# Capacitor Bank Unbalance Protection Calculations and Sensitivity Analysis

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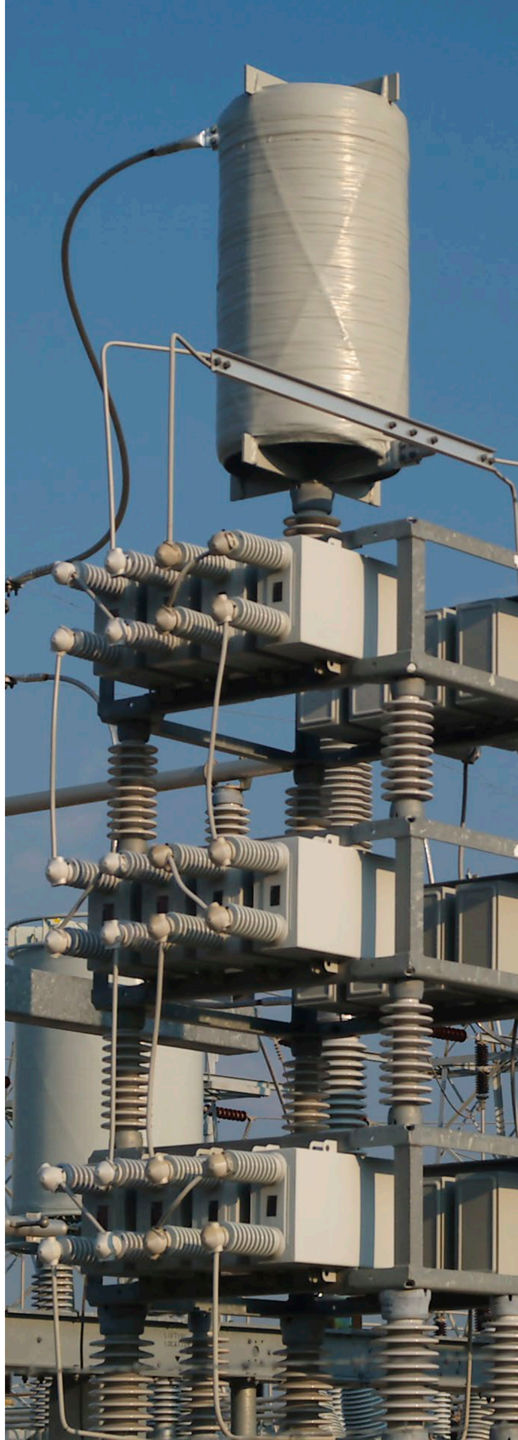
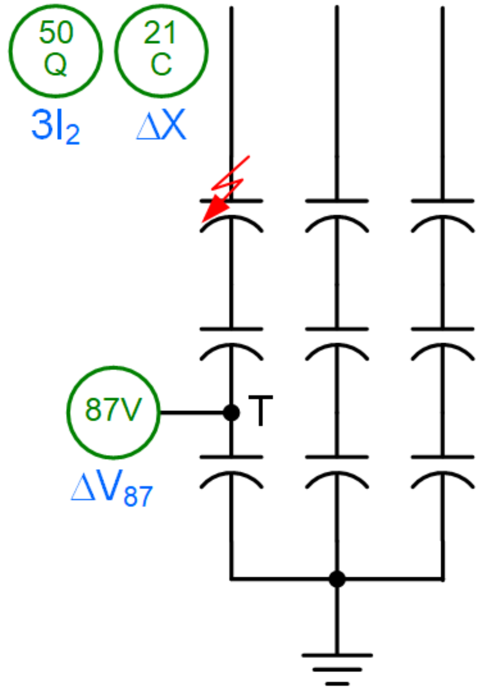
# Outline

- Common bank configurations and unbalance protection methods
- Capacitor unit arrangement, failure model, and the per-unit system
- Review of unbalance calculation equations
- Unbalance derivations explained
- Application to settings calculations
- Analysis and insights



