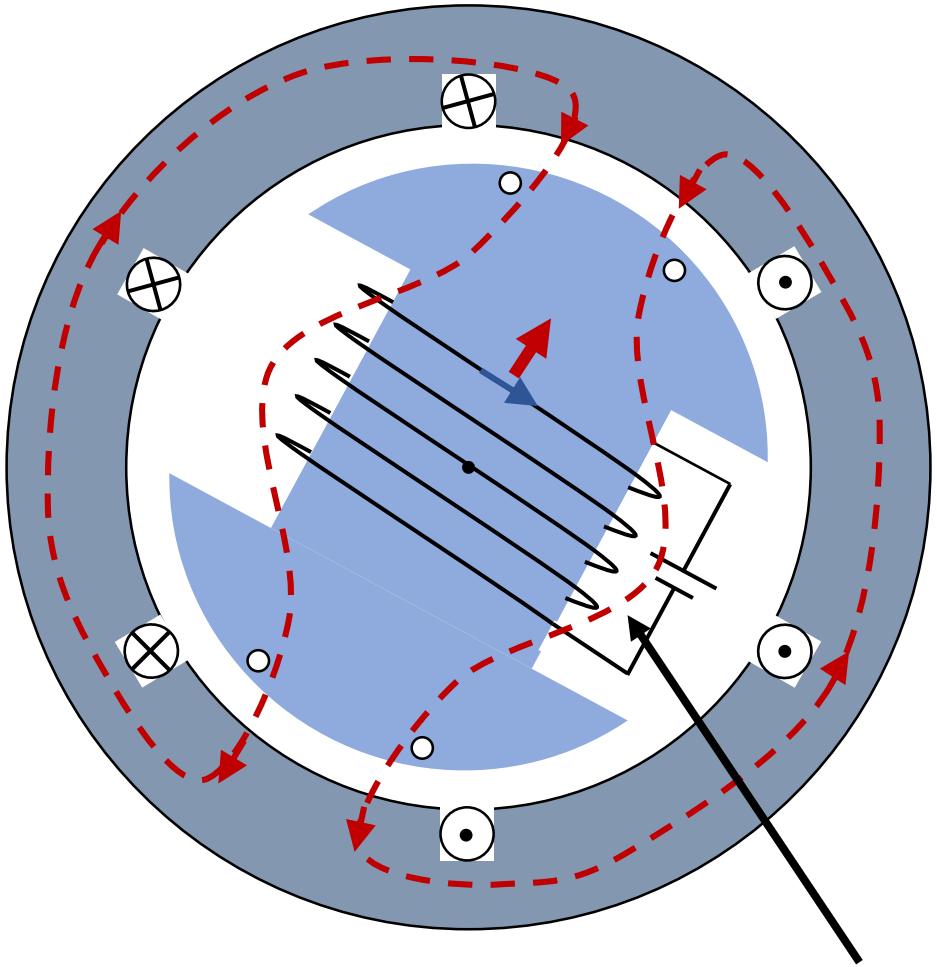


- Increase in stator current → increase in stator flux
- Lenz's law: a change in flux induces current that opposes the change in flux
- Current induced in damper and field windings prevents larger stator flux from entering the rotor
- Stator flux pushed into the airgap, which is a higher reluctance path

→ Lower reactance

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Decay of the induced damper current

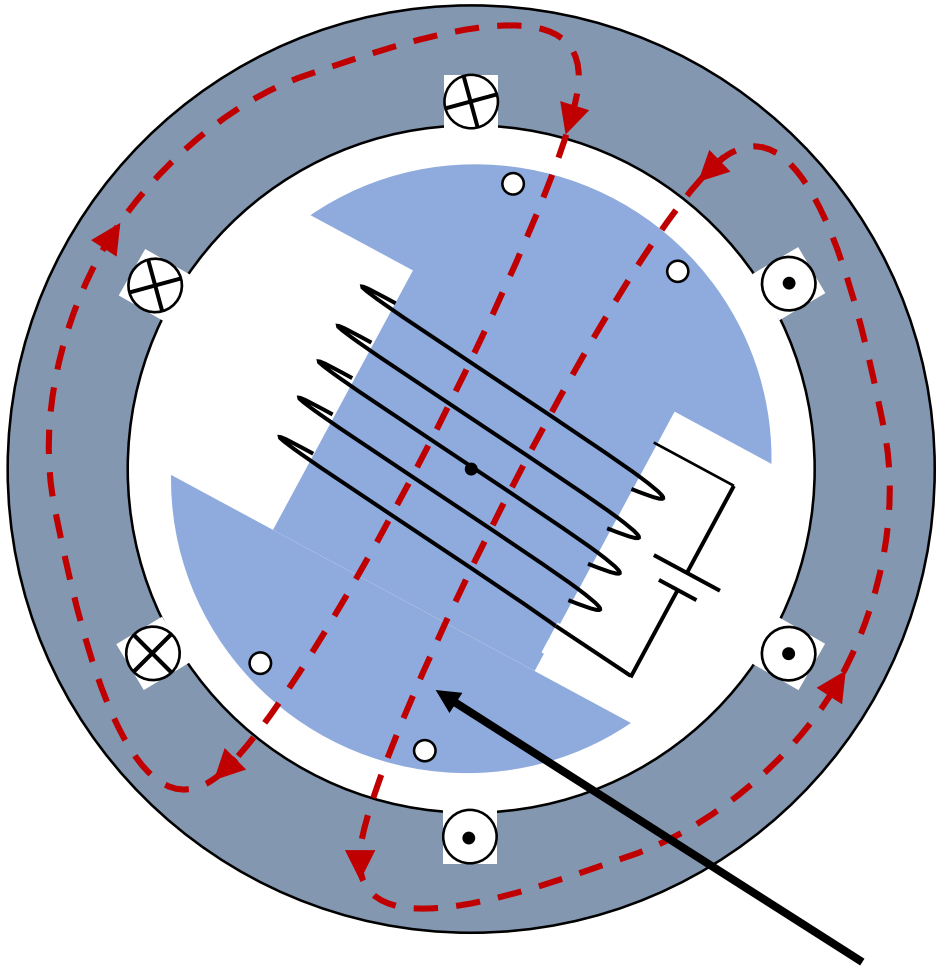


- Currents induced in the damper windings decay with L/R time constant of these windings
- Increased stator flux partially penetrates the rotor
- Induced current prevents this increased stator flux from penetrating the field winding
- Flux path partially through iron
- Lower reluctance

→ Higher reactance

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Back to a steady state

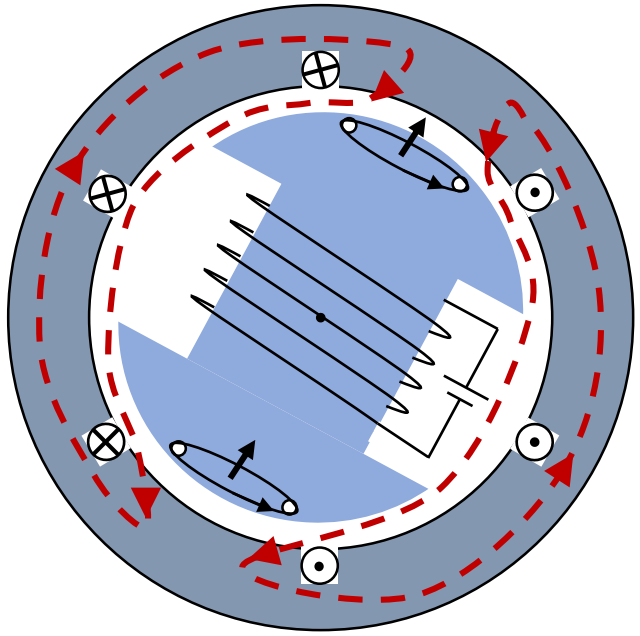


- Currents induced in the field winding decays with L/R time constant of these windings
- Increased stator flux fully penetrates the rotor
- Flux path mostly through iron
- Lower reluctance

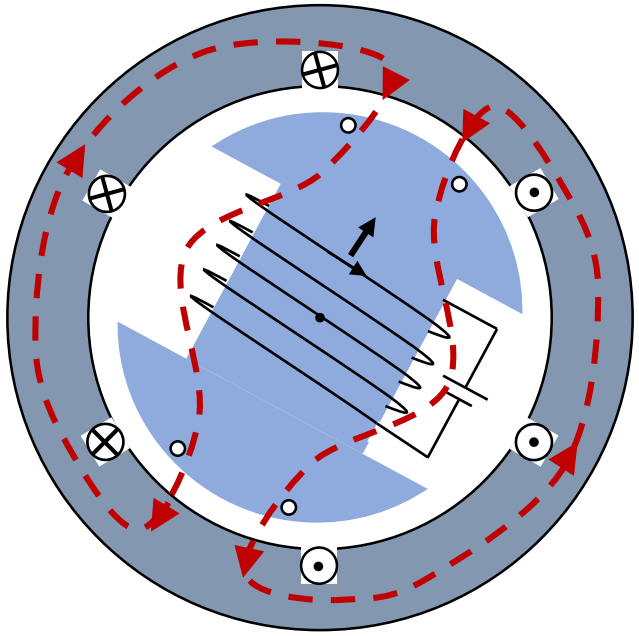
→ Reactance returns to its higher steady state value

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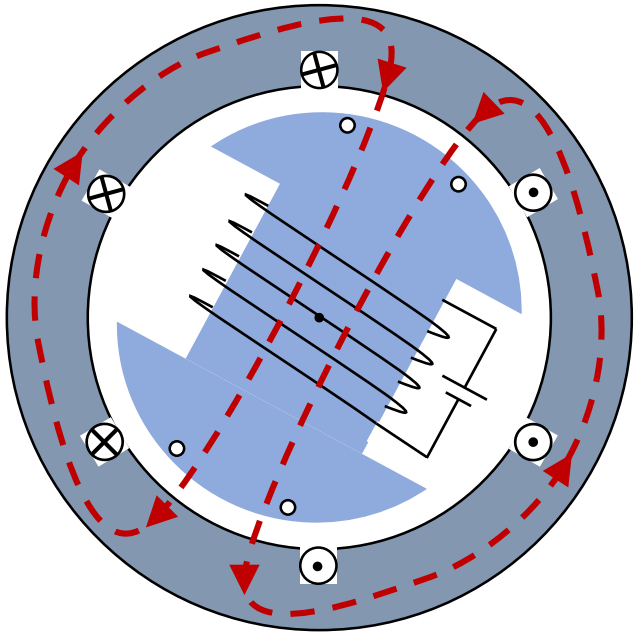
Post-fault evolution of stator flux path



Immediately after the fault



After the damper currents have decayed

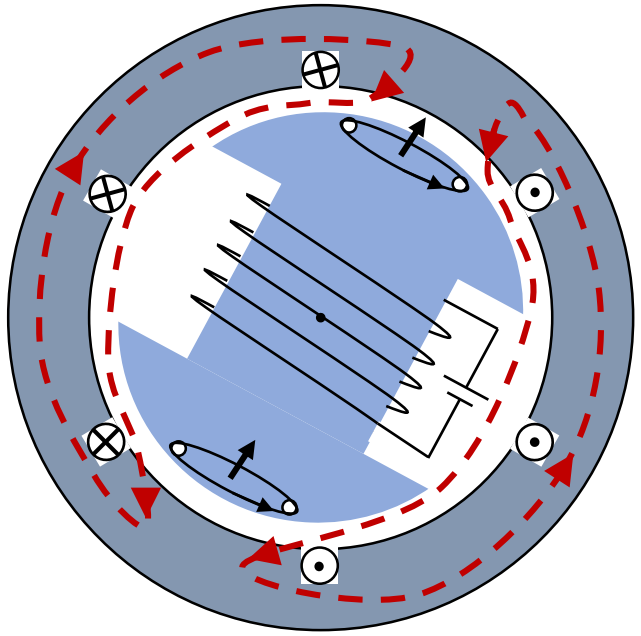


After the field current has decayed

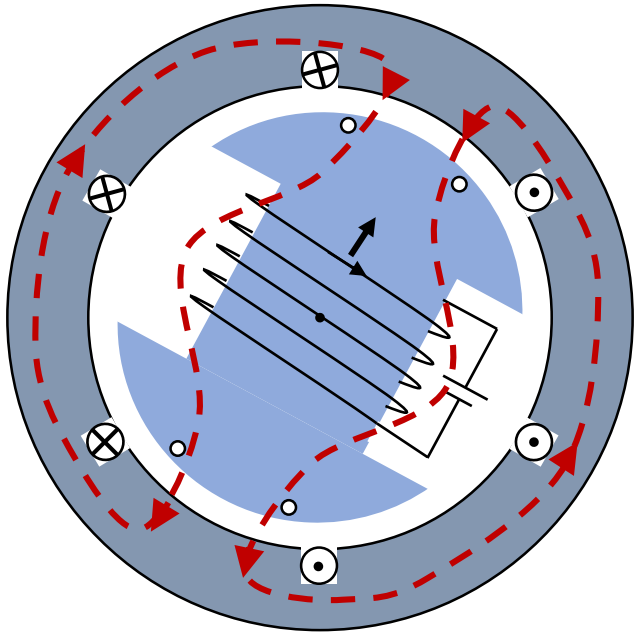
Continuous evolution driven by L/R time constants

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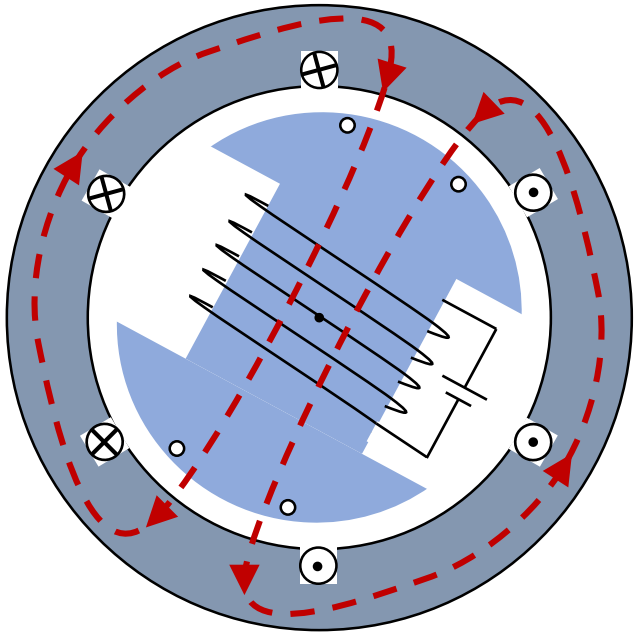
Subtransient, transient and steady periods