# Common bank configurations

## Grounded single-wye

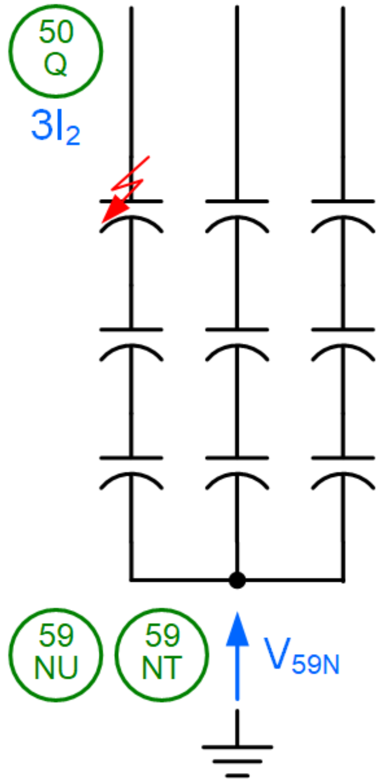


Unbalance protection

- 87V
- 50Q / 51Q / 50QT
- 21C

# Common bank configurations

## Ungrounded single-wye

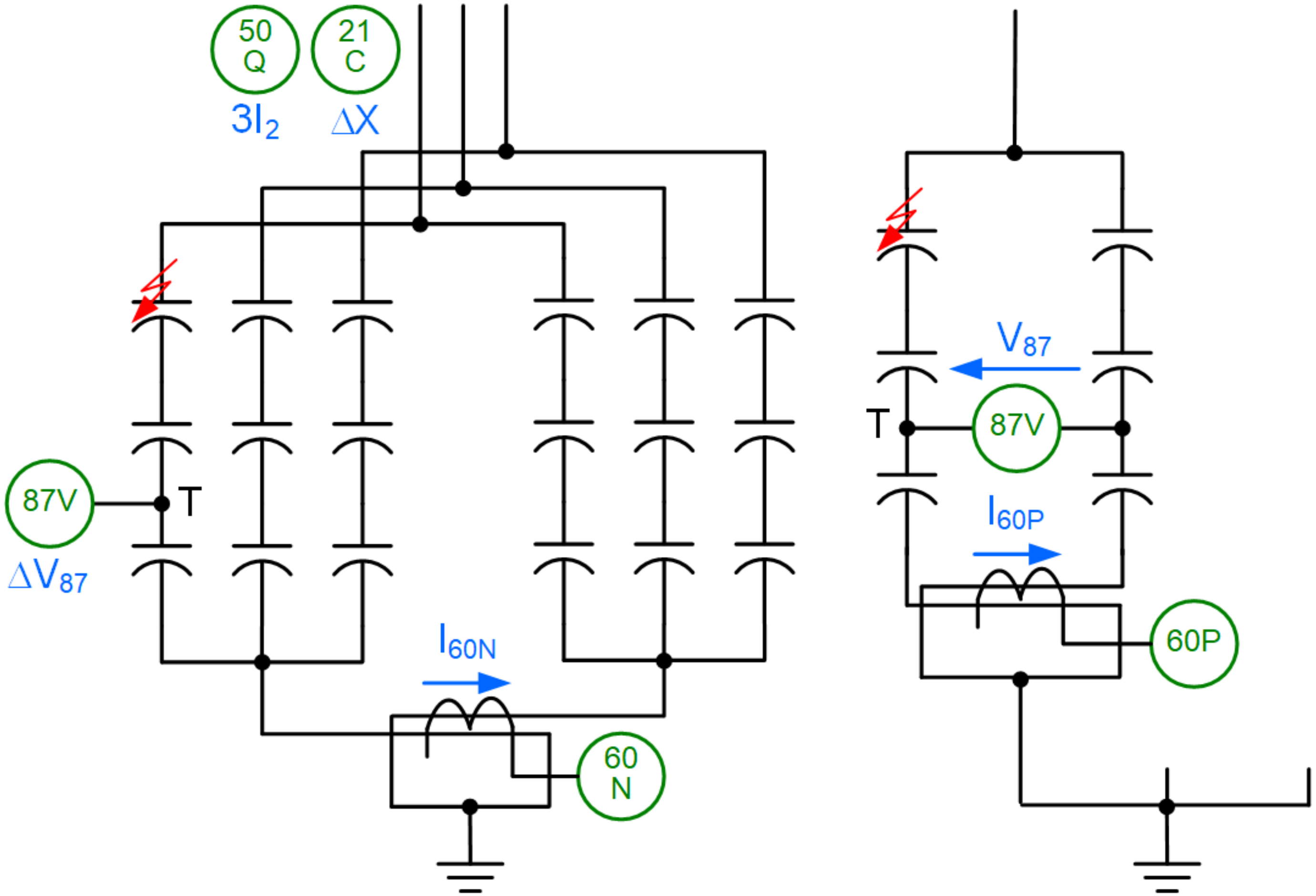


Unbalance protection

- 59NU
- 59NT
- 50Q / 51Q / 50QT

# Common bank configurations

## Grounded double-wye

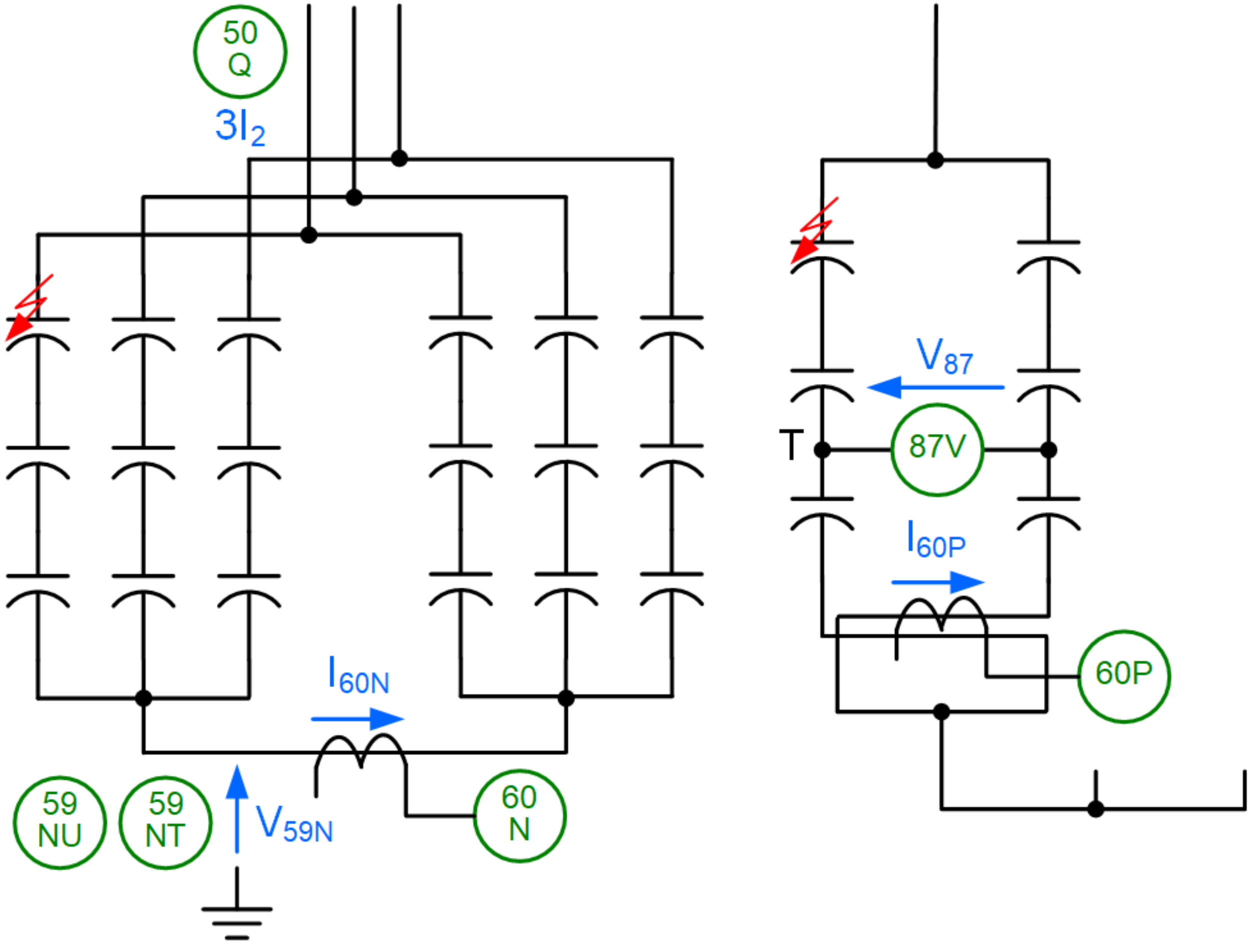


Unbalance protection

- 87V (tap-bus, tap-tap)
- 60P
- 60N
- 50Q / 51Q / 50QT
- 21C

# Common bank configurations

## Ungrounded double-wye

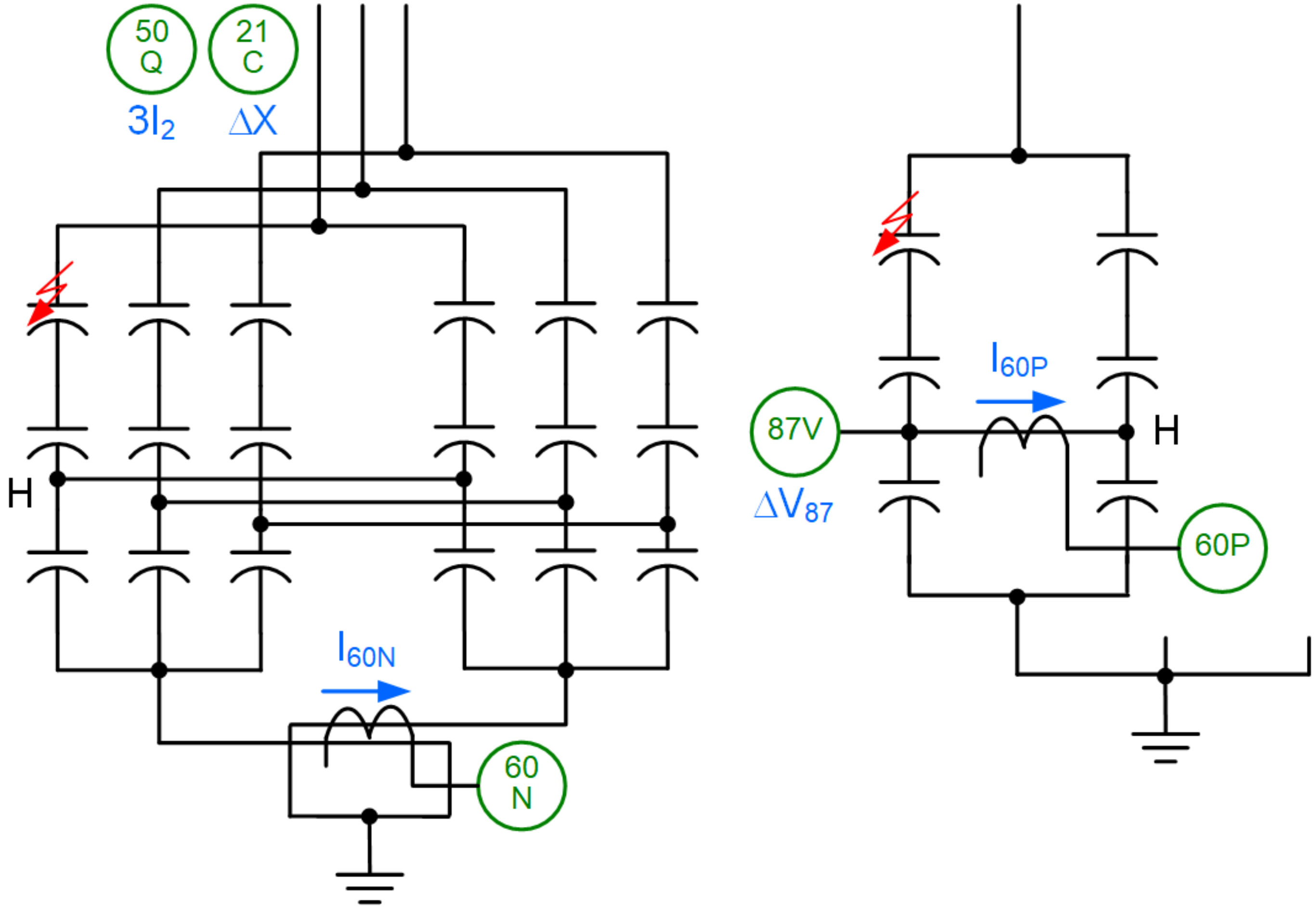


Unbalance protection

- 87V (tap-tap)
- 60P
- 60N
- 59NU
- 59NT
- 50Q / 51Q / 50QT

# Common bank configurations

## Grounded H-bridge

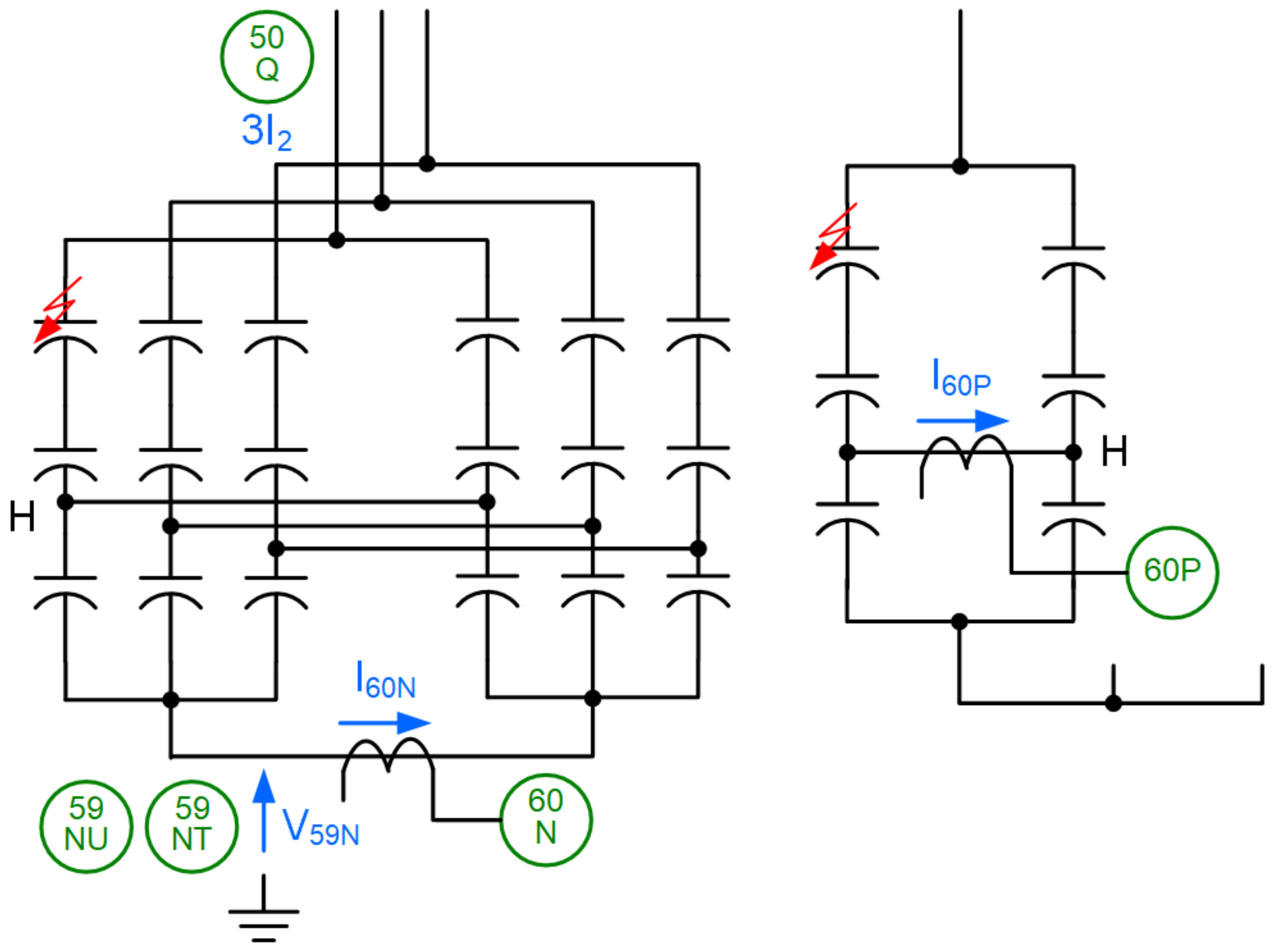


Unbalance protection

- 87V (tap-bus)
- 60P
- 60N
- 50Q / 51Q / 50QT
- 21C

# Common bank configurations

## Ungrounded H-bridge



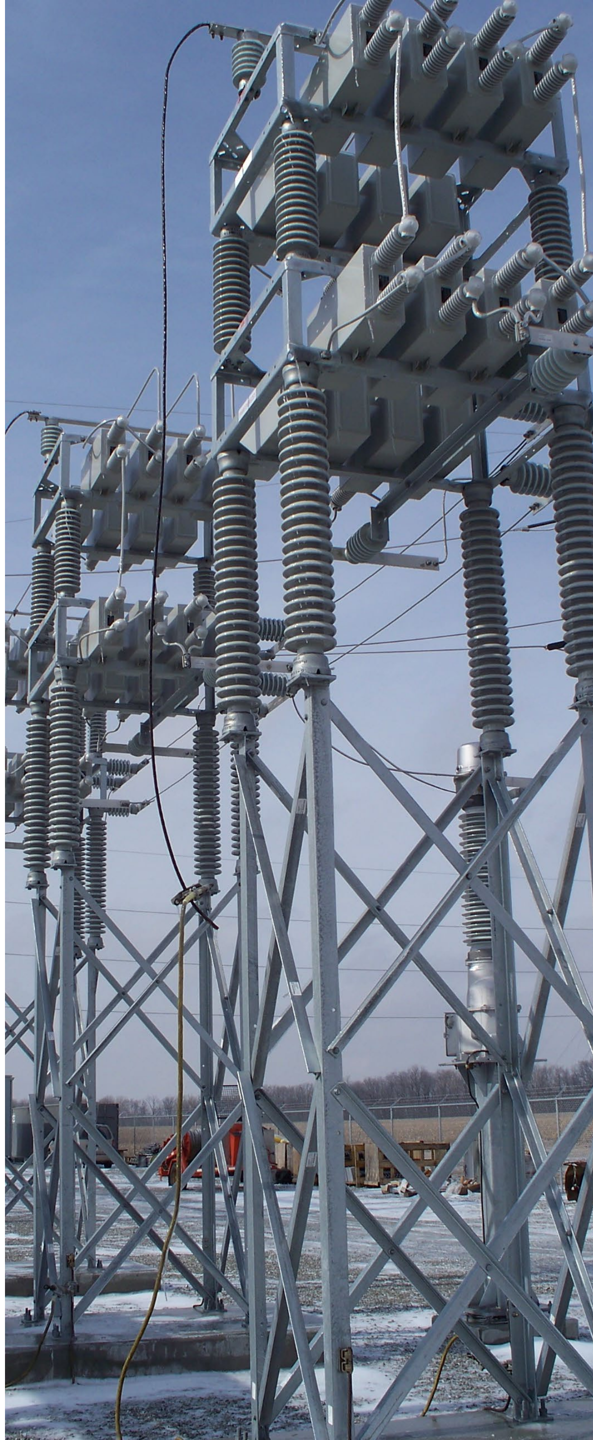
Unbalance protection

- 60P
- 60N
- 59NU
- 59NT
- 50Q / 51Q / 50QT

# Motivation

## Present approach

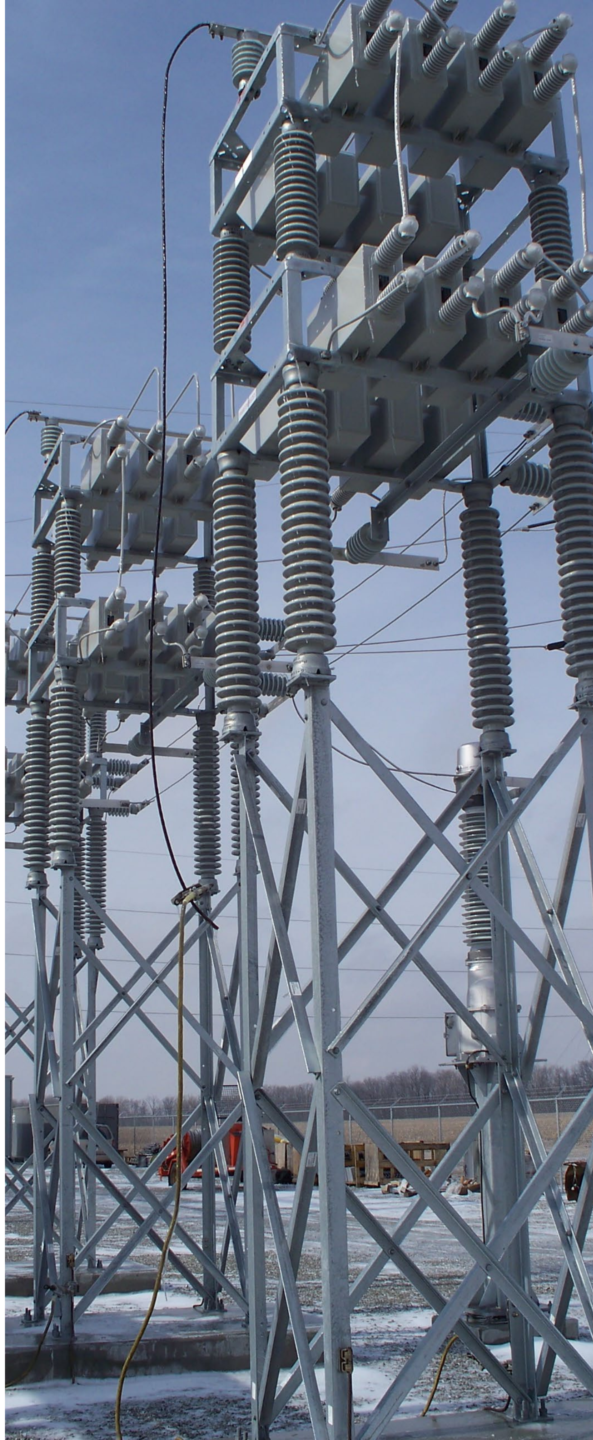
- Setting unbalance protection elements (alarm, trip) requires calculating their operating signals for unit failures
- Short-circuit programs do not support capacitor bank failure calculations
- Step-by-step calculations or home-made software used instead
- Weak justification for selecting alarm vs. trip thresholds



# Motivation

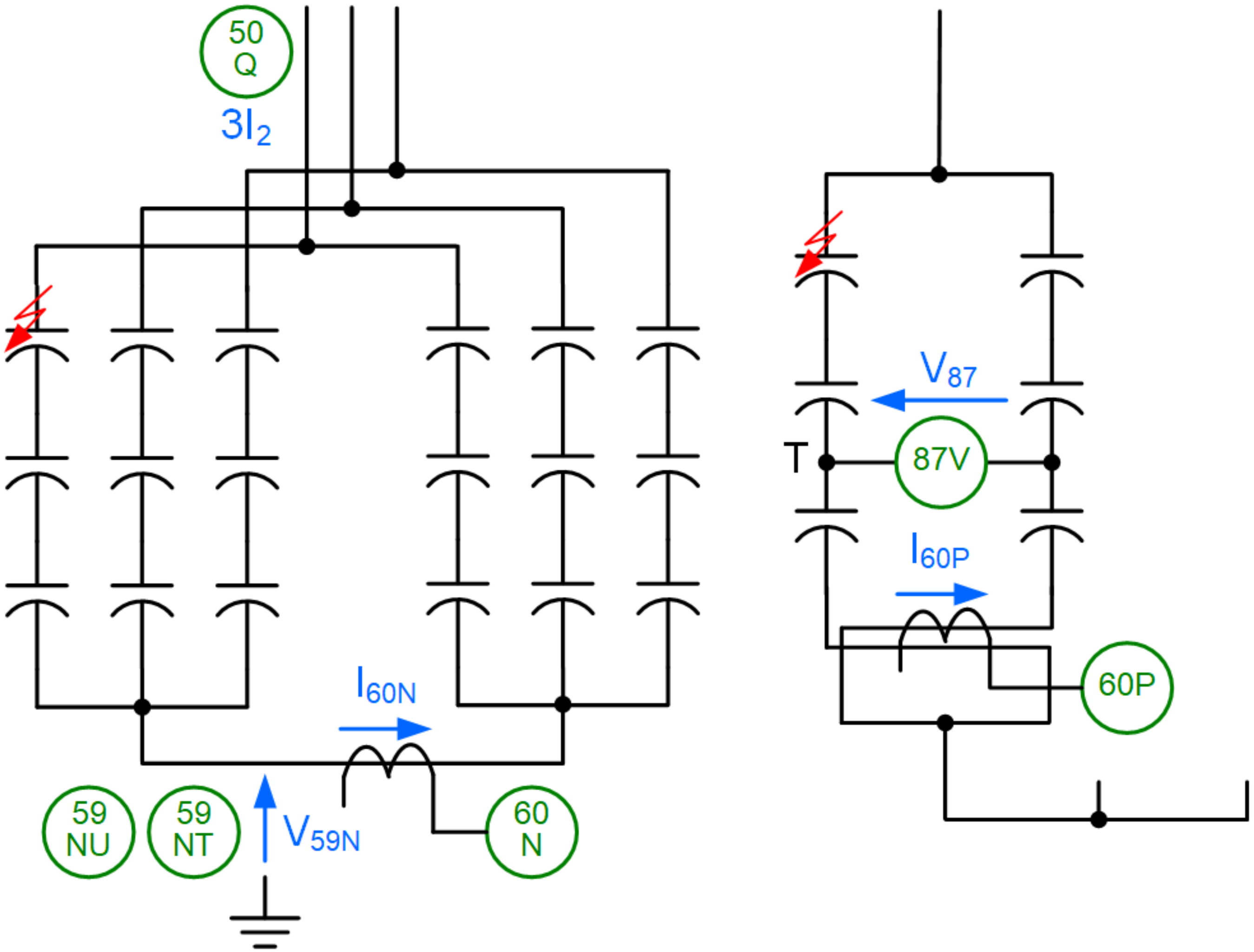
## Our approach

- One-step calculations for
  - All common bank configurations
  - All applicable unbalance protection elements
  - Fail-open and fail-short scenarios
  - Unbalance signal as (1) a function of failure size and (2) a function of healthy unit overvoltage
- Settings calculations
  - Alarm based on failure size
  - Trip before overvoltage breaches unit voltage rating



# What is a one-step calculation?

## Ungrounded double-wye bank



Basic bank data:

P number of units in a group

S number of groups in a string

R number of strings in a phase

T per-unit 87V tap position

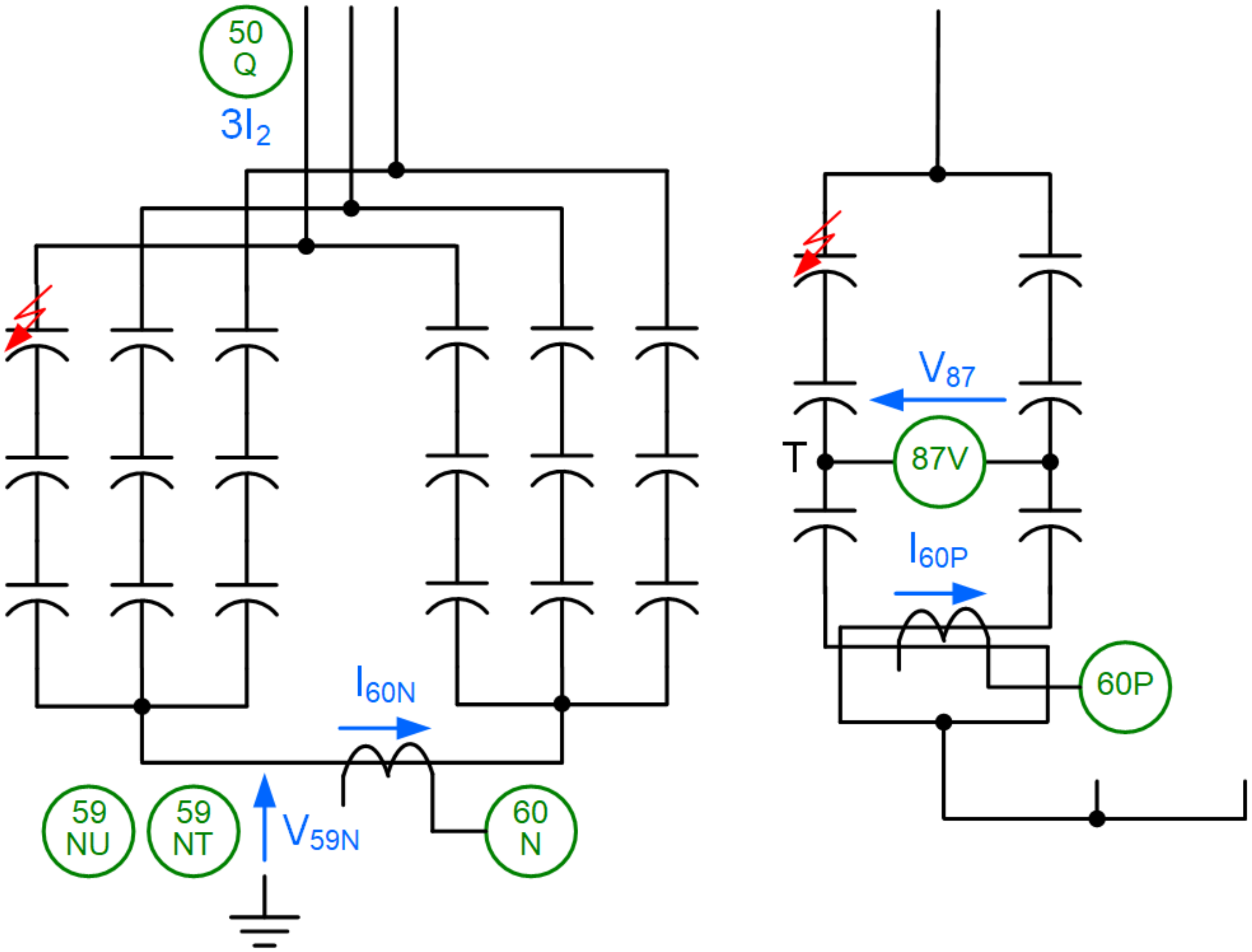
Basic failure data:

F number of failed units

Fused bank (fail-open scenario)

# What is a one-step calculation?

## Ungrounded double-wye bank



$$V_{59N} = \frac{F}{6SPR - F(6SR - 6R + 1)}$$

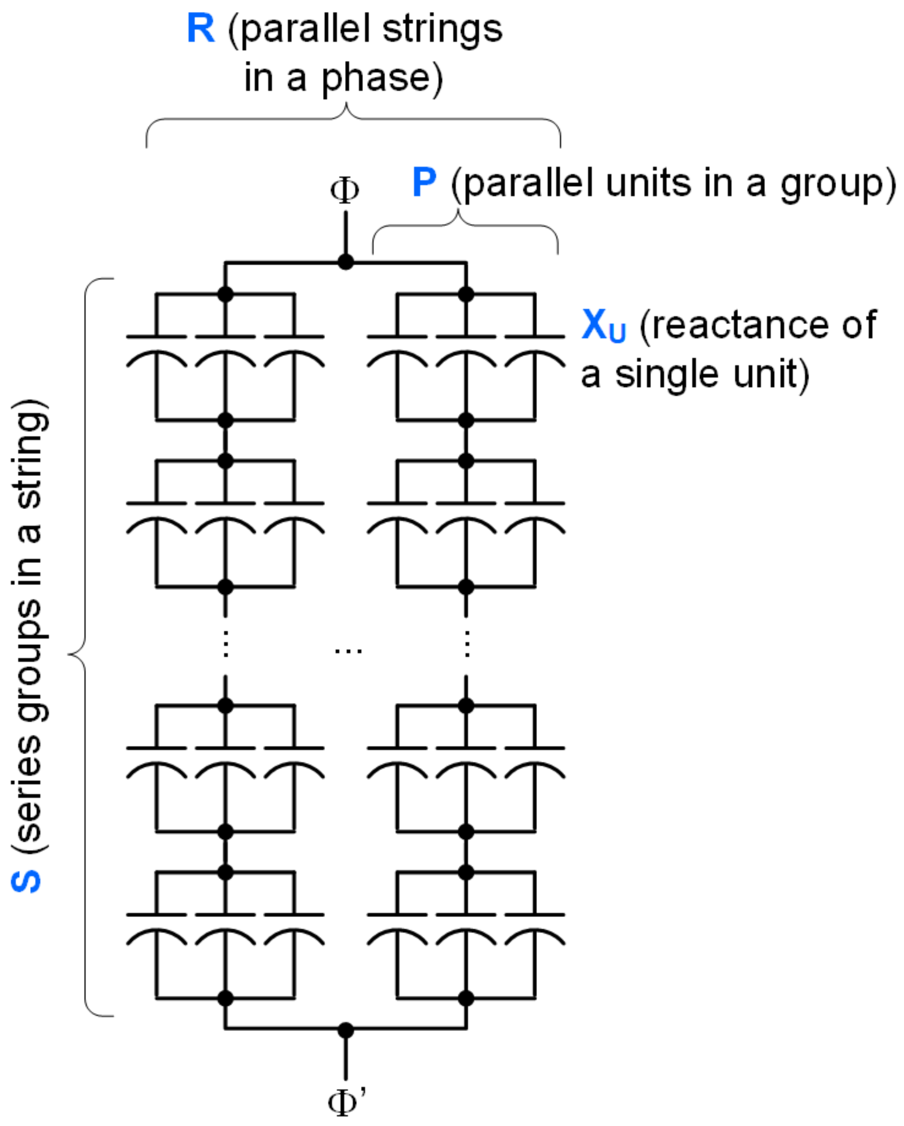
$$V_{87} = \frac{6TF}{6SRP - F\left(6SR - \frac{6R - 5T - 1}{1 - T}\right)}$$