Subtransient state
Valid for a few 10’s ms



Transient state
Valid for a few 100’s ms

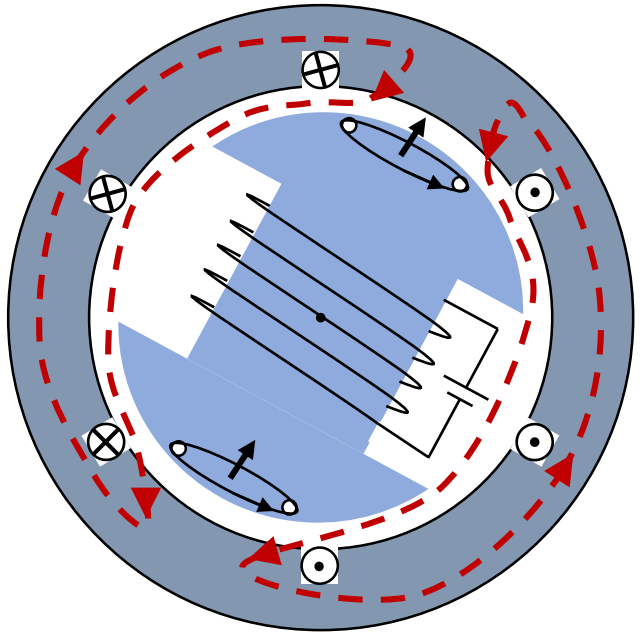


Steady state

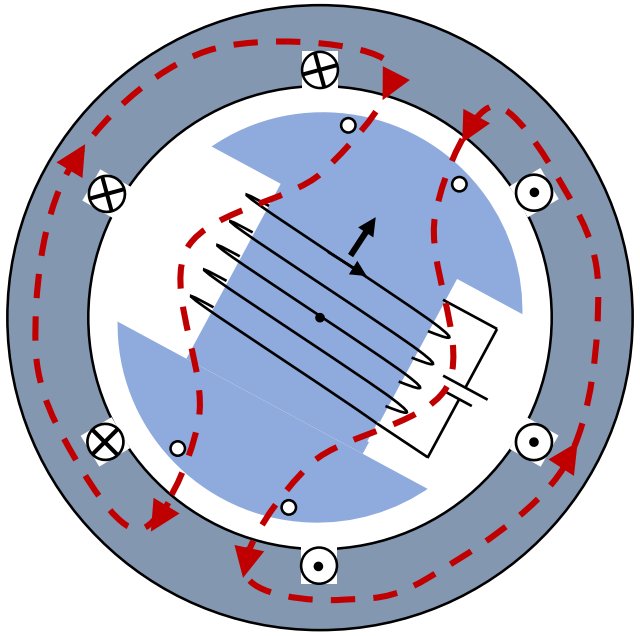
Model continuous evolution using three states

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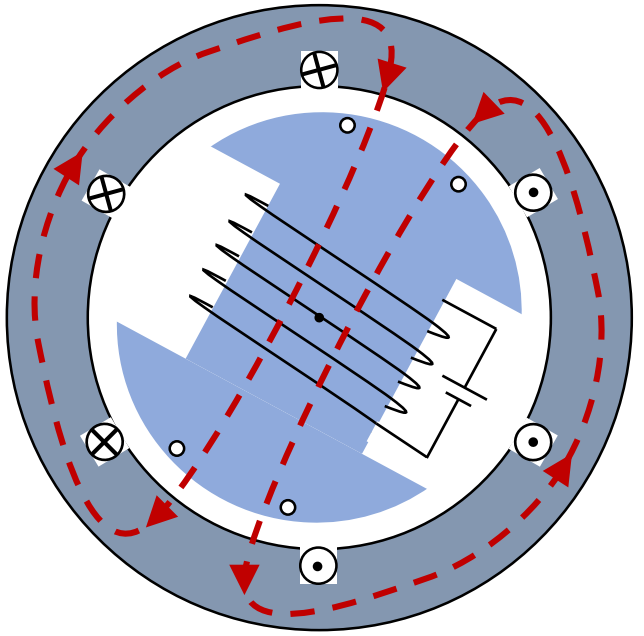
Subtransient, transient and synchronous reactances



Subtransient state
Subtransient reactance X''



Transient state
Transient reactance X'

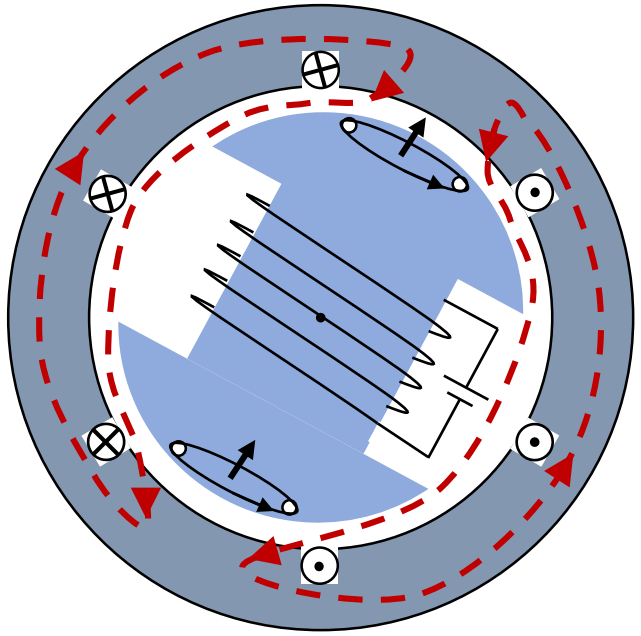


Steady state
Synchronous reactance X_S

$$X'' < X' < X_S$$

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Modeling generators for fault calculations



Subtransient state

Subtransient reactance X''

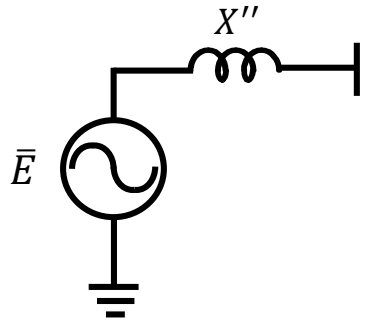
$$X'' < X' < X_S$$

- Subtransient state is valid immediately after the fault
- Has the smallest reactance

→ Largest fault current

→ Worse case

- Model used for fault calculations:

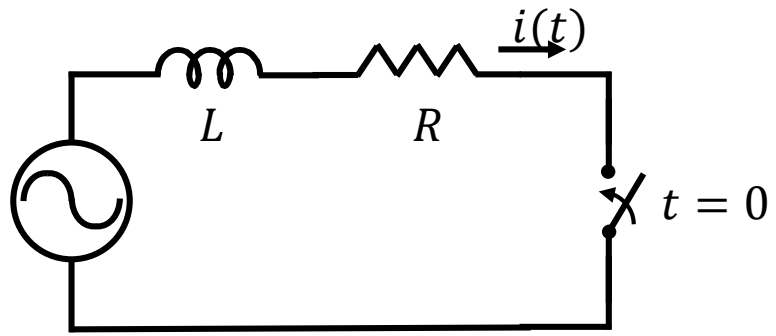


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dc component of fault currents

- Apply KVL to this circuit:

$v(t) = \sqrt{2}Vsin(\omega t + \varphi)$



- $L\frac{di(t)}{dt} + Ri(t) = \sqrt{2}Vsin(\omega t + \varphi) \;\; t \geq 0$

- First order differential equation

→ $i(t) = i_f(t) + i_n(t)$

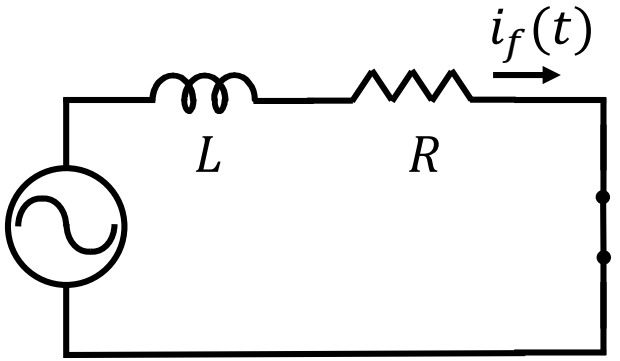
- $i_f(t)$: Forced response
- $i_n(t)$: Natural response

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Forced response

- Forced response = steady state solution
- Solve in the phasor domain
- $\bar{I} = \frac{\bar{V}}{R+j\omega L} = \frac{V\angle\varphi}{Z\angle\theta} = \frac{V}{Z}\angle(\varphi - \theta)$
  - $Z = \sqrt{R^2 + (\omega L)^2}$
  - $\theta = arctg\left(\frac{\omega L}{R}\right)$
- Transform back to time domain:
- $i_f(t) = \frac{\sqrt{2}V}{Z} sin(\omega t + \varphi - \theta)$

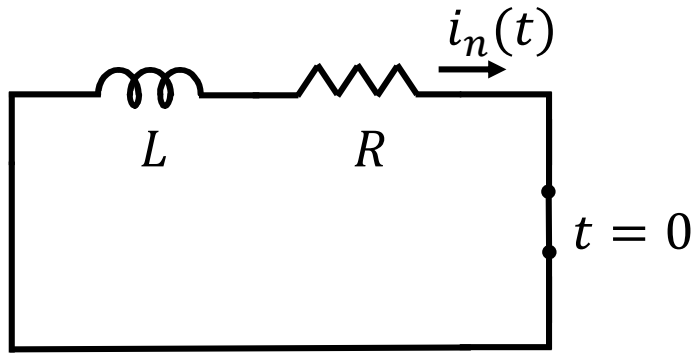
$v(t) = \sqrt{2}Vsin(\omega t + \varphi)$



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Natural response

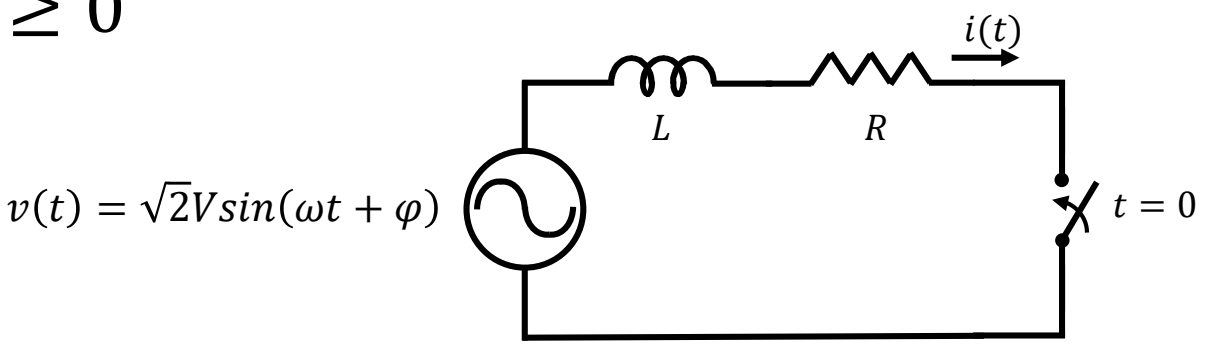
- Natural response = transient response of an RL circuit
- Has the following form:
  - $i_n(t) = Ae^{-\frac{t}{\tau}}$
  - With $\tau = L/R$



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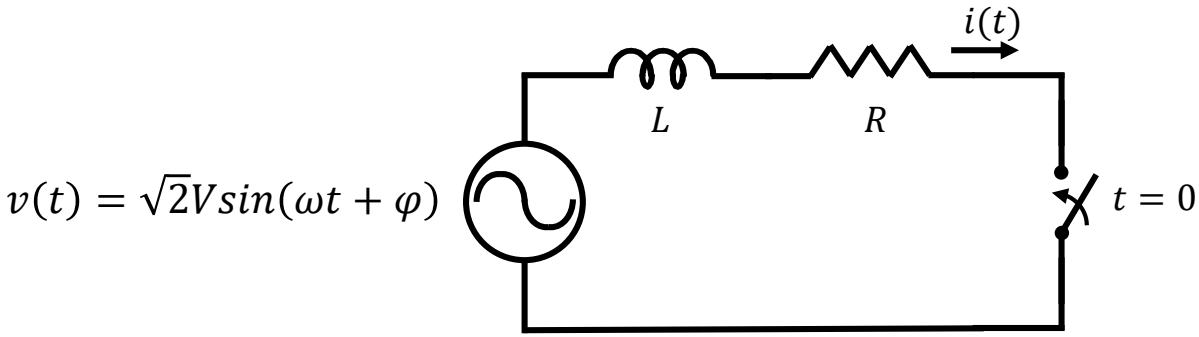
Total response

- $L\frac{di(t)}{dt} + Ri(t) = \sqrt{2}Vsin(\omega t + \varphi) \quad t \geq 0$
- $i(t) = i_f(t) + i_n(t)$
  - $i_f(t)$: Forced response
  - $i_n(t)$: Natural response
- $i(t) = \frac{\sqrt{2}V}{Z}\sin(\omega t + \varphi - \theta) + Ae^{-\frac{t}{\tau}} \quad t \geq 0$
- A?
- Use the initial conditions to determine A



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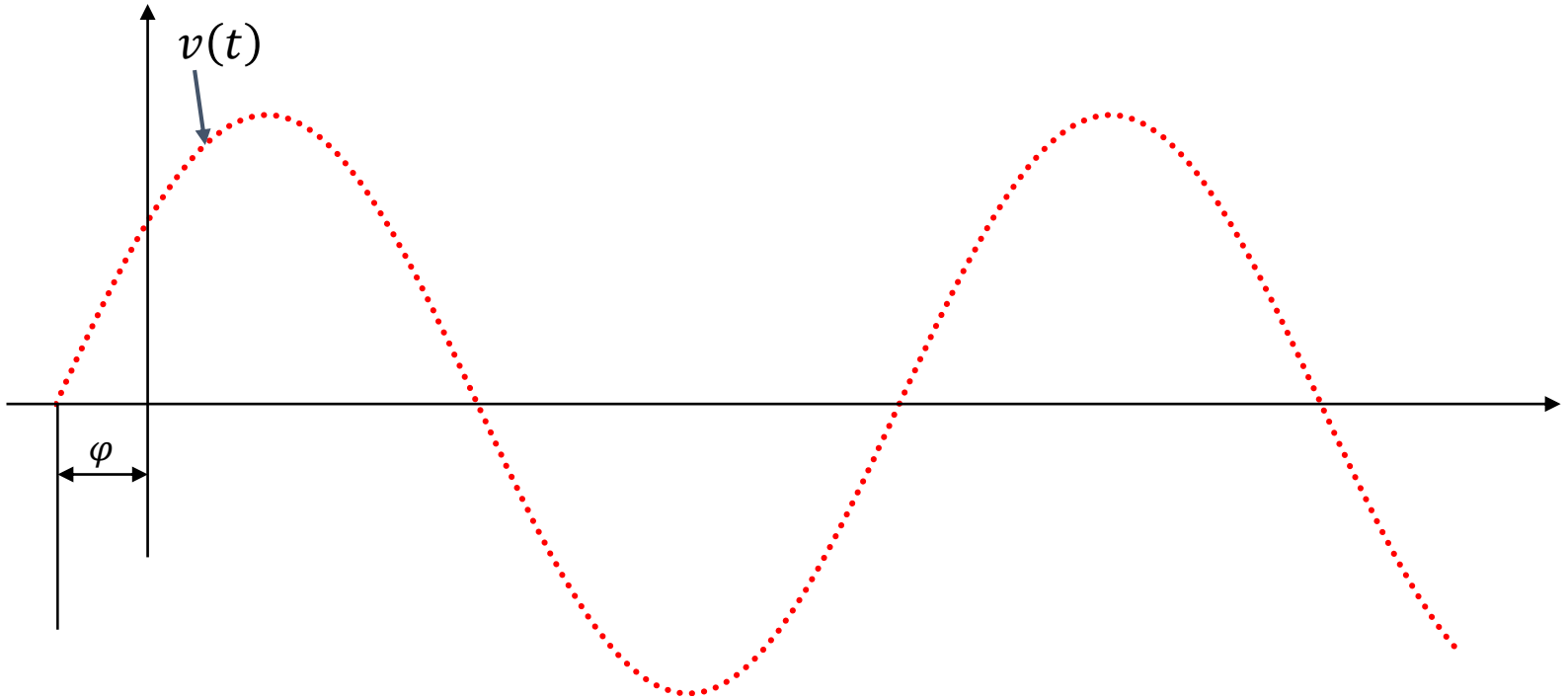
Initial conditions