$$3I_2 = \frac{3F}{6SPR - F(6SR - 6R + 1)}$$

$$I_{60P} = \frac{3F}{6SPR - F(6SR - 6R + 1)}$$

$$I_{60N} = \frac{1}{2}\frac{3F}{6SPR - F(6SR - 6R + 1)}$$

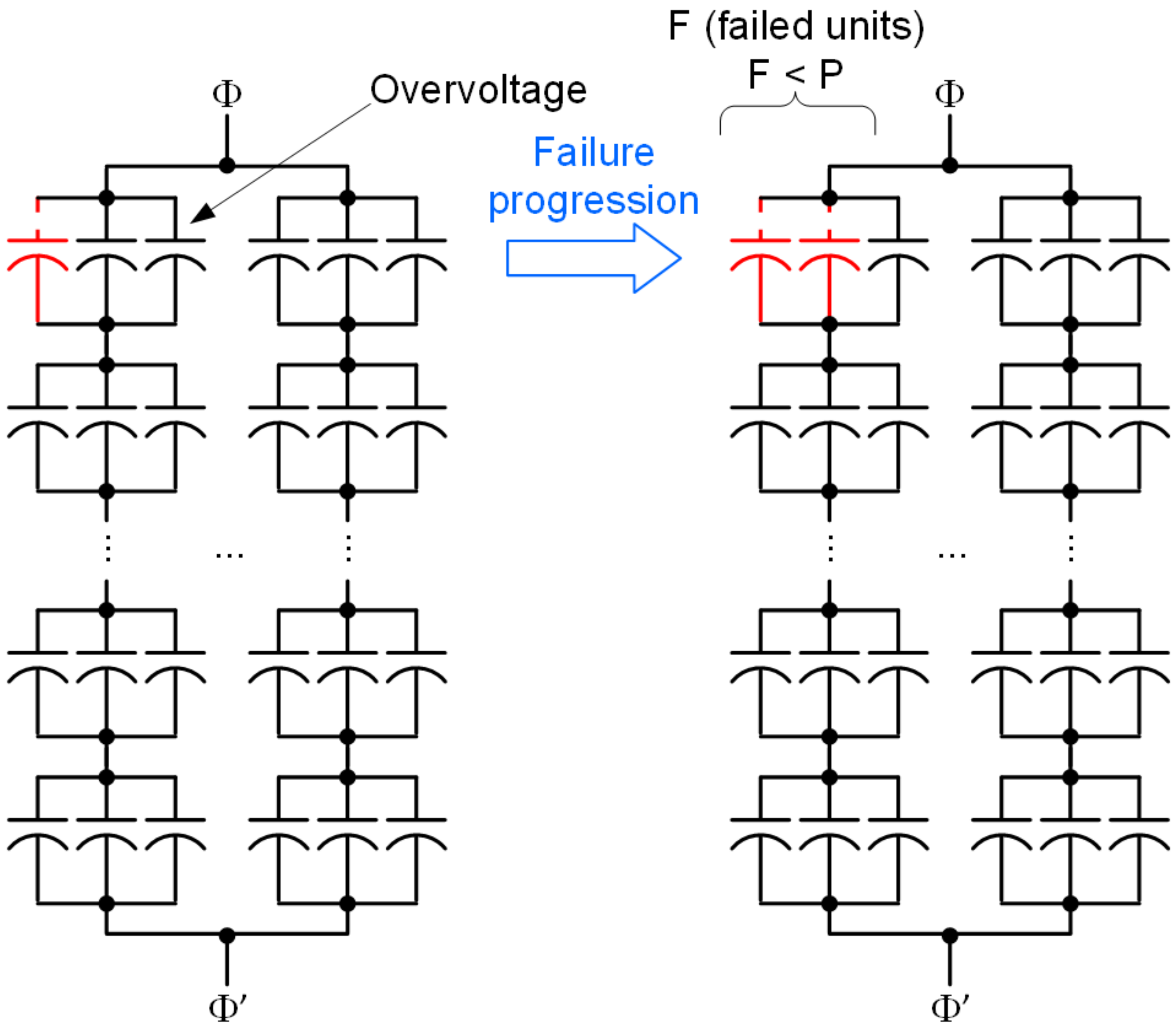
# Capacitor unit arrangement



- For simplicity and symmetry, we use the same model for
  - Fuseless banks
  - Internally fused banks
  - Externally fused banks
- Not all combinations apply to practical banks, but
- All practical banks are covered by our calculations

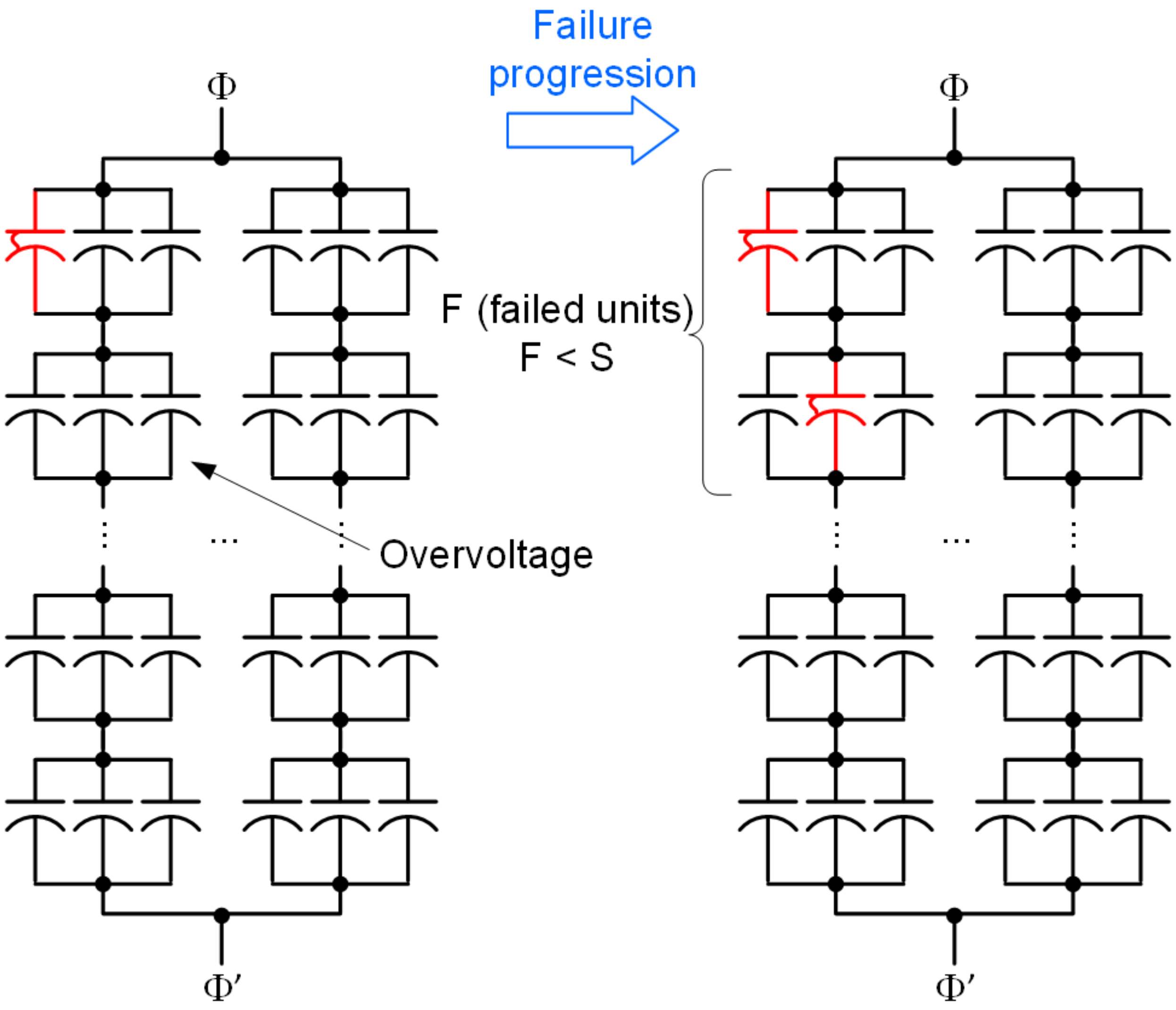
# Capacitor unit failure models

## Fail-open scenario



# Capacitor unit failure models

## Fail-short scenario



# Per-unit system

- Per-unit short-circuit calculations serve us well in many applications
- In per unit, the capacitor unbalance calculations simplify considerably
- In per unit, it is easy to spot errors and see patterns

**Base voltage**
phase-to-ground system nominal voltage

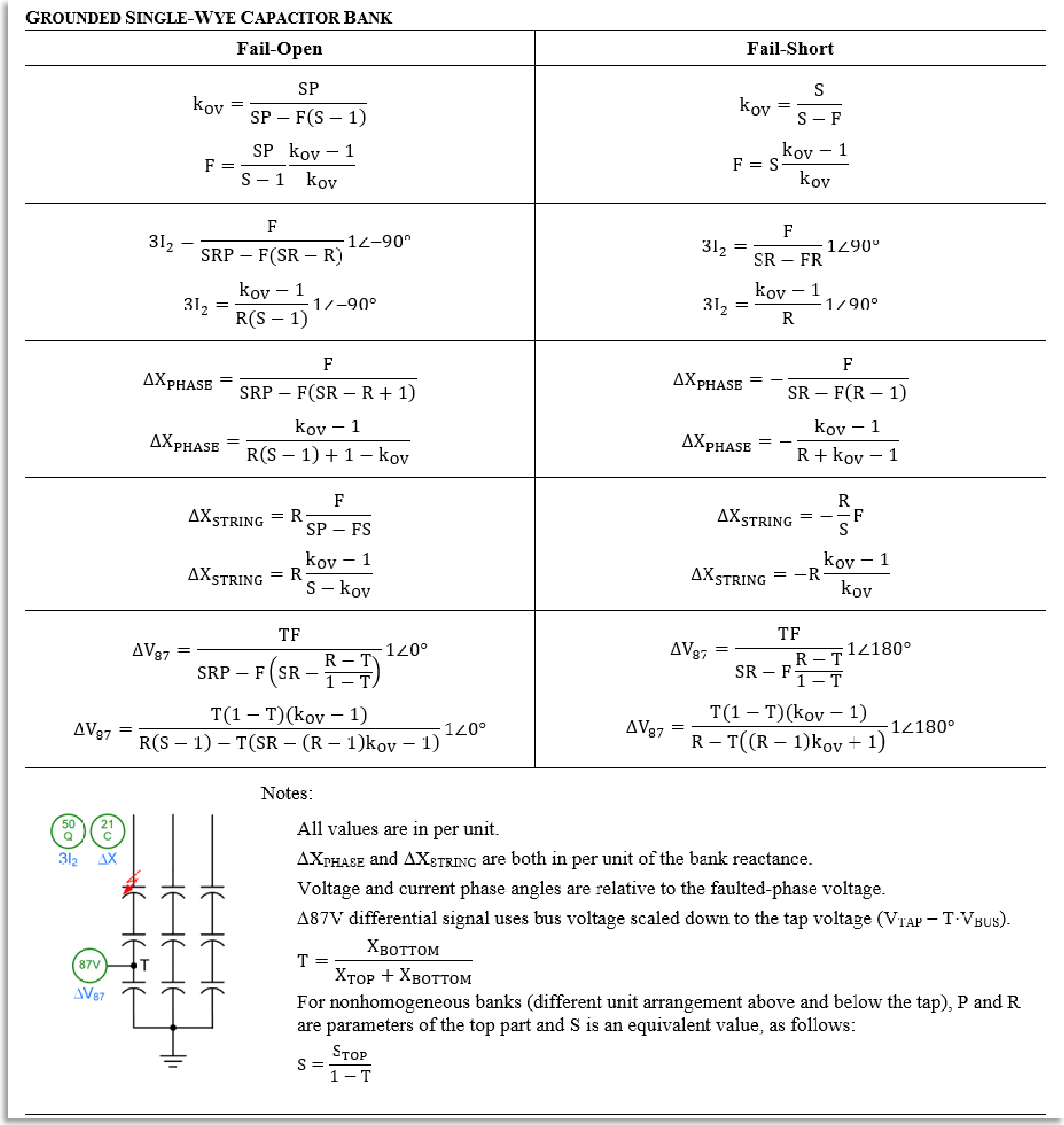
**Base current**
bank current under nominal system voltage