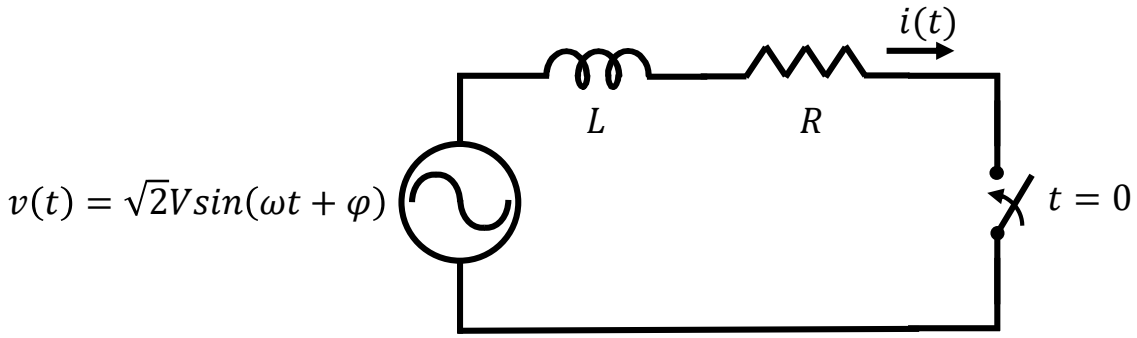


- $i(t) = \frac{\sqrt{2}V}{Z} sin(\omega t + \varphi - \theta) + Ae^{-\frac{t}{\tau}} \qquad t \geq 0$
- Before the switch closes, the current is zero
- Current in an inductance cannot change instantaneously
- $i(0^+) = \frac{\sqrt{2}V}{Z} sin(\varphi - \theta) + Ae^{-\frac{0}{\tau}} = 0 \implies A = -\frac{\sqrt{2}V}{Z} sin(\varphi - \theta)$
- $i(t) = \frac{\sqrt{2}V}{Z}\left(sin(\omega t + \varphi - \theta) - sin(\varphi - \theta)e^{-\frac{t}{\tau}}\right) \qquad t \geq 0$

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dc component of fault current



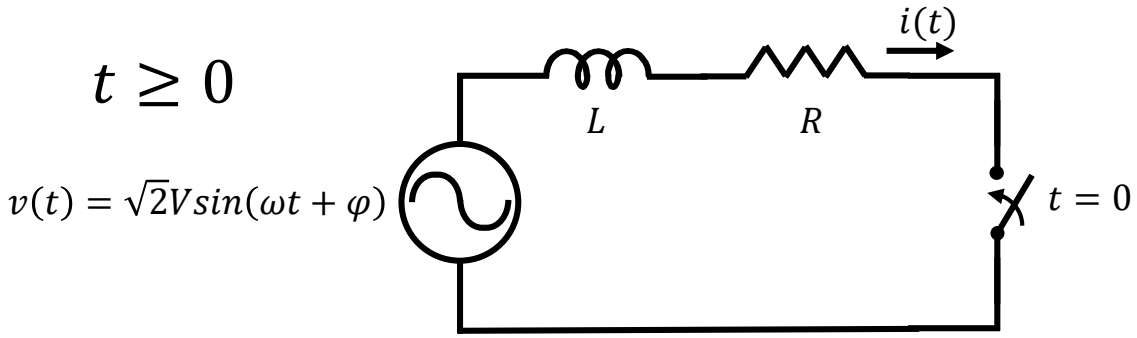


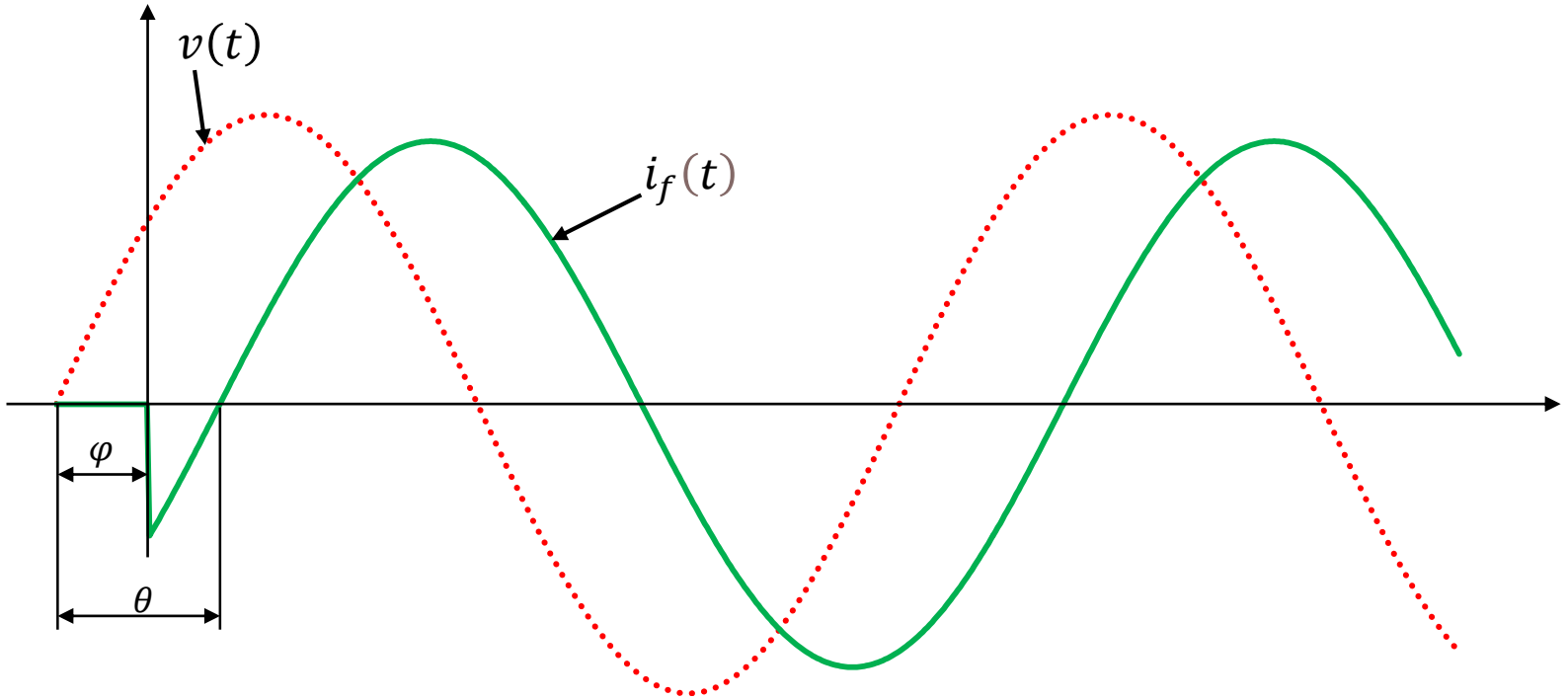
$\varphi = 40°, \theta = 70°$ and $\tau = \frac{2}{3}T$ $\quad\quad$ $\theta = arctg\left(\frac{\omega L}{R}\right)$ $\quad$ $\tau = L/R$

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dc component of fault current

$$i(t) = \frac{\sqrt{2}V}{Z}\left(sin(\omega t + \varphi - \theta) - sin(\varphi - \theta)e^{-\frac{t}{\tau}}\right) \qquad t \geq 0$$



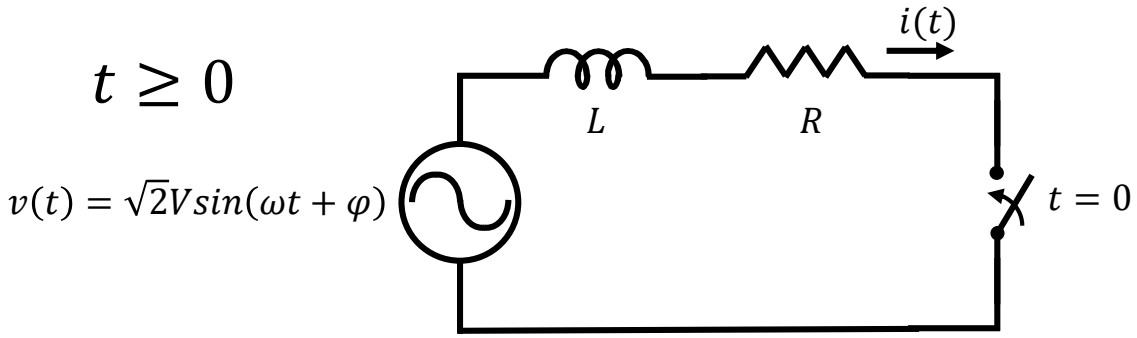


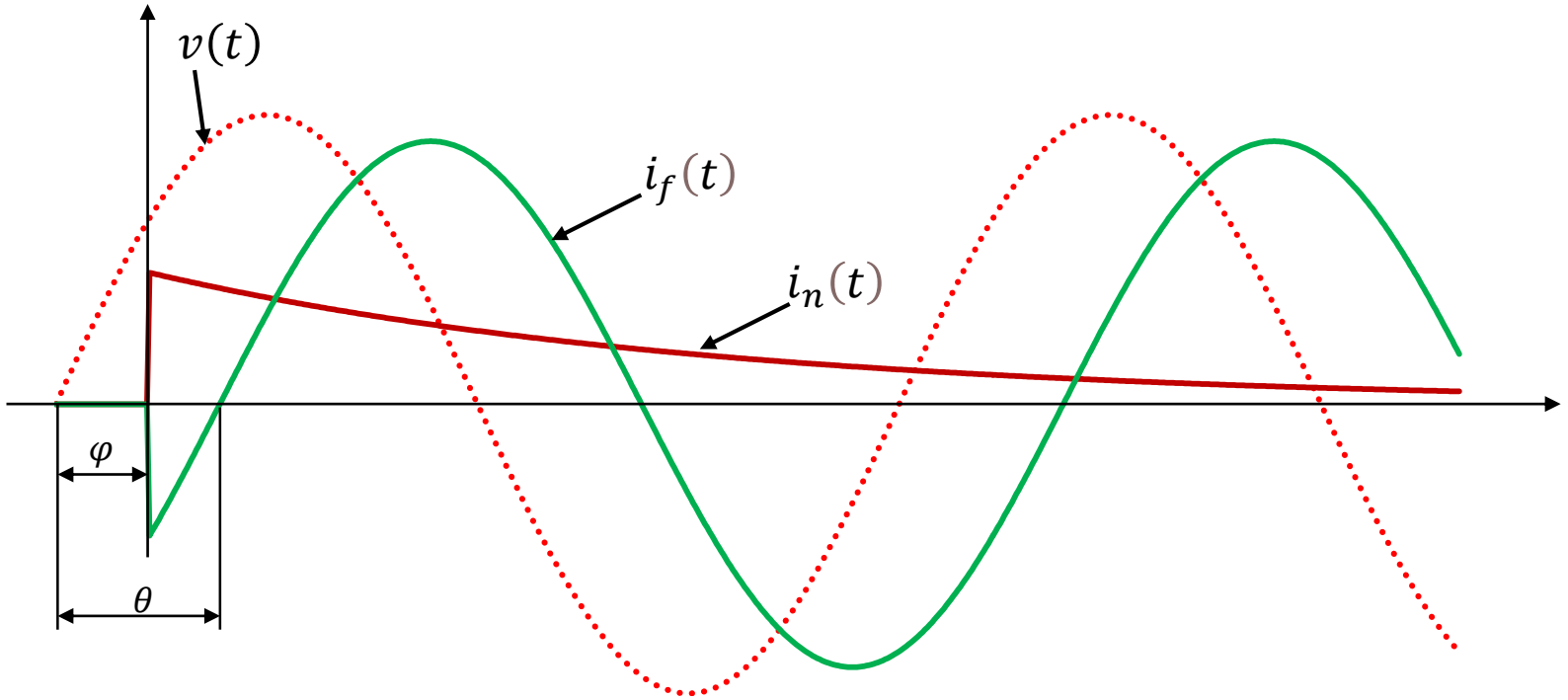
$\varphi = 40°, \theta = 70°$ and $\tau = \frac{2}{3}T$ $\qquad \theta = arctg\left(\frac{\omega L}{R}\right) \qquad \tau = L/R$

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dc component of fault current

$$i(t) = \frac{\sqrt{2}V}{Z}\left(sin(\omega t + \varphi - \theta) - sin(\varphi - \theta)e^{-\frac{t}{\tau}}\right) \qquad t \geq 0$$



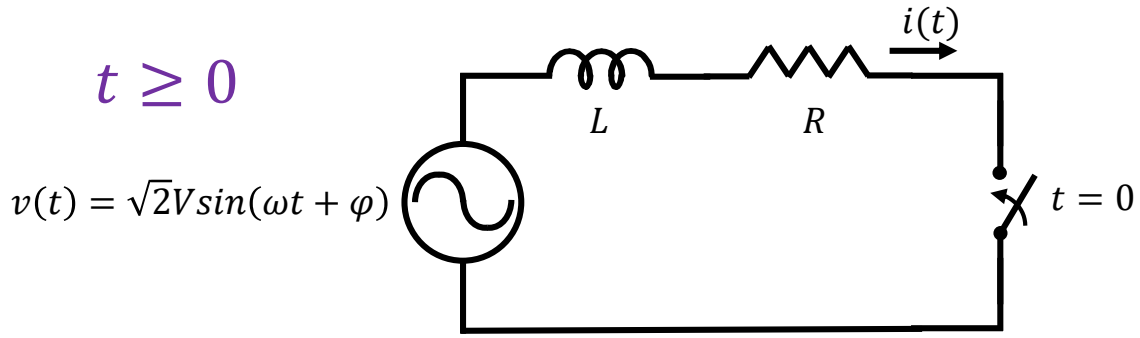


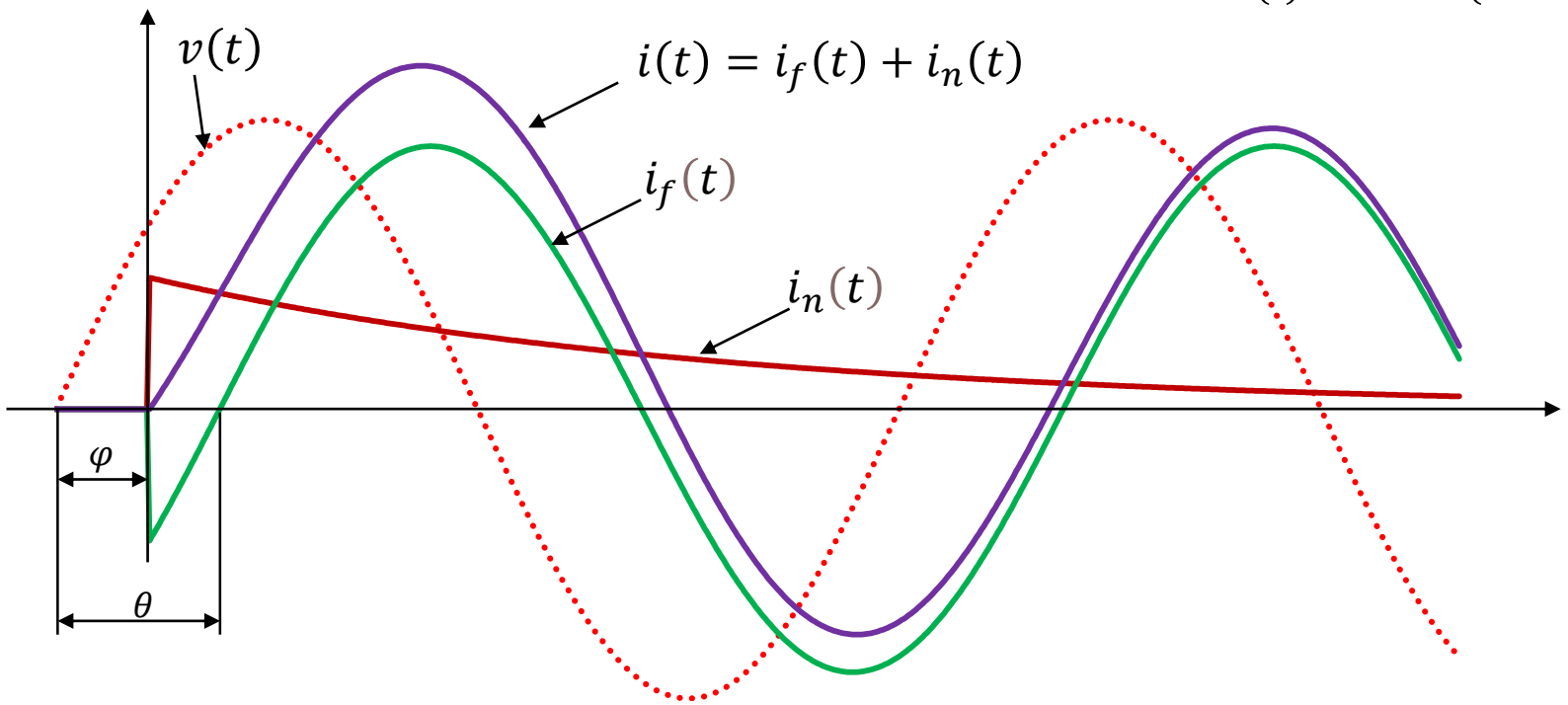
$\varphi = 40°, \theta = 70°$ and $\tau = \frac{2}{3}T$ $\qquad \theta = arctg\left(\frac{\omega L}{R}\right) \qquad \tau = L/R$

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dc offset

$$i(t) = \frac{\sqrt{2}V}{Z}\left(sin(\omega t + \varphi - \theta) - sin(\varphi - \theta)e^{-\frac{t}{\tau}}\right) \qquad t \geq 0$$





The Natural response increases the fault current for these values of φ and θ!

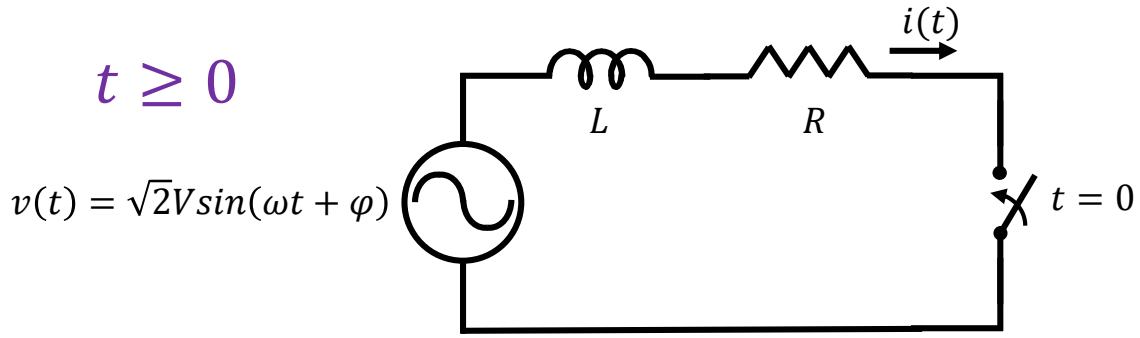
It adds a dc offset to the ac fault current

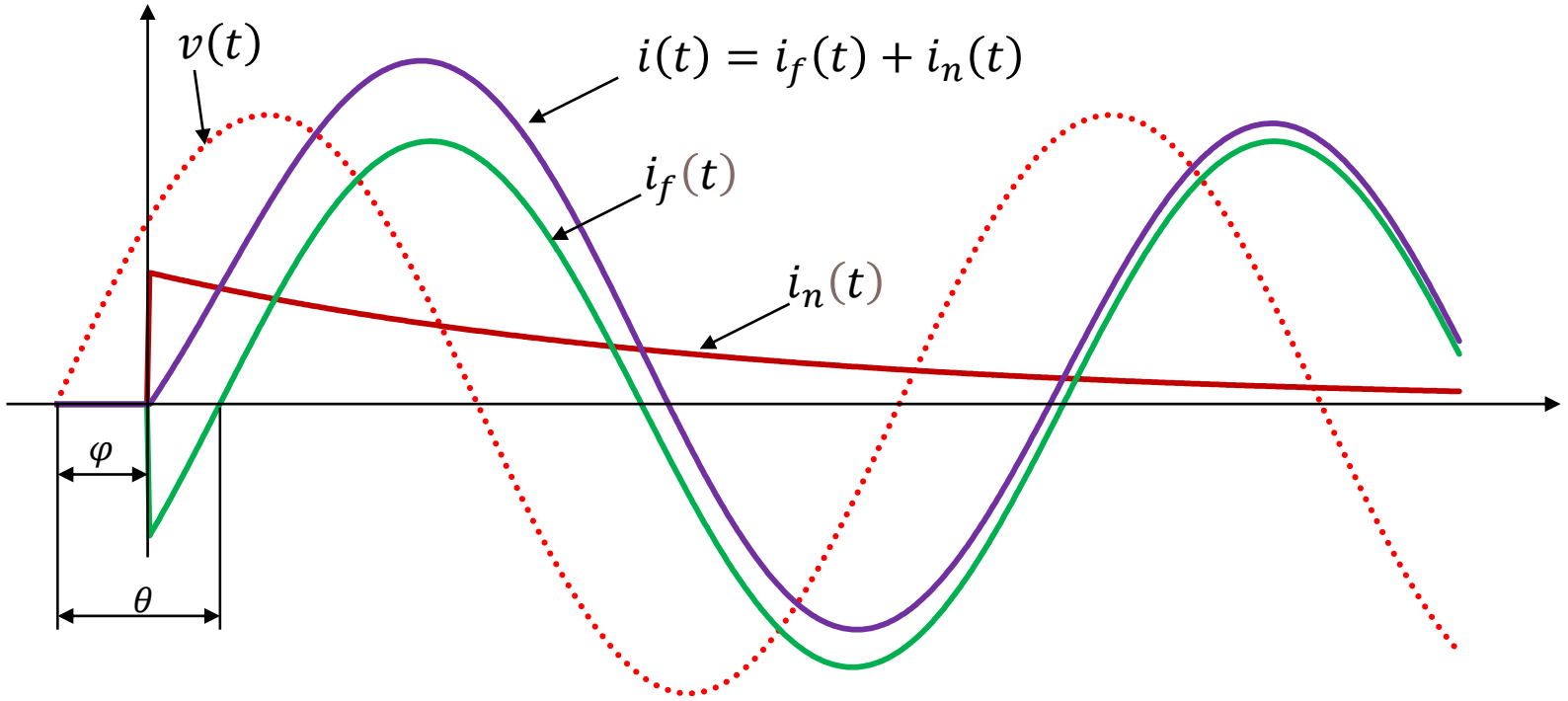
$\varphi = 40°, \theta = 70°$ and $\tau = \frac{2}{3}T$ $\qquad \theta = arctg\left(\frac{\omega L}{R}\right) \qquad \tau = L/R$

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dc offset

$$i(t) = \frac{\sqrt{2}V}{Z}\left(sin(\omega t + \varphi - \theta) - sin(\varphi - \theta)e^{-\frac{t}{\tau}}\right) \qquad t \geq 0$$





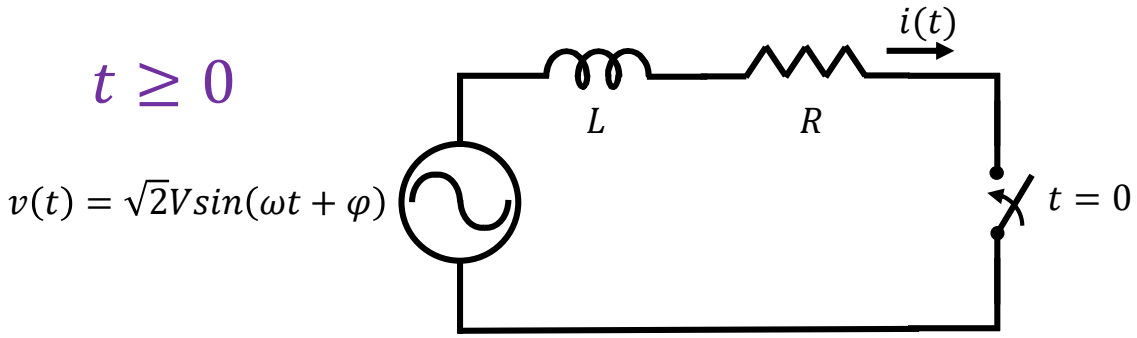
This dc offset is zero for $\varphi - \theta = 0°$ and maximum for $\varphi - \theta = 90°$

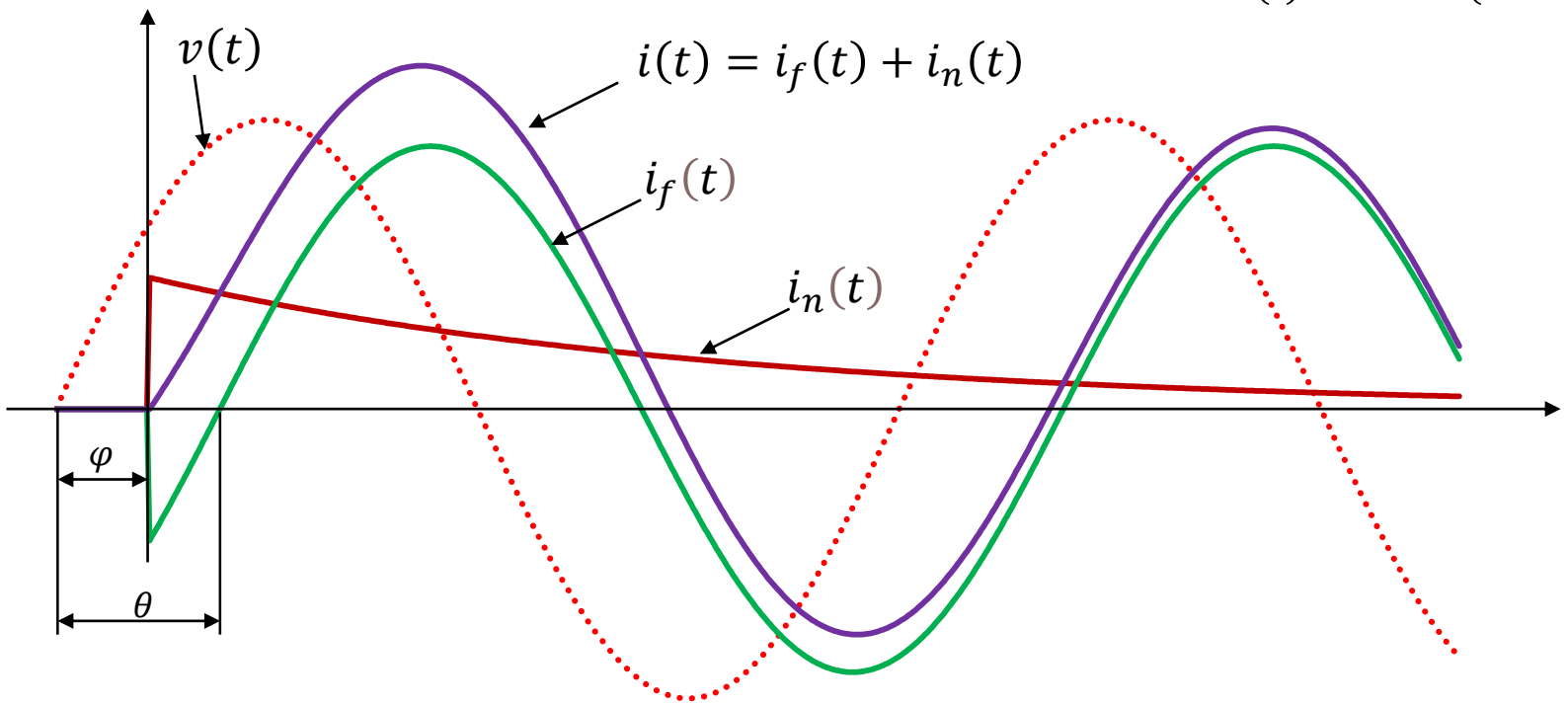
$\varphi = 40°, \theta = 70°$ and $\tau = \frac{2}{3}T$ $\qquad \theta = arctg\left(\frac{\omega L}{R}\right) \qquad \tau = L/R$

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dc offset

$$i(t) = \frac{\sqrt{2}V}{Z}\left(sin(\omega t + \varphi - \theta) - sin(\varphi - \theta)e^{-\frac{t}{\tau}}\right) \qquad t \geq 0$$





φ: phase angle of the voltage when the fault occurs

We don't have control over φ!