**Base reactance**
base voltage / base current

**Secondary value**
per-unit value • base value / instrument transformer ratio

# Key output of this work

- Appendix A
- One page for each bank configuration
- Fail-open and fail-short columns
- Self-contained reference material



GROUNDED SINGLE-WYE CAPACITOR BANK

| Fail-Open | Fail-Short |
|---|---|
| $k_{OV} = \frac{SP}{SP - F(S-1)}$<br>$F = \frac{SP}{S-1}\frac{k_{OV}-1}{k_{OV}}$ | $k_{OV} = \frac{S}{S-F}$<br>$F = S\frac{k_{OV}-1}{k_{OV}}$ |
| $3I_2 = \frac{F}{SRP - F(SR-R)} 1\angle{-90°}$<br>$3I_2 = \frac{k_{OV}-1}{R(S-1)} 1\angle{-90°}$ | $3I_2 = \frac{F}{SR - FR} 1\angle 90°$<br>$3I_2 = \frac{k_{OV}-1}{R} 1\angle 90°$ |
| $\Delta X_{PHASE} = \frac{F}{SRP - F(SR - R + 1)}$<br>$\Delta X_{PHASE} = \frac{k_{OV}-1}{R(S-1) + 1 - k_{OV}}$ | $\Delta X_{PHASE} = -\frac{F}{SR - F(R-1)}$<br>$\Delta X_{PHASE} = -\frac{k_{OV}-1}{R + k_{OV} - 1}$ |
| $\Delta X_{STRING} = R\frac{F}{SP - FS}$<br>$\Delta X_{STRING} = R\frac{k_{OV}-1}{S - k_{OV}}$ | $\Delta X_{STRING} = -\frac{R}{S}F$<br>$\Delta X_{STRING} = -R\frac{k_{OV}-1}{k_{OV}}$ |
| $\Delta V_{87} = \frac{TF}{SRP - F\left(SR - \frac{R-T}{1-T}\right)} 1\angle 0°$<br>$\Delta V_{87} = \frac{T(1-T)(k_{OV}-1)}{R(S-1) - T(SR - (R-1)k_{OV} - 1)} 1\angle 0°$ | $\Delta V_{87} = \frac{TF}{SR - F\frac{R-T}{1-T}} 1\angle 180°$<br>$\Delta V_{87} = \frac{T(1-T)(k_{OV}-1)}{R - T\left((R-1)k_{OV} + 1\right)} 1\angle 180°$ |

Notes:

All values are in per unit.

$\Delta X_{PHASE}$ and $\Delta X_{STRING}$ are both in per unit of the bank reactance.

Voltage and current phase angles are relative to the faulted-phase voltage.

Δ87V differential signal uses bus voltage scaled down to the tap voltage ($V_{TAP} - T \cdot V_{BUS}$).

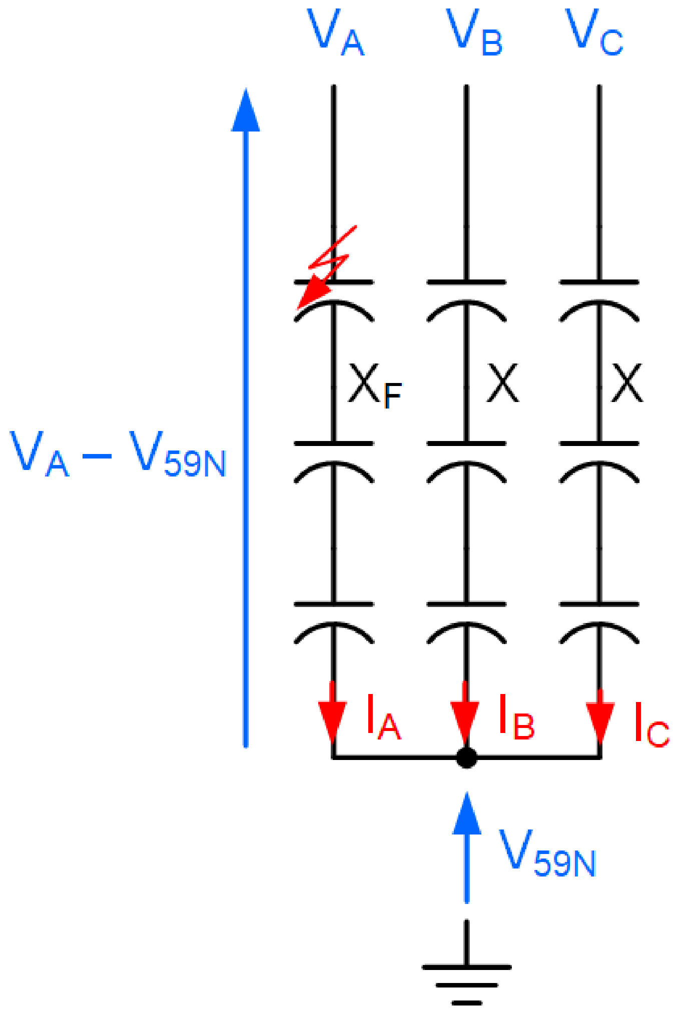
$$T = \frac{X_{BOTTOM}}{X_{TOP} + X_{BOTTOM}}$$

For nonhomogeneous banks (different unit arrangement above and below the tap), P and R are parameters of the top part and S is an equivalent value, as follows:

$$S = \frac{S_{TOP}}{1-T}$$

# Unbalance derivations

## $V_{59N}$ in an ungrounded single-wye bank



$$I_A + I_B + I_C = 0$$

$$\frac{V_A - V_{59N}}{-jX_F} + \frac{V_B - V_{59N}}{-jX} + \frac{V_C - V_{59N}}{-jX} = 0$$

$$V_B = a^2 \cdot V_A, \qquad V_C = a \cdot V_A, \qquad a = 1\angle 120°$$

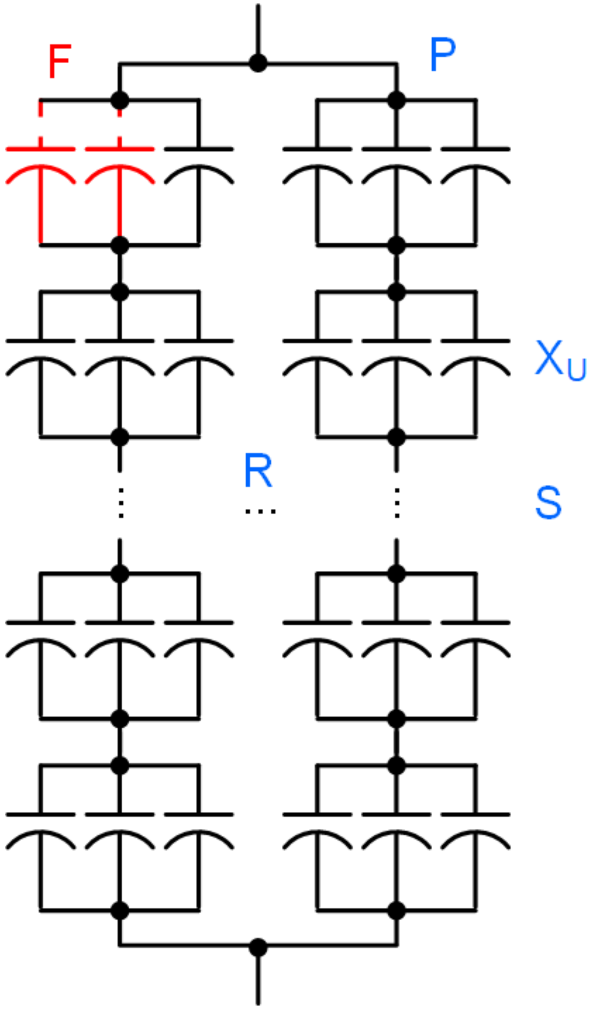
$$V_{59N} \cdot \left(\frac{1}{X_F} + \frac{2}{X}\right) = V_A \cdot \left(\frac{1}{X_F} + \frac{a^2 + a}{X}\right)$$

$$V_{59N} \cdot \left(\frac{X + 2 \cdot X_F}{X \cdot X_F}\right) = V_A \cdot \left(\frac{X - X_F}{X \cdot X_F}\right)$$

$$V_{59N} = V_A \cdot \left(\frac{X - X_F}{X + 2 \cdot X_F}\right)$$

# Unbalance derivations

## $V_{59N}$ in an ungrounded single-wye bank



$$V_{59N} = V_A \cdot \left( \frac{X - X_F}{X + 2 \cdot X_F} \right)$$

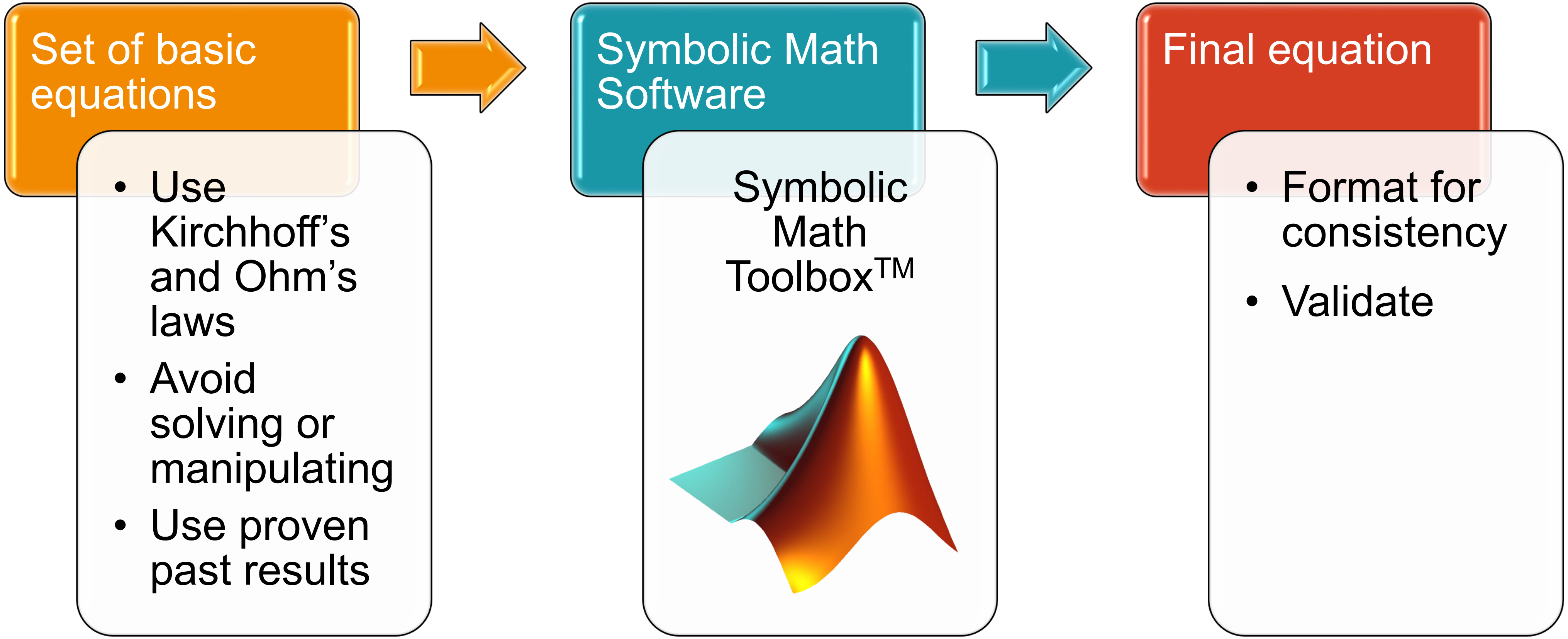
$$X = \frac{X_U}{P} \cdot S \cdot \frac{1}{R}$$

$$(X_F)^{-1} = \left( \frac{X_U}{P - F} + \frac{X_U}{P} \cdot (S - 1) \right)^{-1} + \left( \frac{X_U}{P} \cdot S \cdot \frac{1}{R - 1} \right)^{-1}$$

$$\boxed{V_{59N(PU)} = \frac{F}{3 \cdot S \cdot P \cdot R - F \cdot (3 \cdot S \cdot R - 3 \cdot R + 1)} \cdot 1\angle 180°}$$

# Unbalance derivations

## Methodology



Set of basic equations

- Use Kirchhoff’s and Ohm’s laws
- Avoid solving or manipulating
- Use proven past results

Symbolic Math Software

Symbolic Math Toolbox™

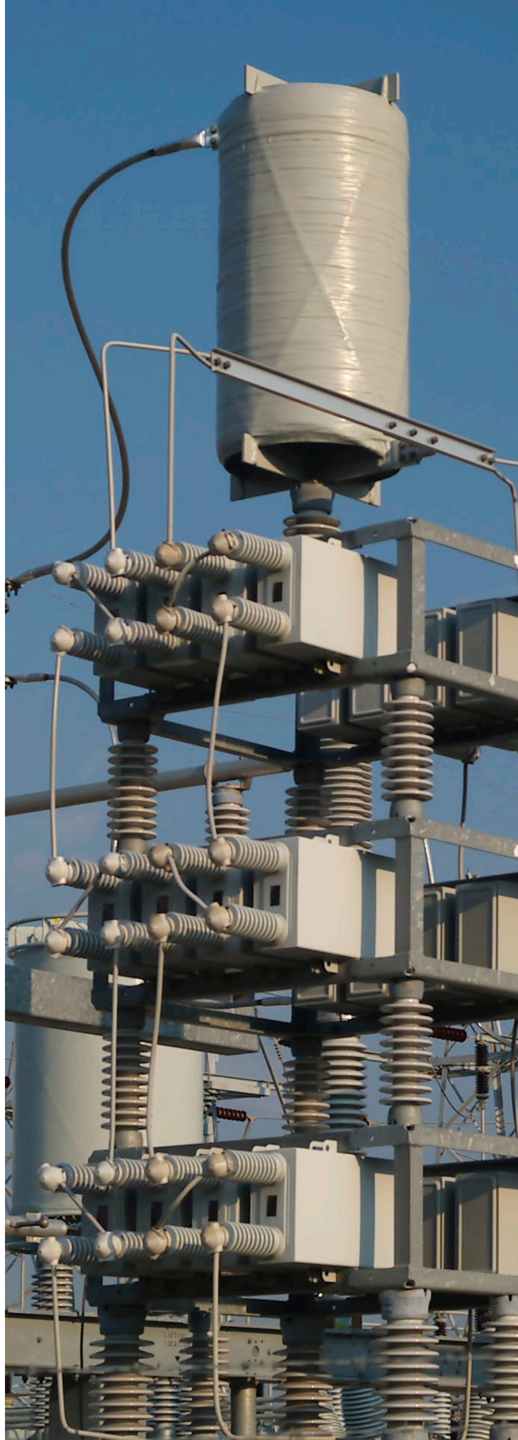
Final equation

- Format for consistency
- Validate

# Unbalance derivations

## Validation

- Inspect for expected results
- Inspect for symmetry with other equations
- Run RTDS simulations for all bank configurations by using different bank parameters
- Compare with known examples (e.g., C37.99, past projects)



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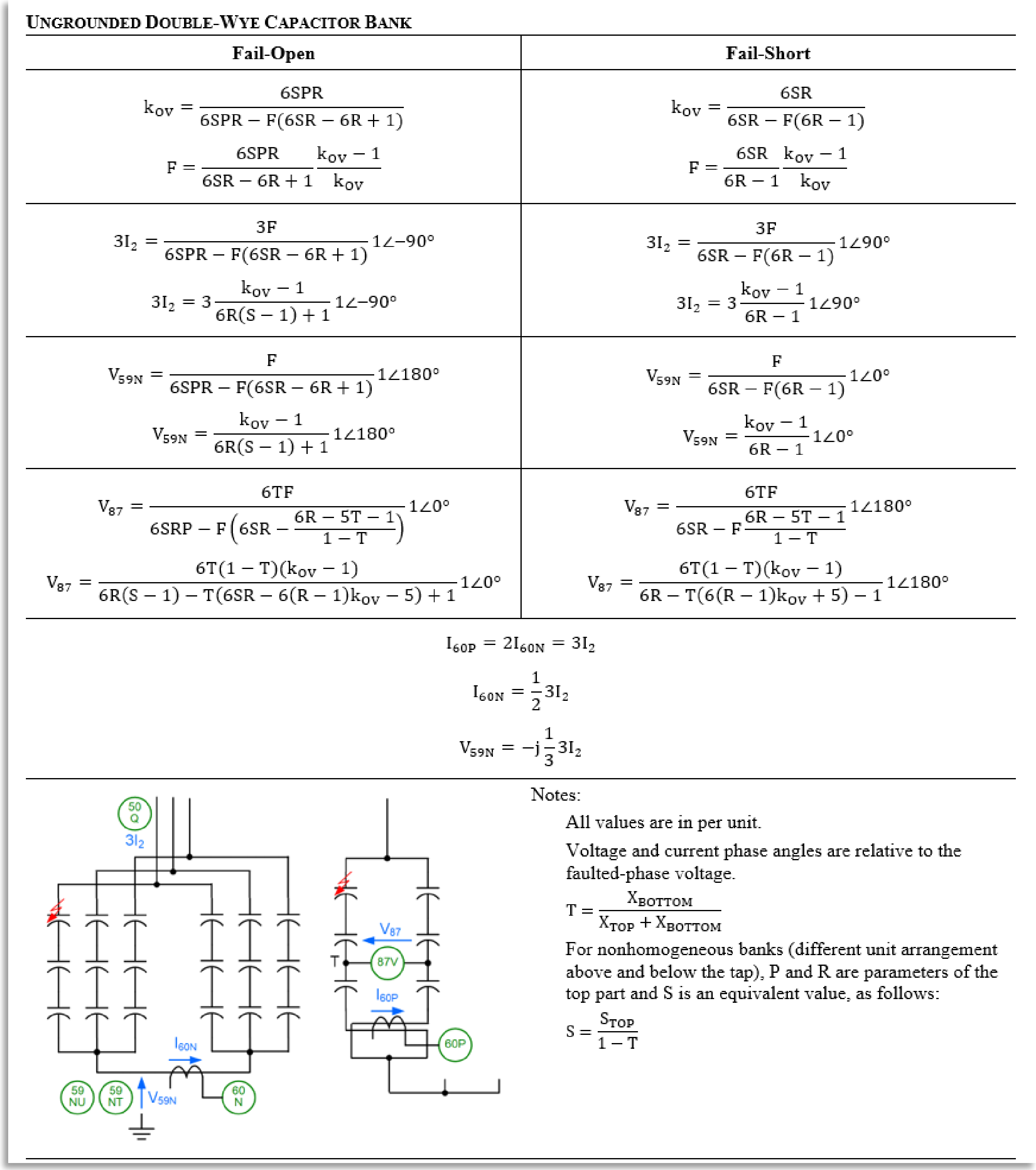


### UNGROUNDED DOUBLE-WYE CAPACITOR BANK

| **Fail-Open** | **Fail-Short** |
|---|---|
| $k_{OV} = \frac{6SPR}{6SPR - F(6SR - 6R + 1)}$<br>$F = \frac{6SPR}{6SR - 6R + 1} \frac{k_{OV} - 1}{k_{OV}}$ | $k_{OV} = \frac{6SR}{6SR - F(6R - 1)}$<br>$F = \frac{6SR}{6R - 1} \frac{k_{OV} - 1}{k_{OV}}$ |
| $3I_2 = \frac{3F}{6SPR - F(6SR - 6R + 1)} 1\angle{-90°}$<br>$3I_2 = 3 \frac{k_{OV} - 1}{6R(S - 1) + 1} 1\angle{-90°}$ | $3I_2 = \frac{3F}{6SR - F(6R - 1)} 1\angle 90°$<br>$3I_2 = 3 \frac{k_{OV} - 1}{6R - 1} 1\angle 90°$ |
| $V_{59N} = \frac{F}{6SPR - F(6SR - 6R + 1)} 1\angle 180°$<br>$V_{59N} = \frac{k_{OV} - 1}{6R(S - 1) + 1} 1\angle 180°$ | $V_{59N} = \frac{F}{6SR - F(6R - 1)} 1\angle 0°$<br>$V_{59N} = \frac{k_{OV} - 1}{6R - 1} 1\angle 0°$ |
| $V_{87} = \frac{6TF}{6SRP - F\left(6SR - \frac{6R - 5T - 1}{1 - T}\right)} 1\angle 0°$<br>$V_{87} = \frac{6T(1 - T)(k_{OV} - 1)}{6R(S - 1) - T(6SR - 6(R - 1)k_{OV} - 5) + 1} 1\angle 0°$ | $V_{87} = \frac{6TF}{6SR - F\frac{6R - 5T - 1}{1 - T}} 1\angle 180°$<br>$V_{87} = \frac{6T(1 - T)(k_{OV} - 1)}{6R - T(6(R - 1)k_{OV} + 5) - 1} 1\angle 180°$ |

$$I_{60P} = 2I_{60N} = 3I_2$$

$$I_{60N} = \frac{1}{2} 3I_2$$

$$V_{59N} = -j\frac{1}{3} 3I_2$$

Notes:

All values are in per unit.

Voltage and current phase angles are relative to the faulted-phase voltage.

$$T = \frac{X_{BOTTOM}}{X_{TOP} + X_{BOTTOM}}$$

For nonhomogeneous banks (different unit arrangement above and below the tap), P and R are parameters of the top part and S is an equivalent value, as follows:

$$S = \frac{S_{TOP}}{1 - T}$$

# Introducing overvoltage factor

$$k_{OV} = \frac{\text{Voltage across the most stressed healthy unit due to a failure}}{\text{Unit voltage during nominal system conditions}}$$

- In the paper, we have
  - Derived $k_{OV}$ as a function of failure size for all bank configurations and the fail-open and fail-short failure modes
  - Expressed each unbalance signal as a function of $k_{OV}$
- You can calculate the highest permissible $k_{OV}$ and use it to calculate trip thresholds

$$k_{OV} = 1.1 \cdot \frac{V_U}{\left(\frac{V_{NOM}}{\sqrt{3} \cdot S}\right)} = 1.1 \cdot \frac{S \cdot V_U}{V_{BASE}}$$

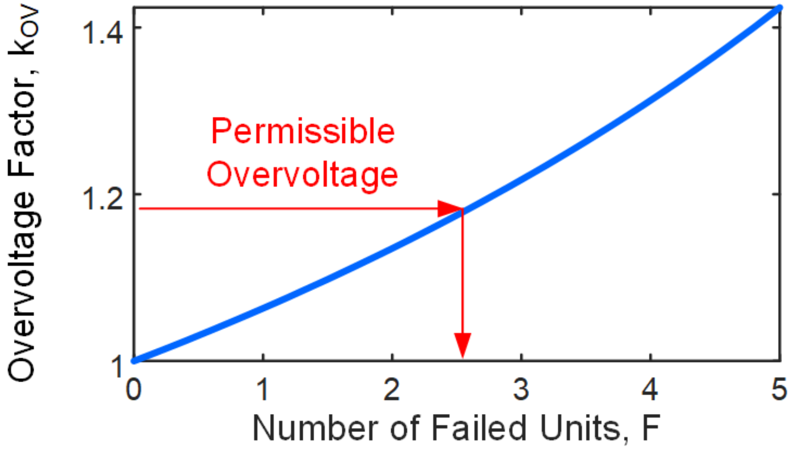
# Setting trip thresholds
## Ungrounded single-wye bank, fail-open example

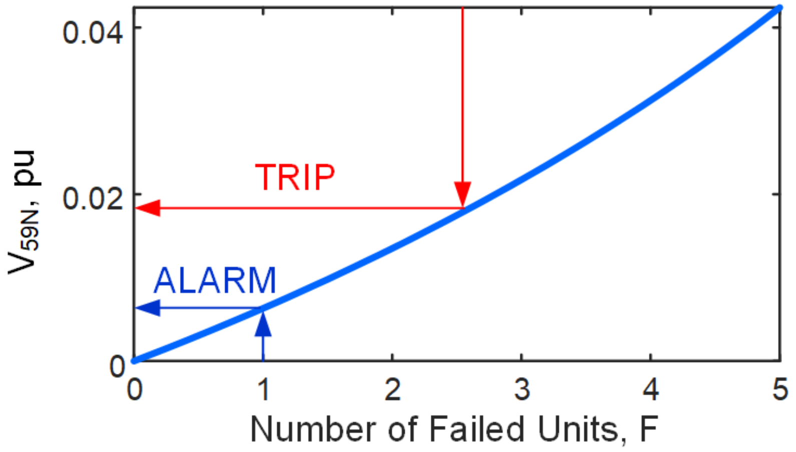
$$k_{OV} = \frac{3SPR}{3SPR - F(3SR - 3R + 1)}$$