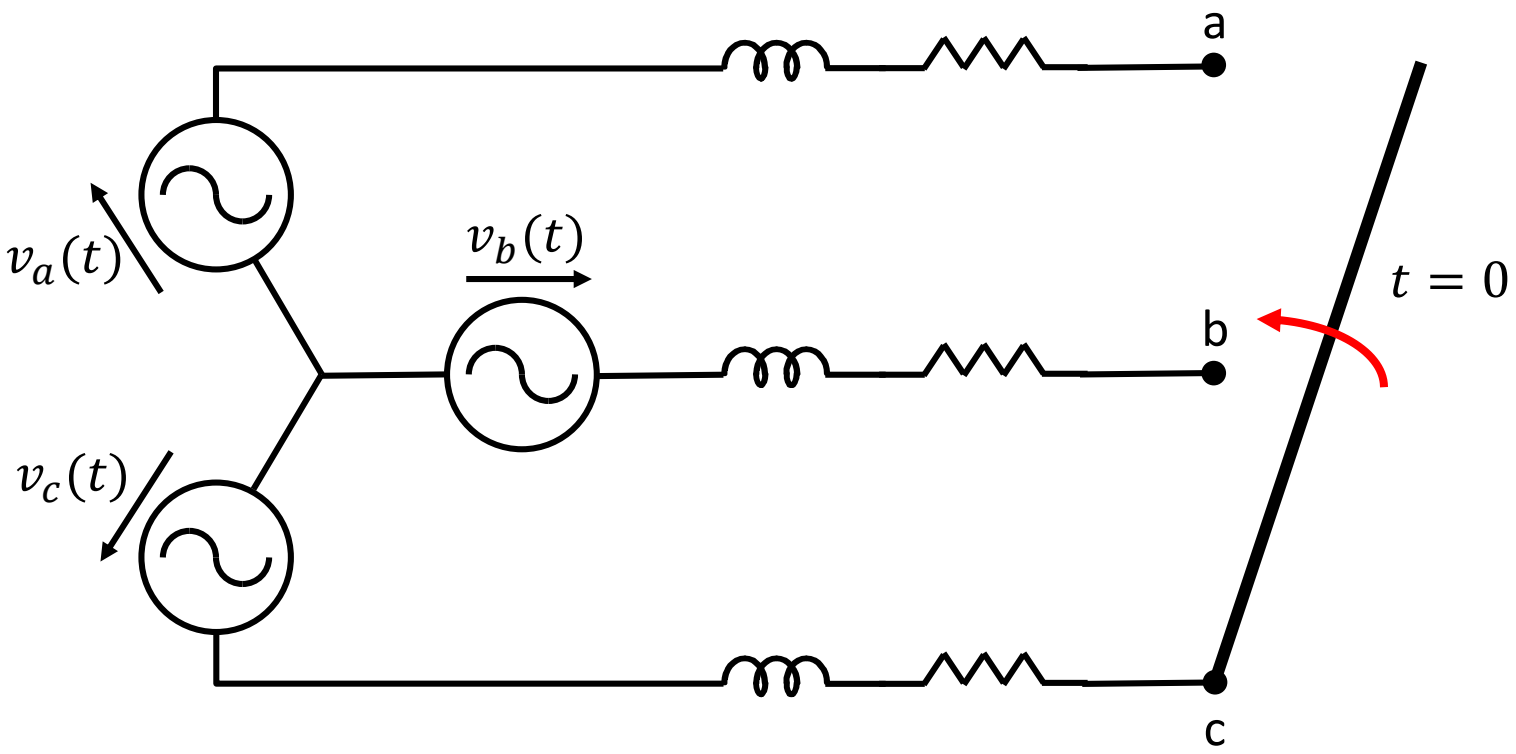
φ is called the "point on phase" of the fault

dc offset depends on the "point on phase" of the fault

$\varphi = 40°, \theta = 70°$ and $\tau = \frac{2}{3}T$

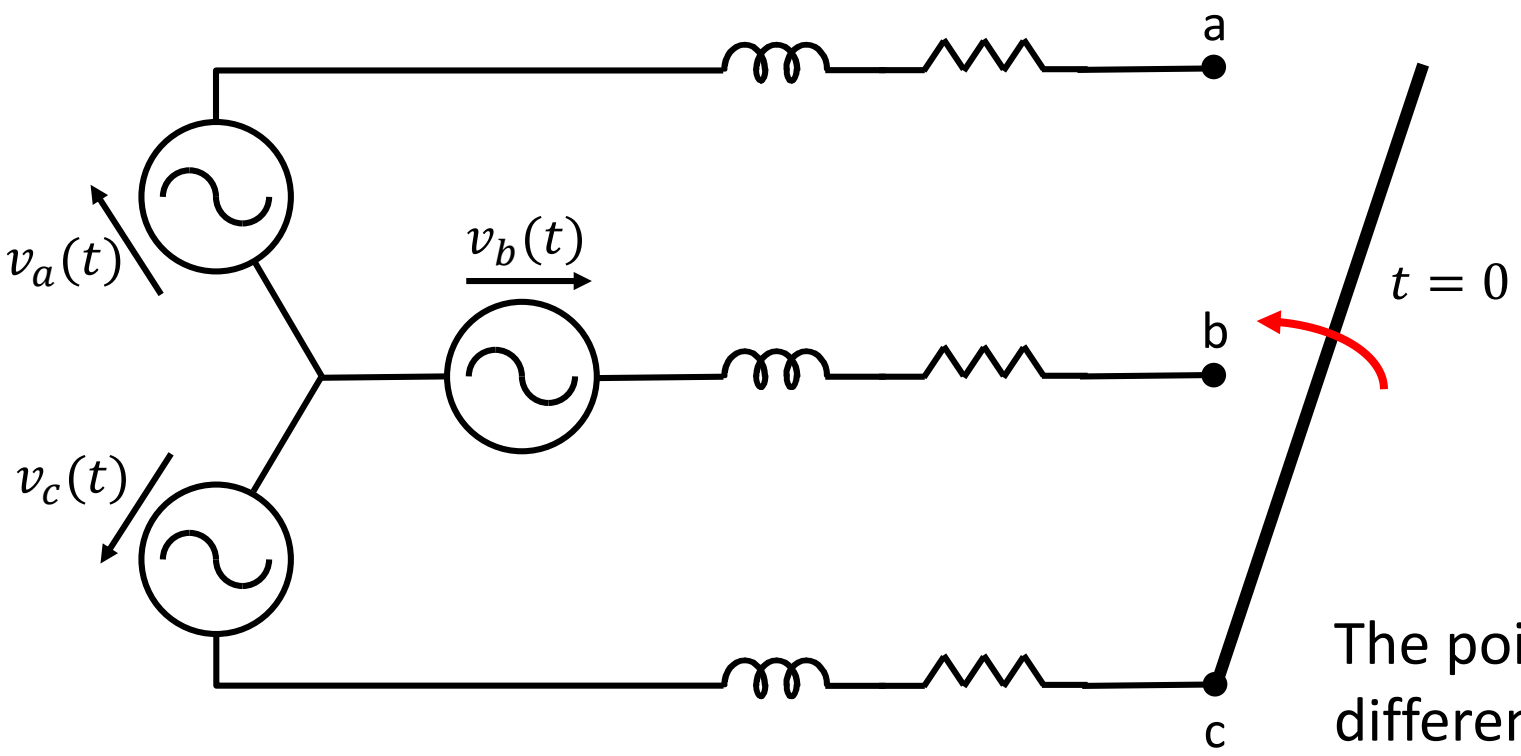
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Fault in a three-phase RL circuit



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Fault in a three-phase RL circuit



$$v_a(t) = \sqrt{2}Vsin(\omega t + \varphi)$$

$$v_b(t) = \sqrt{2}Vsin(\omega t + \varphi - 120°)$$

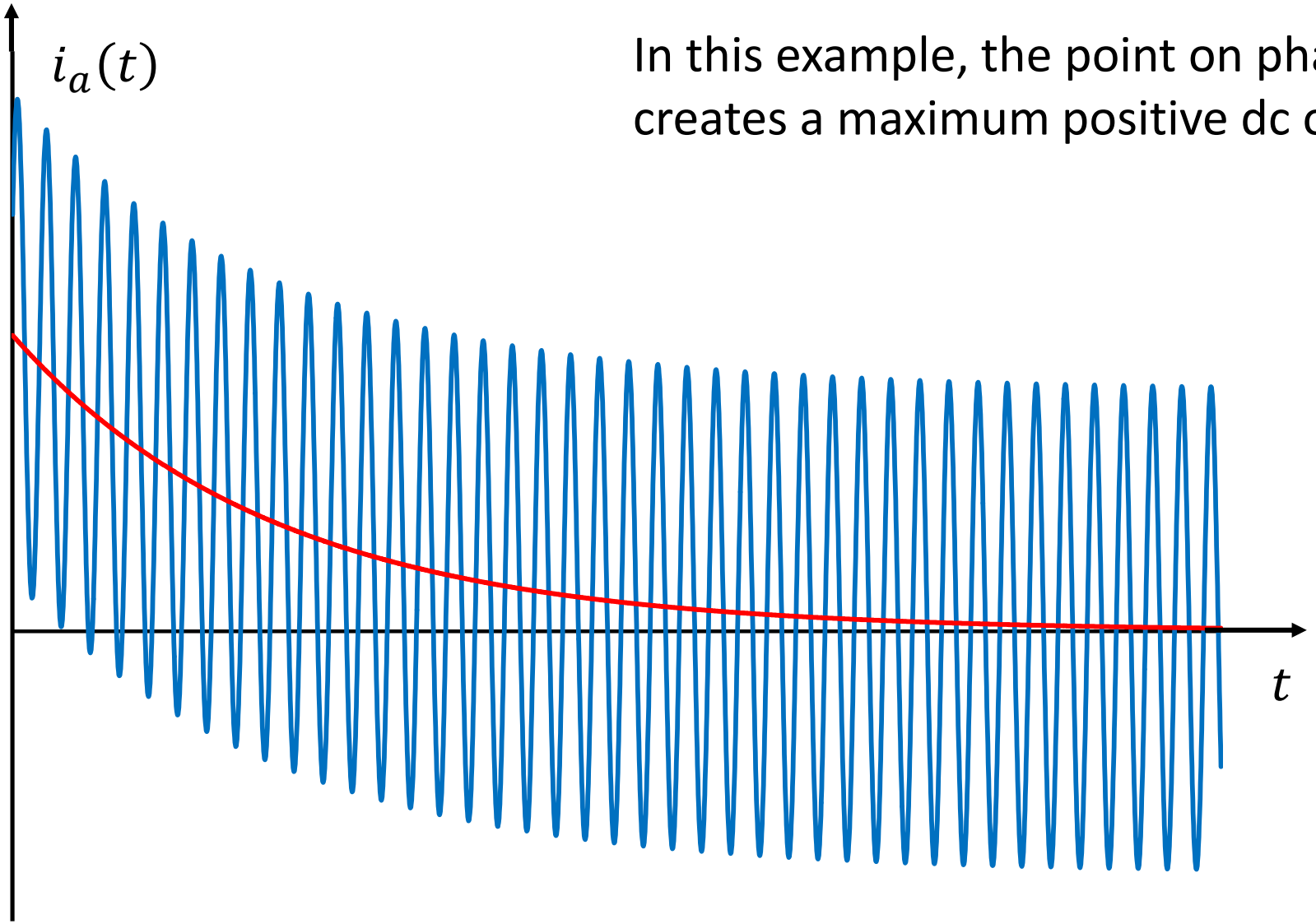
$$v_c(t) = \sqrt{2}Vsin(\omega t + \varphi + 120°)$$

The point on phase of the fault is different for each phase

→ The dc offset is different for each phase

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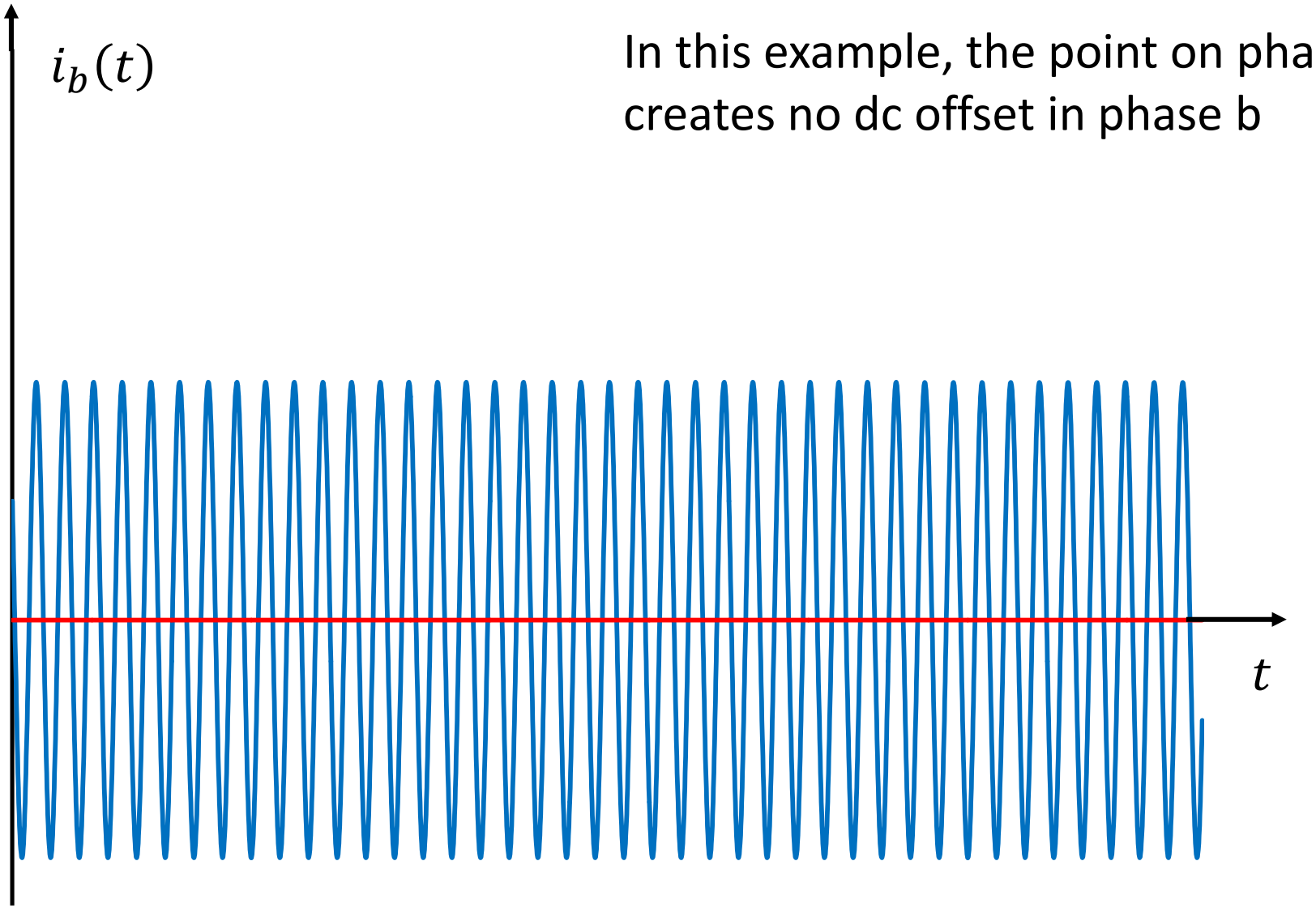
Fault in a balanced three-phase RL circuit



In this example, the point on phase of the fault creates a maximum positive dc offset in phase a

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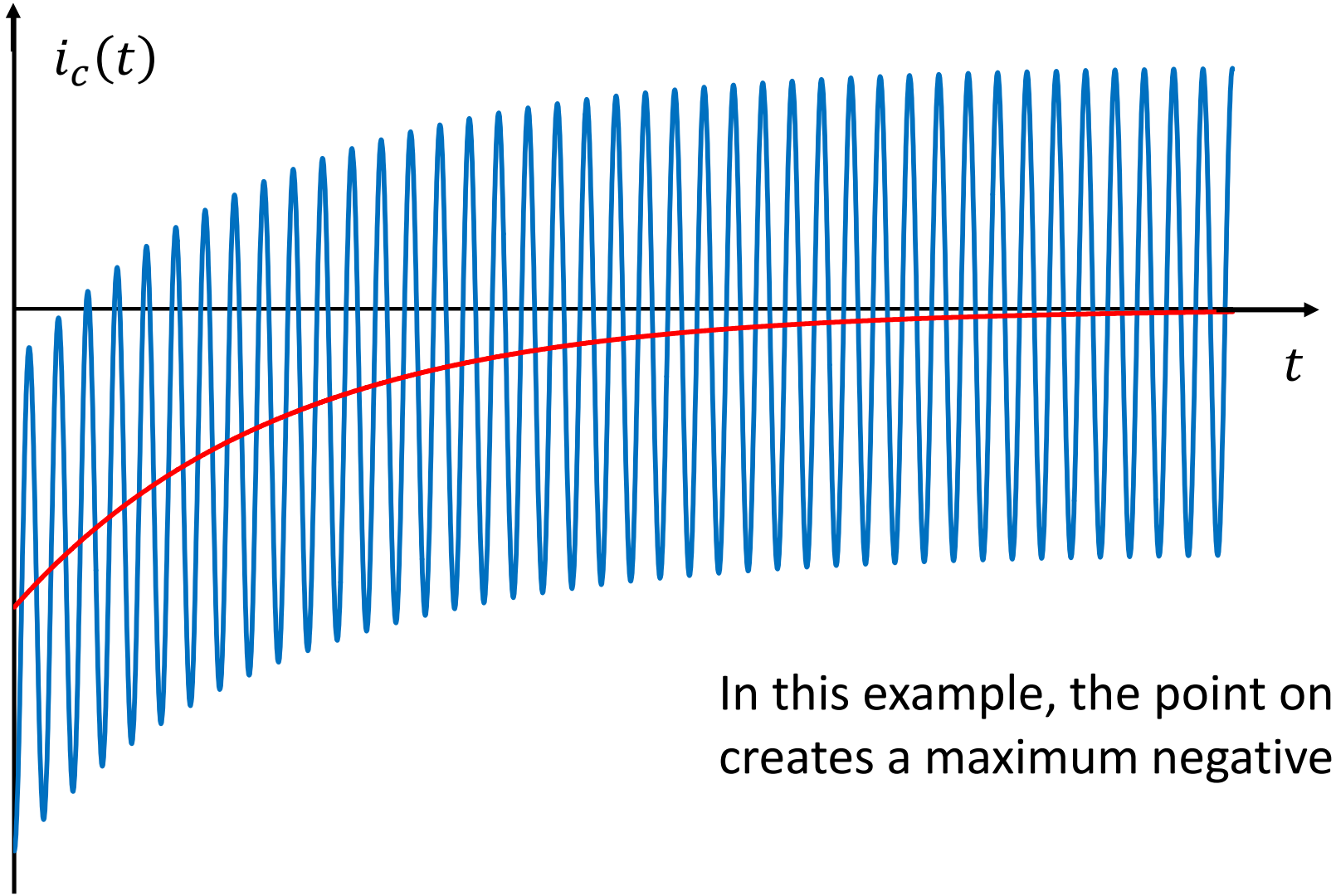
Fault in a balanced three-phase RL circuit



In this example, the point on phase of the fault creates no dc offset in phase b

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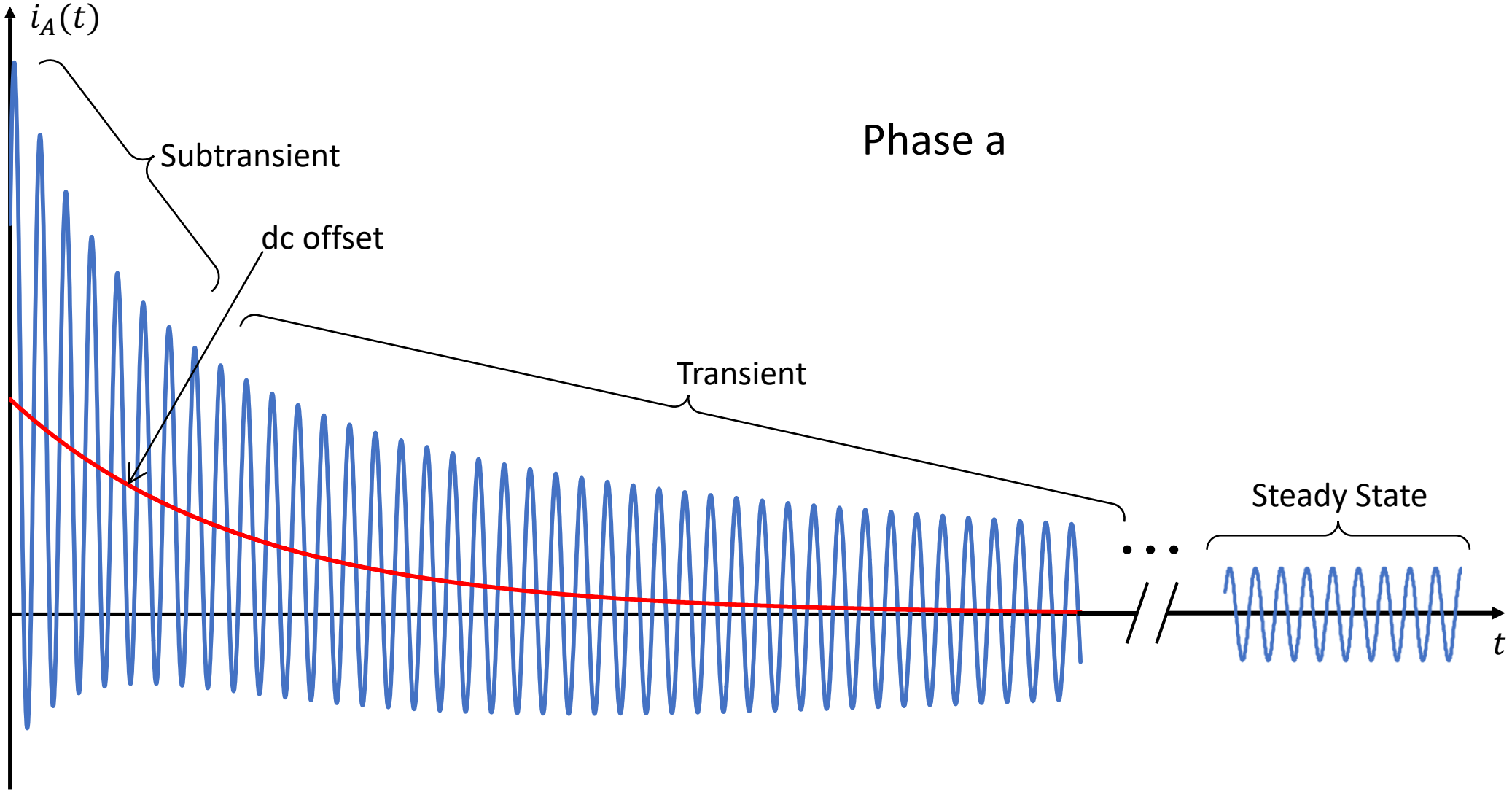
Fault in a balanced three-phase RL circuit



In this example, the point on phase of the fault creates a maximum negative dc offset in phase c

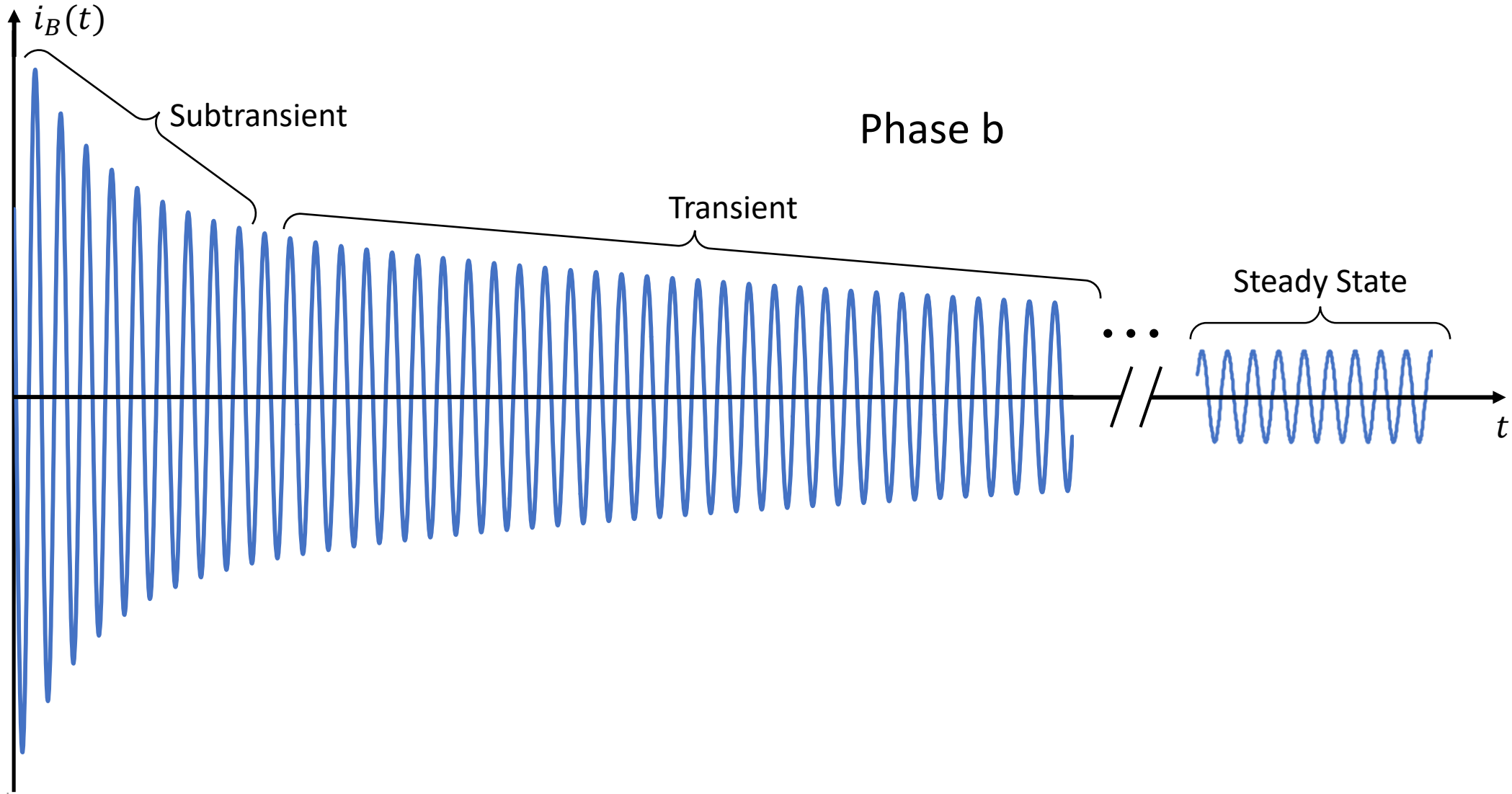
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Fault at the terminals of a generator