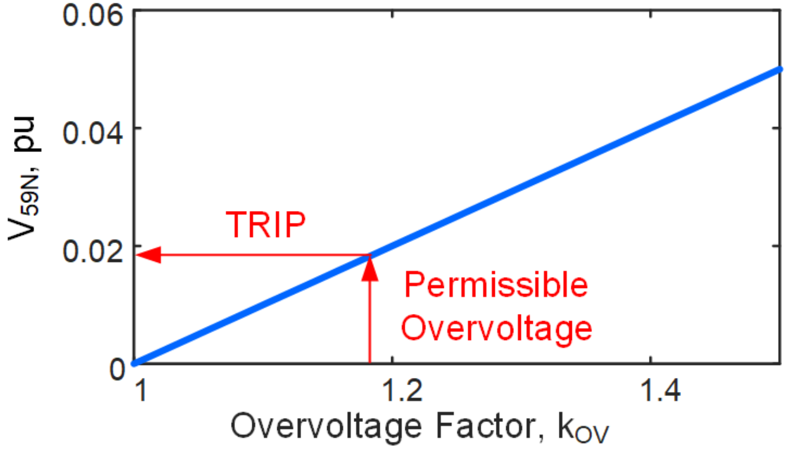
$$F = \frac{3SPR}{3SR - 3R + 1} \cdot \frac{k_{OV} - 1}{k_{OV}}$$

$$V_{59N} = \frac{F}{3SPR - F(3SR - 3R + 1)}$$

$$\boxed{V_{59N} = \frac{k_{OV} - 1}{3R(S - 1) + 1}}$$







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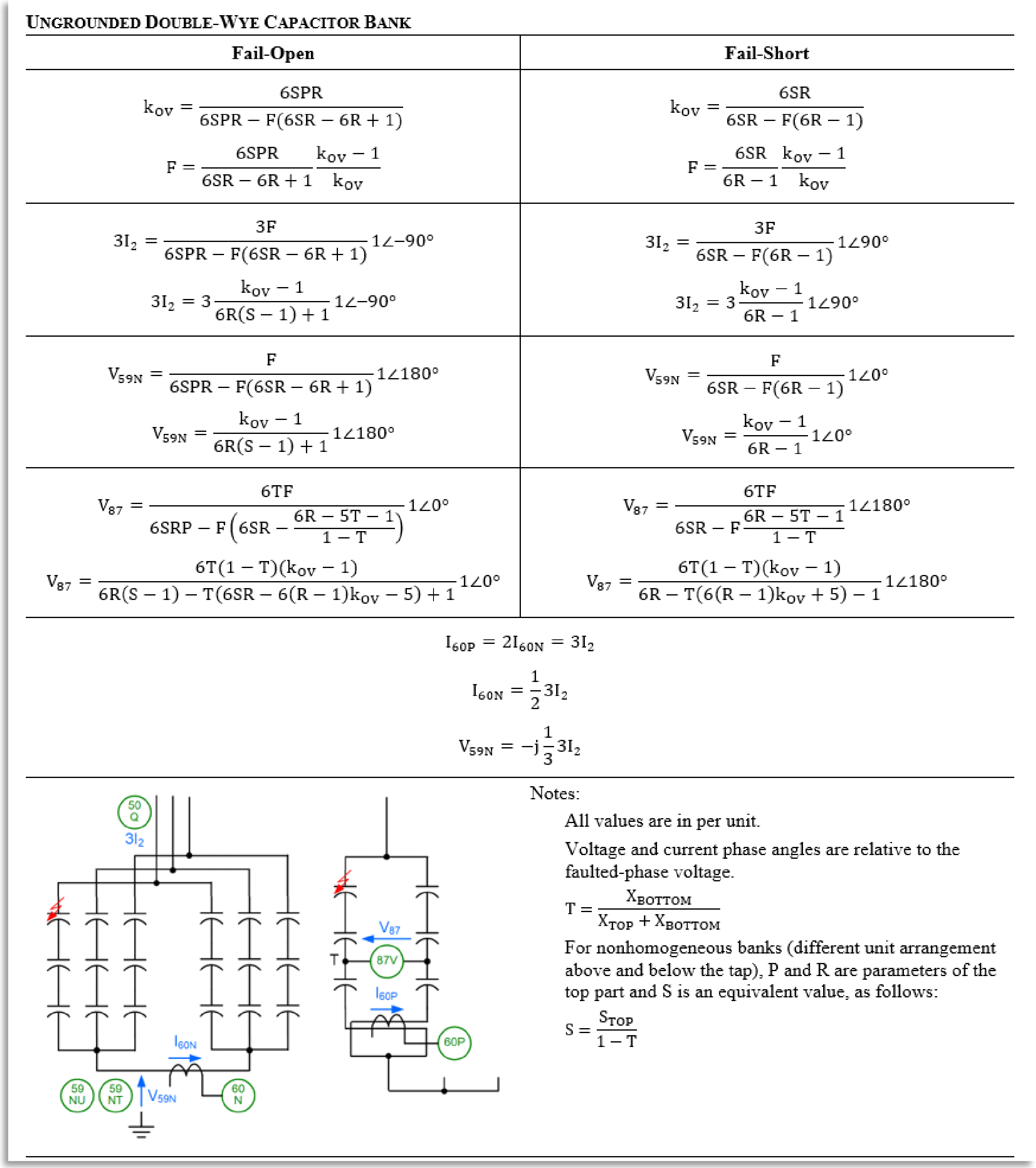

UNGROUNDED DOUBLE-WYE CAPACITOR BANK

| Fail-Open | Fail-Short |
|---|---|
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| $3I_2 = \frac{3F}{6SPR - F(6SR - 6R + 1)} 1\angle{-90°}$<br>$3I_2 = 3\frac{k_{OV} - 1}{6R(S - 1) + 1} 1\angle{-90°}$ | $3I_2 = \frac{3F}{6SR - F(6R - 1)} 1\angle 90°$<br>$3I_2 = 3\frac{k_{OV} - 1}{6R - 1} 1\angle 90°$ |
| $V_{59N} = \frac{F}{6SPR - F(6SR - 6R + 1)} 1\angle 180°$<br>$V_{59N} = \frac{k_{OV} - 1}{6R(S - 1) + 1} 1\angle 180°$ | $V_{59N} = \frac{F}{6SR - F(6R - 1)} 1\angle 0°$<br>$V_{59N} = \frac{k_{OV} - 1}{6R - 1} 1\angle 0°$ |
| $V_{87} = \frac{6TF}{6SRP - F\left(6SR - \frac{6R - 5T - 1}{1 - T}\right)} 1\angle 0°$<br>$V_{87} = \frac{6T(1 - T)(k_{OV} - 1)}{6R(S - 1) - T(6SR - 6(R - 1)k_{OV} - 5) + 1} 1\angle 0°$ | $V_{87} = \frac{6TF}{6SR - F\frac{6R - 5T - 1}{1 - T}} 1\angle 180°$<br>$V_{87} = \frac{6T(1 - T)(k_{OV} - 1)}{6R - T(6(R - 1)k_{OV} + 5) - 1} 1\angle 180°$ |

$$I_{60P} = 2I_{60N} = 3I_2$$

$$I_{60N} = \frac{1}{2}3I_2$$

$$V_{59N} = -j\frac{1}{3}3I_2$$

Notes:

All values are in per unit.

Voltage and current phase angles are relative to the faulted-phase voltage.

$T = \frac{X_{BOTTOM}}{X_{TOP} + X_{BOTTOM}}$

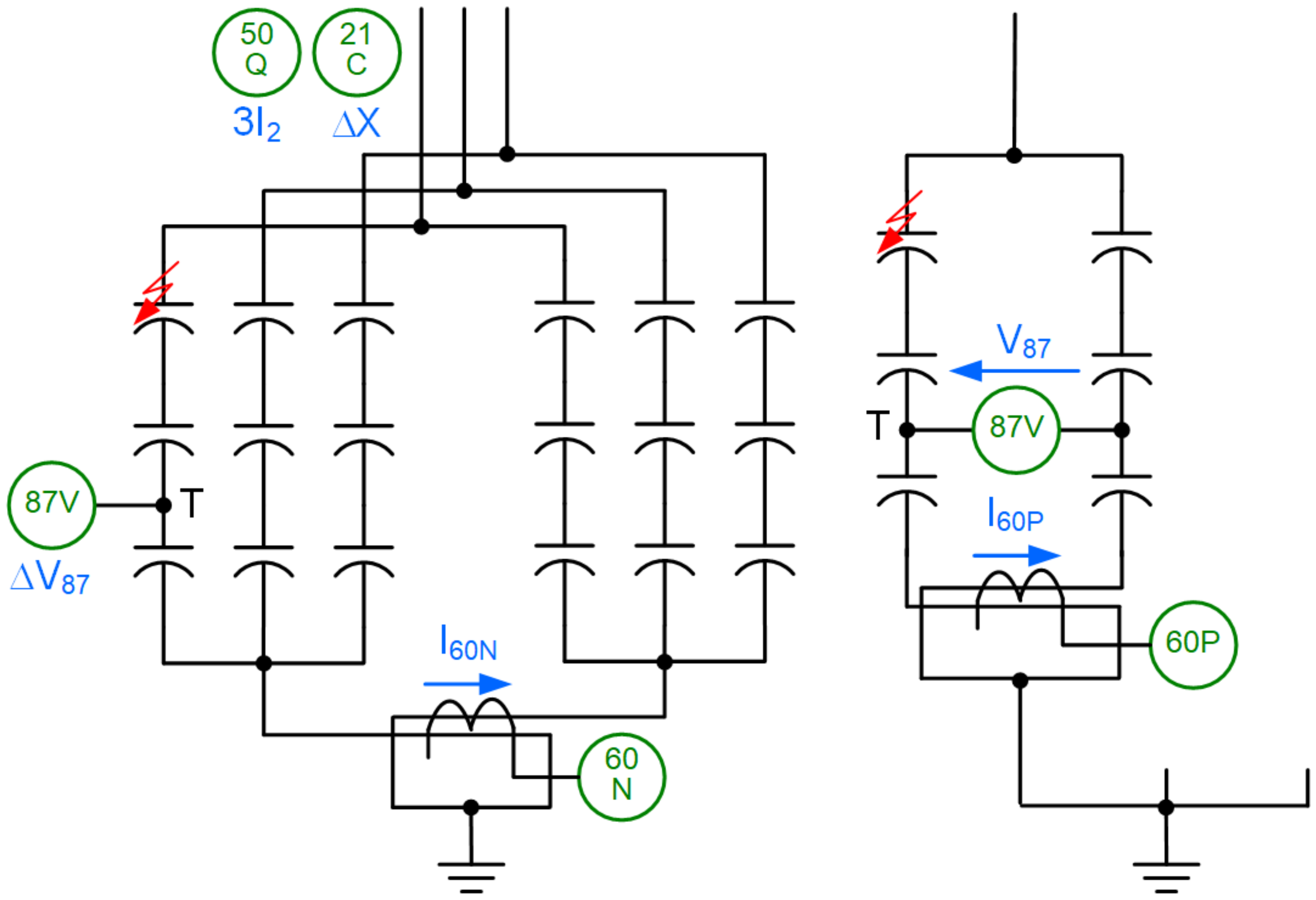
For nonhomogeneous banks (different unit arrangement above and below the tap), P and R are parameters of the top part and S is an equivalent value, as follows:

$S = \frac{S_{TOP}}{1 - T}$

# Grounded double-wye bank example

## Basic data

| PARAMETER | VALUE |
|---|---|
| Voltage (kV LL) | 138 |
| Bus Voltage PTR | 1200:1 |
| Bank Nominal Power (MVAr) | 100 |
| Breaker CTR | 2000:5 |
| Units in a Group, P | 15 |
| Groups in a String, S | 6 |
| Strings in a Phase, R | 1 |
| Unit Voltage Rating, kV | 13.8 |
| Unit Type | Externally fused |
| 87V Tap | One bottom group |
| 87V Tap PTR | 120:1 |
| 60N CTR | 20:5 |



# Grounded double-wye bank example

## Supporting variables

| PARAMETER | VALUE |
|---|---|
| Voltage (kV LL) | 138 |
| Bus Voltage PTR | 1200:1 |
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| Breaker CTR | 2000:5 |
| Units in a Group, P | 15 |
| Groups in a String, S | 6 |
| Strings in a Phase, R | 1 |
| Unit Voltage Rating, kV | 13.8 |
| Unit Type | Externally fused |
| 87V Tap | One bottom group |
| 87V Tap PTR | 120:1 |
| 60N CTR | 20:5 |