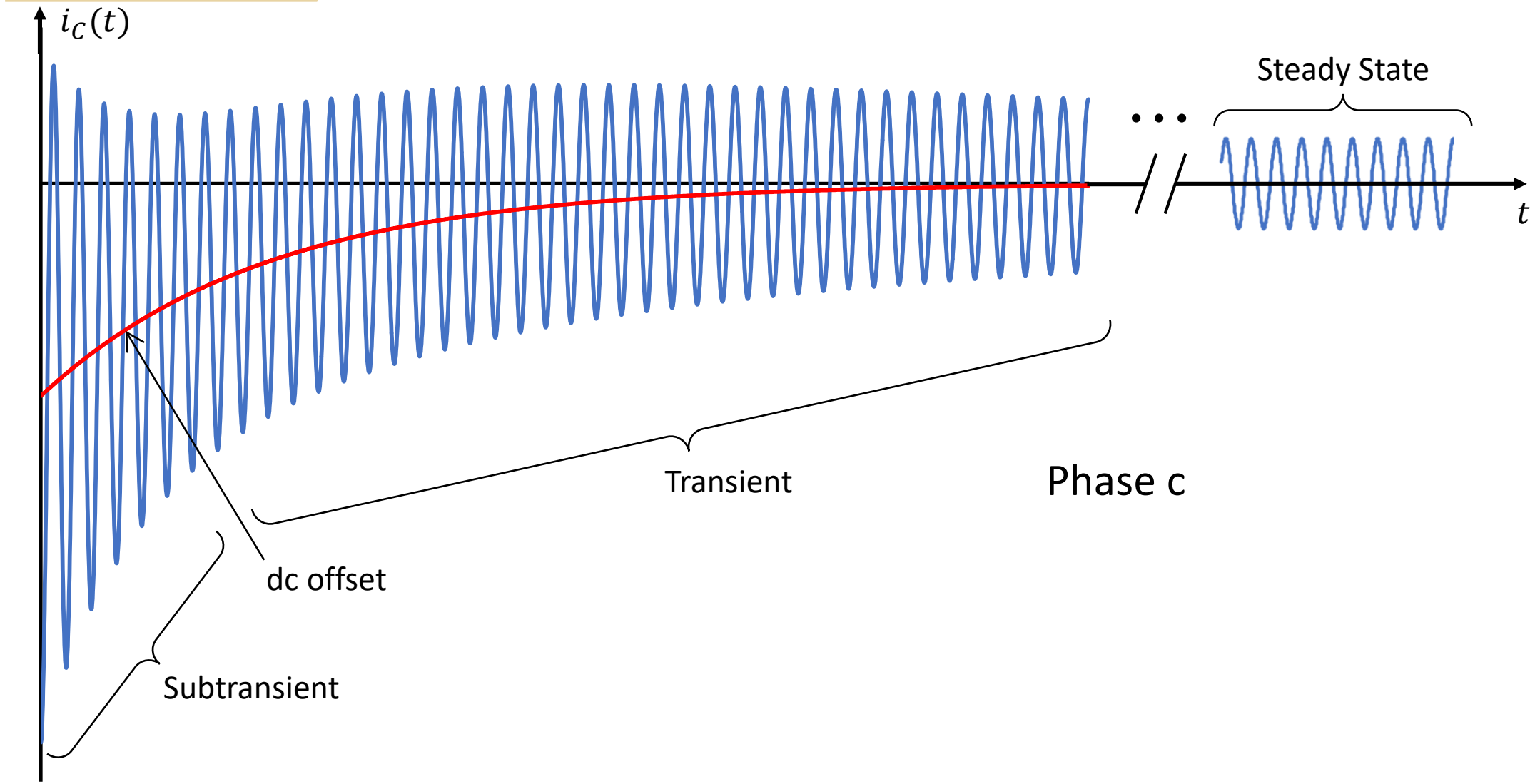
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Fault at the terminals of a generator



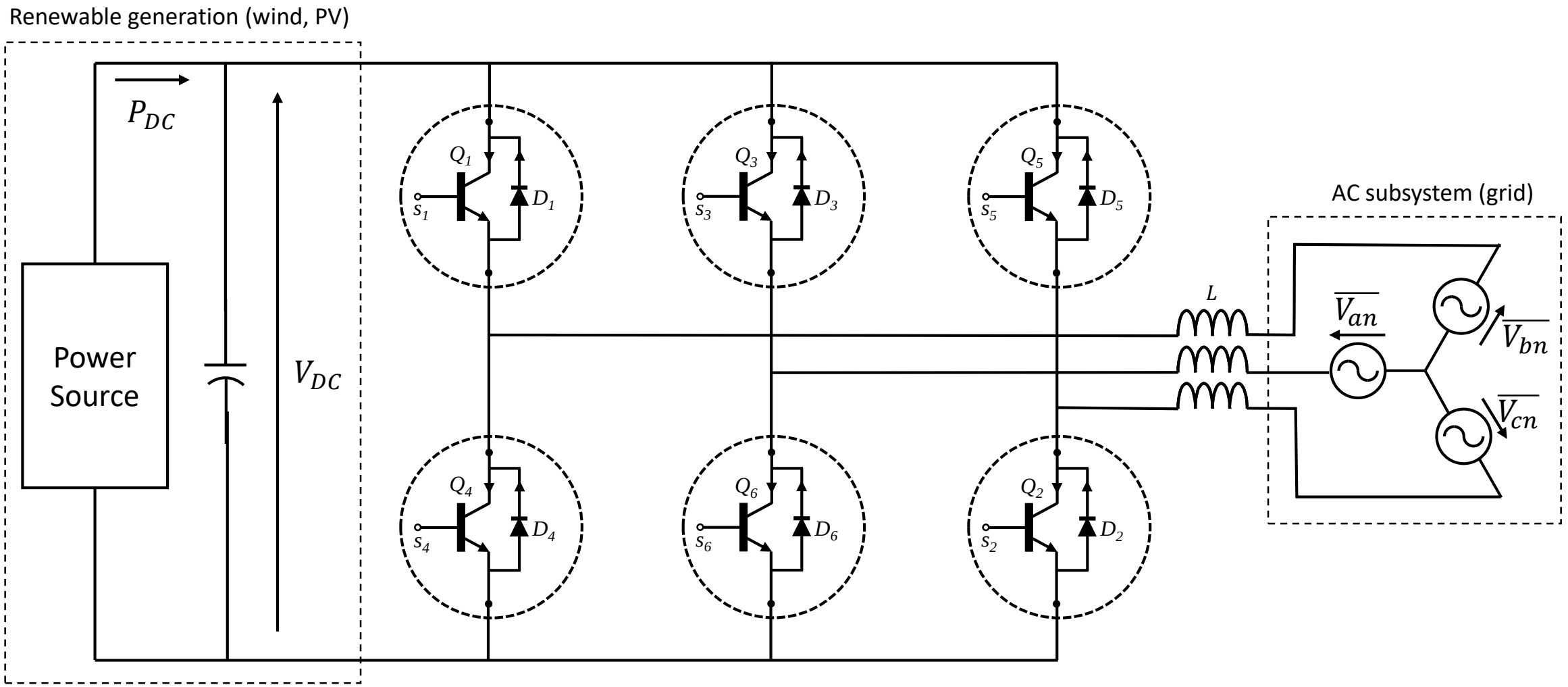
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Fault at the terminals of a generator



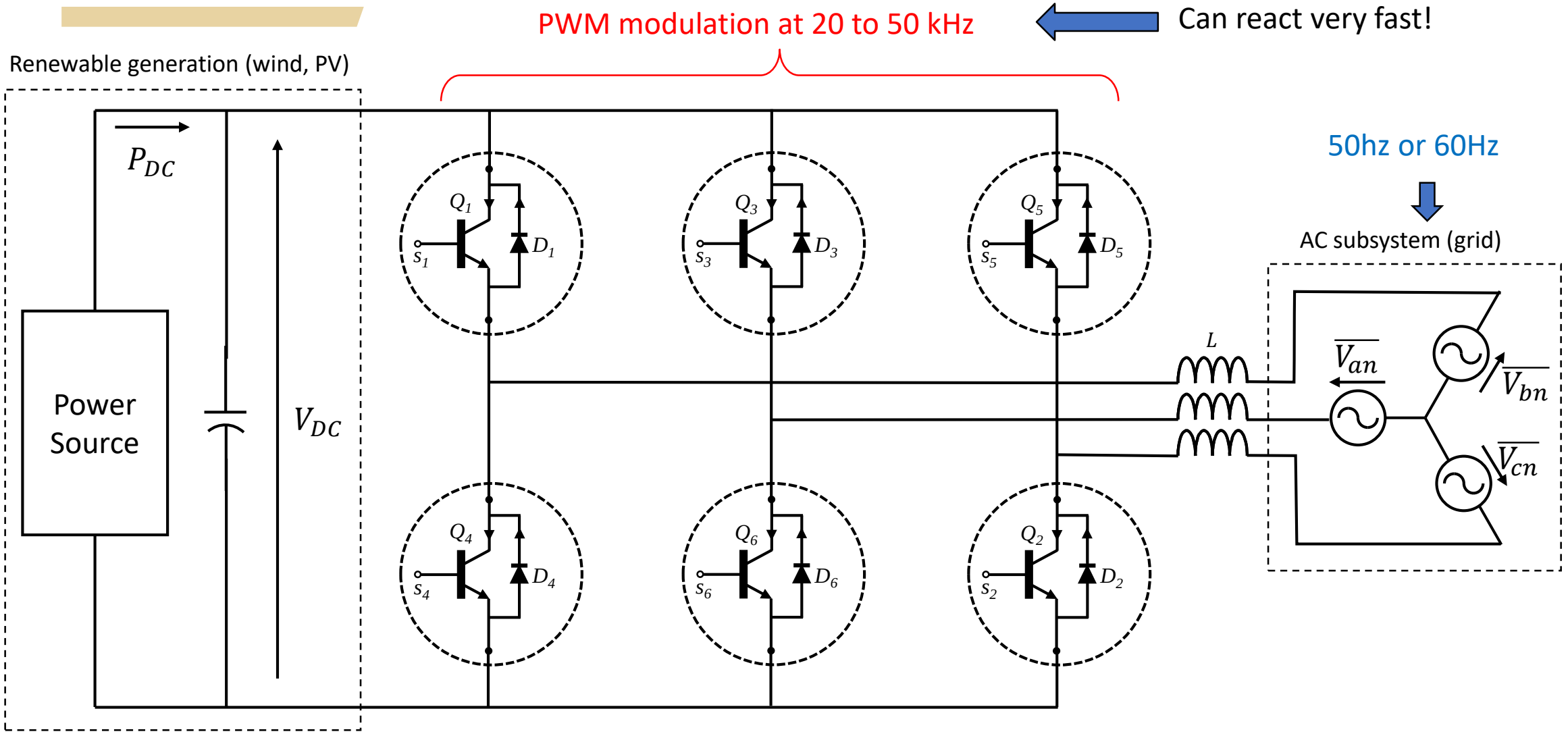
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Faults and inverter-based generation



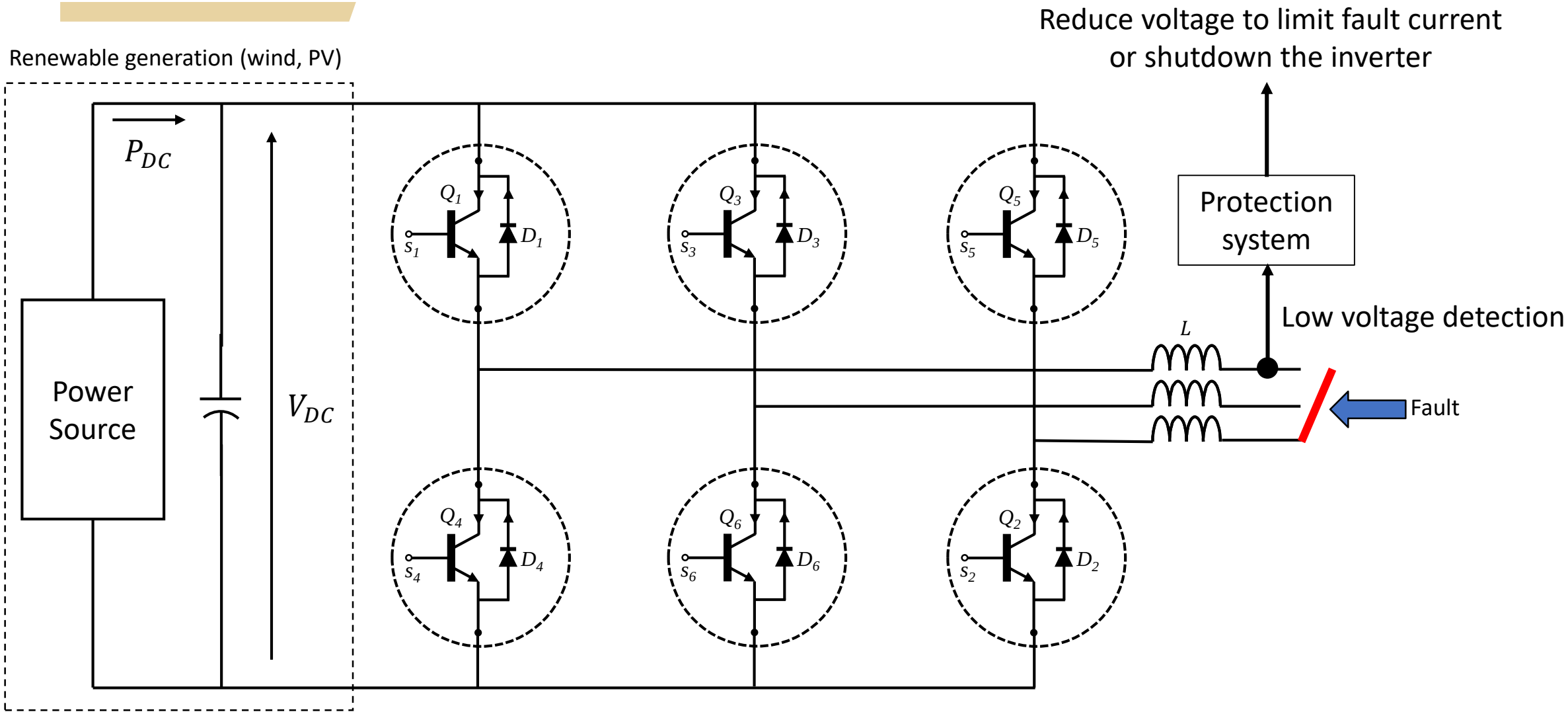
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Faults and inverter-based generation



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Faults and inverter-based generation



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Faults and inverter-based generation

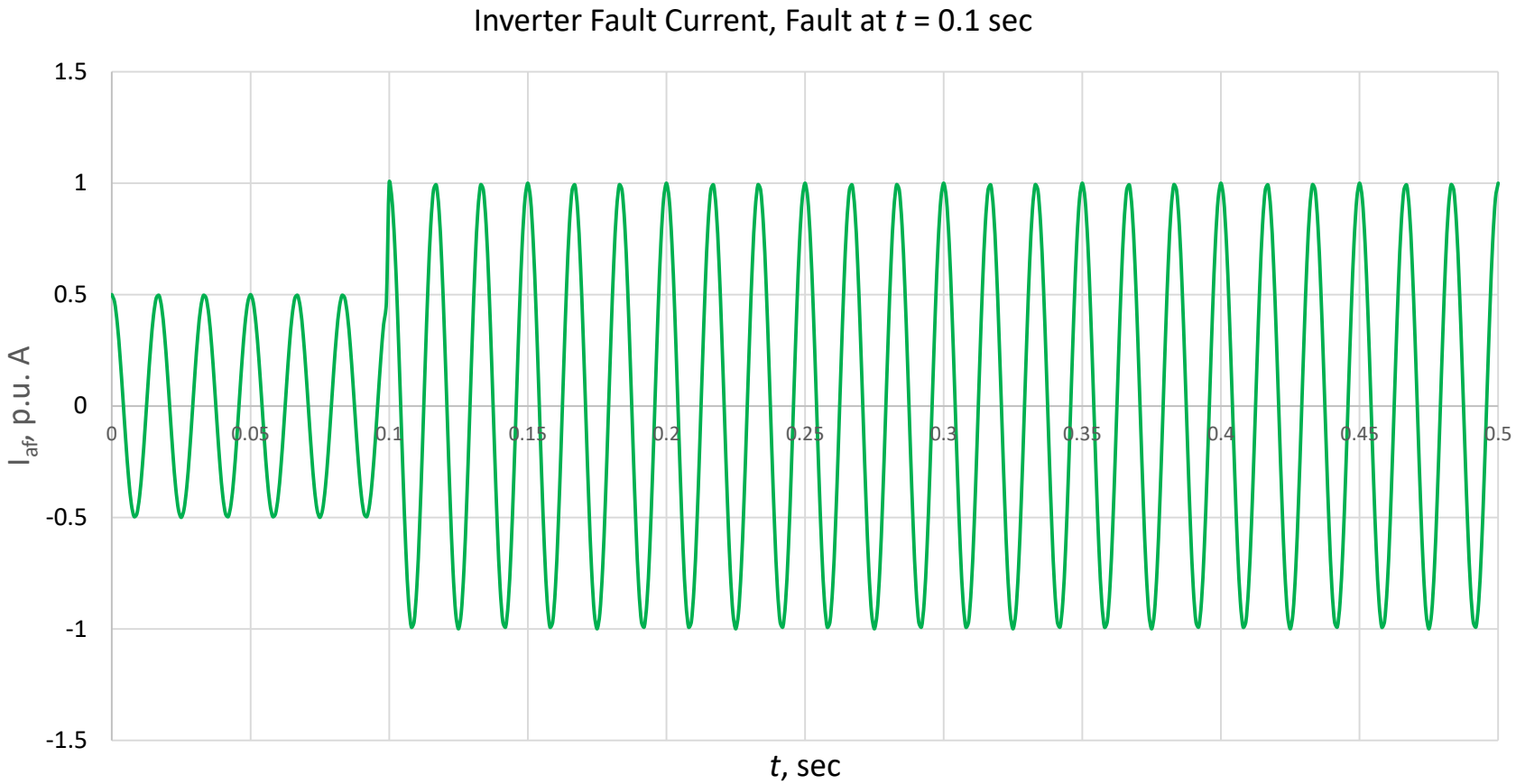
- Thanks to their high switching frequency, inverters can be controlled fast

→ Can limit the fault currents to avoid destroying semiconductor switches

- Near-instantaneous increase to current limit
- Steady-state thereafter

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Conceptual representation of fault current in an inverter



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Faults and inverter-based generation

- Good:
  - Much less fault current than from a generator
  - Prevents damage to power electronics
  - Prevents damage to other components (conductors, transformers, …)
- Bad:
  - Current limited to nominal value → can’t detect fault based on current

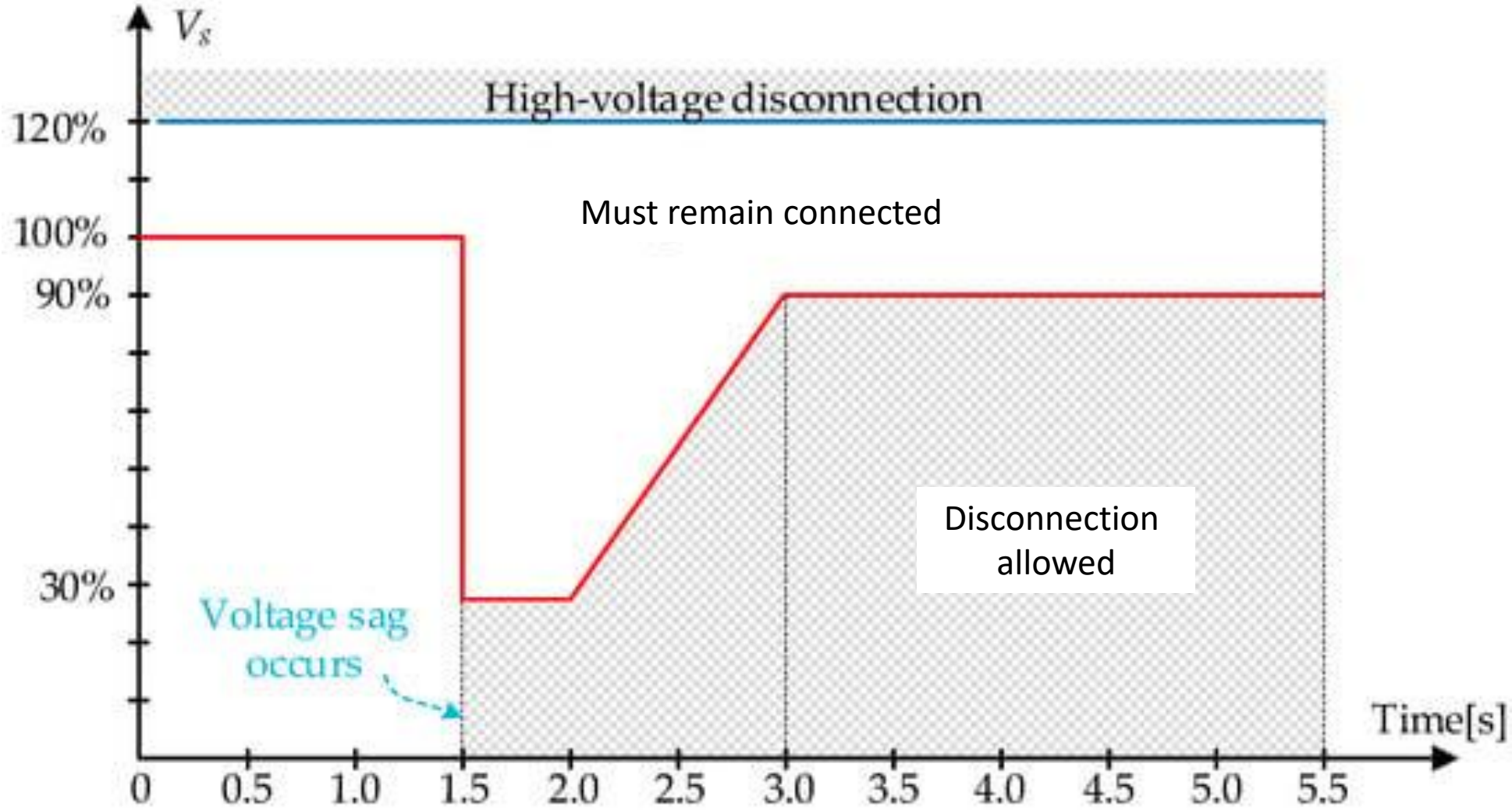
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Low Voltage Ride Through (LVRT)

- Inverters detect a fault by monitoring their terminal voltage
- They should disconnect if the voltage is excessively low
  - Because this indicates a fault in their close vicinity
- However, faults can cause a voltage sag over a wide area
- Not all inverter-based generation in this area should disconnect
  - This could create a dangerous load/generation imbalance
- Low Voltage Ride Through requirement on inverter-based generation

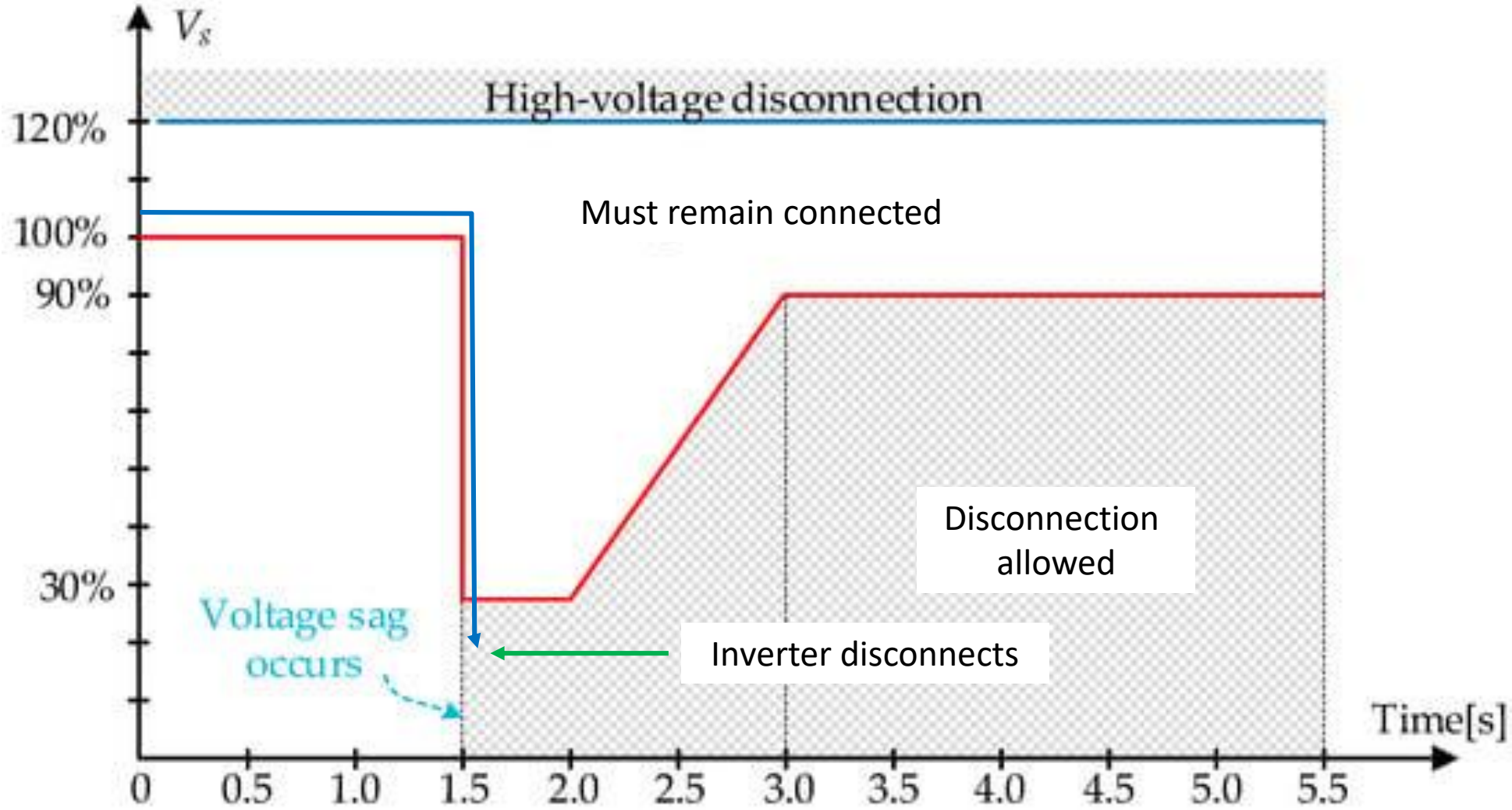
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Low Voltage Ride Through requirement (IEEE Standard)



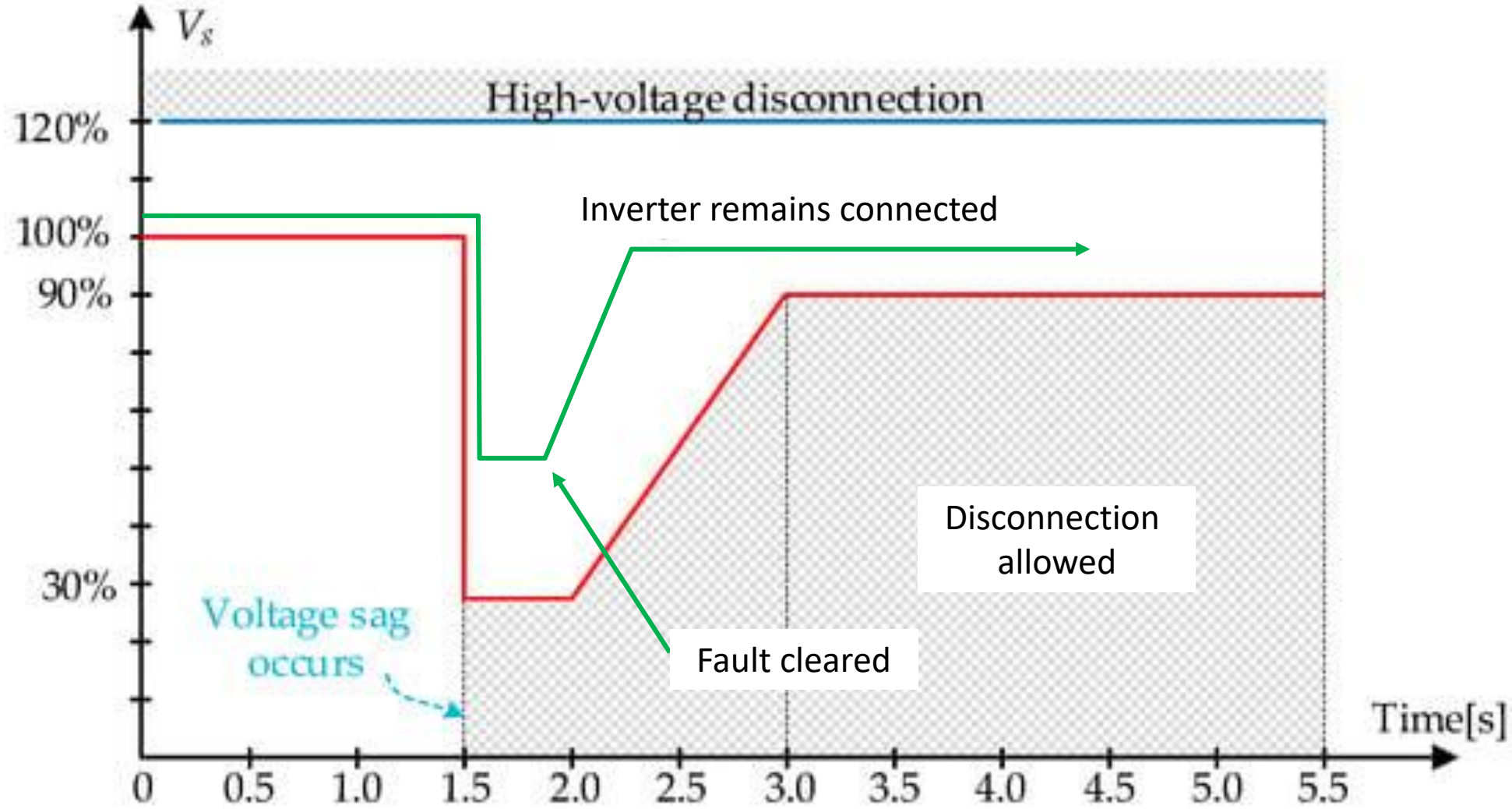
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Fault close to an inverter



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Fault further afield



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