### Highest permissible overvoltage factor

$$\mathrm{k_{OV}} = 1.1 \cdot \frac{13.8}{\left(\frac{138}{\sqrt{3} \cdot 6}\right)} = 1.143$$

### Tap position

$$\mathrm{T} = \frac{1}{6} = 0.1667$$

### Base voltage, current, and impedance

$$\mathrm{V_{BASE}} = \frac{138\ \mathrm{kV}}{\sqrt{3}} = 79.674\ \mathrm{kV}$$

$$\mathrm{I_{BASE}} = \frac{100\ \mathrm{MVAr}}{\sqrt{3} \cdot 138\ \mathrm{kV}} = 418.37\ \mathrm{A}$$

$$\mathrm{Z_{BASE}} = \frac{79.674\ \mathrm{kV}}{418.37\ \mathrm{A}} = 190.44\ \Omega$$

# Grounded double-wye bank example

## Alarm thresholds (single unit failure)

| PARAMETER | VALUE |
|---|---|
| Voltage (kV LL) | 138 |
| Bus Voltage PTR | 1200:1 |
| Bank Nominal Power (MVAr) | 100 |
| Breaker CTR | 2000:5 |
| Units in a Group, P | 15 |
| Groups in a String, S | 6 |
| Strings in a Phase, R | 1 |
| Unit Voltage Rating, kV | 13.8 |
| Unit Type | Externally fused |
| 87V Tap | One bottom group |
| 87V Tap PTR | 120:1 |
| 60N CTR | 20:5 |

$$3\mathrm{I}_2 = \mathrm{I}_{60\mathrm{N}} = \frac{1}{2}\frac{\mathrm{F}}{\mathrm{SPR} - \mathrm{F}(\mathrm{SR} - \mathrm{R})} = \cdots$$

$$\ldots = \frac{1}{2} \cdot \frac{1}{6 \cdot 15 \cdot 1 - 1 \cdot (6 \cdot 1 - 1)} = \frac{1}{170} = \cdots$$

$$\ldots = 0.005882 \text{ pu}$$

$$3\mathrm{I}_2 = 0.005882 \text{ pu} \cdot 418.37 \text{ A} \cdot \frac{5}{2000} = 0.0062 \text{ A sec}$$

$$\mathrm{I}_{60\mathrm{N}} = 0.005882 \text{ pu} \cdot 418.37 \text{ A} \cdot \frac{5}{20} = 0.6152 \text{ A sec}$$

# Grounded double-wye bank example

## Alarm thresholds (single unit failure)

| PARAMETER | VALUE |
|---|---|
| Voltage (kV LL) | 138 |
| Bus Voltage PTR | 1200:1 |
| Bank Nominal Power (MVAr) | 100 |
| Breaker CTR | 2000:5 |
| Units in a Group, P | 15 |
| Groups in a String, S | 6 |
| Strings in a Phase, R | 1 |
| Unit Voltage Rating, kV | 13.8 |
| Unit Type | Externally fused |
| 87V Tap | One bottom group |
| 87V Tap PTR | 120:1 |
| 60N CTR | 20:5 |

$$\mathrm{V_{87}} = \frac{\mathrm{TF}}{\mathrm{SRP} - \mathrm{F}\left(\mathrm{SR} - \frac{\mathrm{R}-\mathrm{T}}{1-\mathrm{T}}\right)} = \cdots$$

$$\ldots = \frac{0.1667 \cdot 1}{6 \cdot 1 \cdot 15 - 1 \cdot \left(6 \cdot 1 - \frac{1-0.1667}{1-0.1667}\right)} = \cdots$$

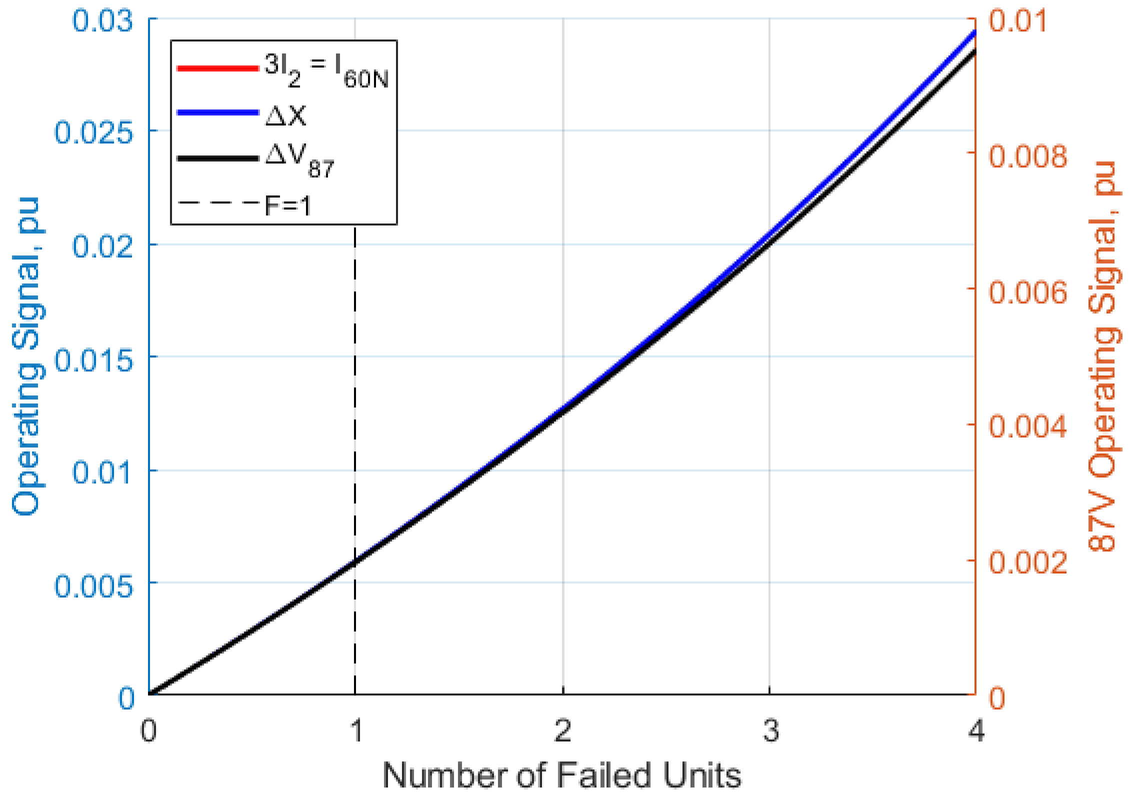
$$\ldots = 0.0019608\ \mathrm{pu}$$

$$\mathrm{V_{87}} = 0.0019608\ \mathrm{pu} \cdot 79.674\ \mathrm{kV} \cdot \frac{1}{120} = 1.302\ \mathrm{V\ sec}$$

# Grounded double-wye bank example

## Alarm thresholds (single unit failure)

| PARAMETER | VALUE |
|---|---|
| Voltage (kV LL) | 138 |
| Bus Voltage PTR | 1200:1 |
| Bank Nominal Power (MVAr) | 100 |
| Breaker CTR | 2000:5 |
| Units in a Group, P | 15 |
| Groups in a String, S | 6 |
| Strings in a Phase, R | 1 |
| Unit Voltage Rating, kV | 13.8 |
| Unit Type | Externally fused |
| 87V Tap | One bottom group |
| 87V Tap PTR | 120:1 |
| 60N CTR | 20:5 |



$$k_{OV} = \frac{SP}{SP - F(S-1)} = \frac{6 \cdot 15}{6 \cdot 15 - 1 \cdot (6-1)} = 1.059$$

# Grounded double-wye bank example

## Trip thresholds (breaching unit voltage rating)

| PARAMETER | VALUE |
|---|---|
| Voltage (kV LL) | 138 |
| Bus Voltage PTR | 1200:1 |
| Bank Nominal Power (MVAr) | 100 |
| Breaker CTR | 2000:5 |
| Units in a Group, P | 15 |
| Groups in a String, S | 6 |
| Strings in a Phase, R | 1 |
| Unit Voltage Rating, kV | 13.8 |
| Unit Type | Externally fused |
| 87V Tap | One bottom group |
| 87V Tap PTR | 120:1 |
| 60N CTR | 20:5 |

$$3\mathrm{I}_2 = \mathrm{I}_{60\mathrm{N}} = \frac{\mathrm{k}_{\mathrm{OV}} - 1}{2\mathrm{R}(\mathrm{S} - 1)} = \frac{1.143 - 1}{2 \cdot 1 \cdot (6 - 1)} = 0.0143\ \mathrm{pu}$$

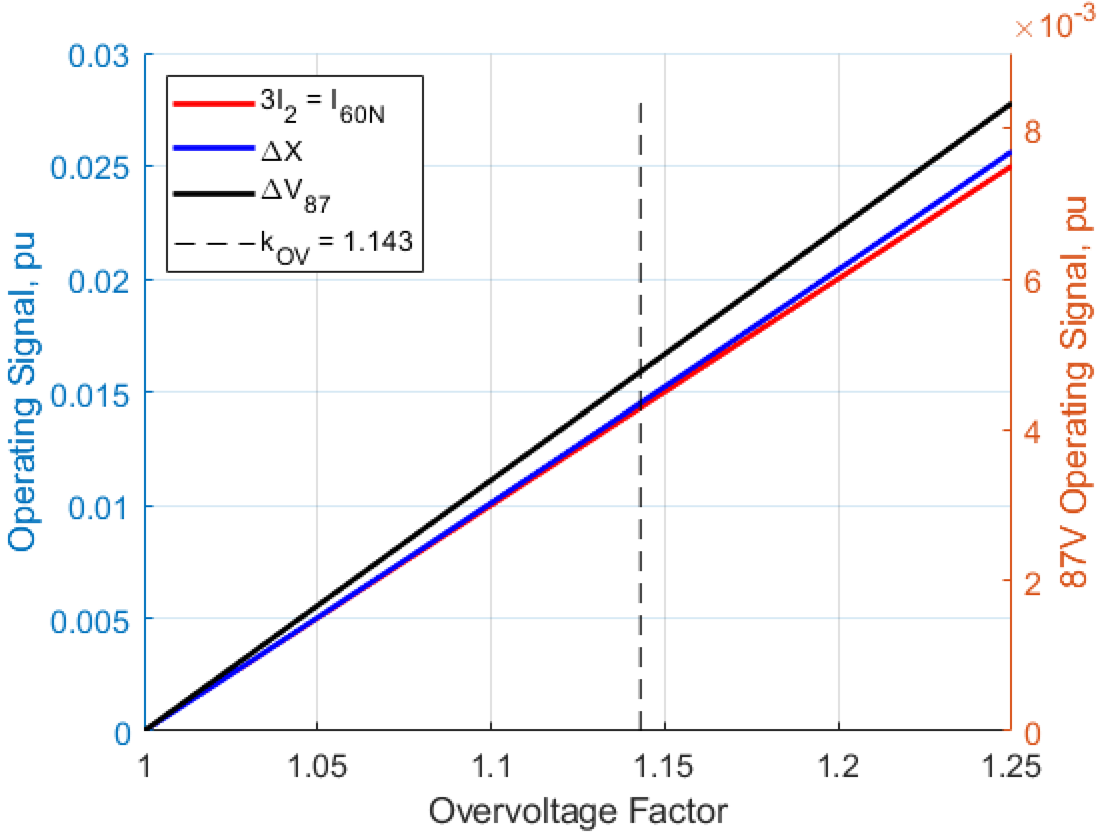
$$3\mathrm{I}_2 = 0.0143\ \mathrm{pu} \cdot 418.37\ \mathrm{A} \cdot \frac{5}{2000} = 0.0150\ \mathrm{A\ sec}$$

$$\mathrm{I}_{60\mathrm{N}} = 0.0143\ \mathrm{pu} \cdot 418.37\ \mathrm{A} \cdot \frac{5}{20} = 1.50\ \mathrm{A\ sec}$$

# Grounded double-wye bank example

## Trip thresholds (breaching unit voltage rating)

| PARAMETER | VALUE |
|---|---|
| Voltage (kV LL) | 138 |
| Bus Voltage PTR | 1200:1 |
| Bank Nominal Power (MVAr) | 100 |
| Breaker CTR | 2000:5 |
| Units in a Group, P | 15 |
| Groups in a String, S | 6 |
| Strings in a Phase, R | 1 |
| Unit Voltage Rating, kV | 13.8 |
| Unit Type | Externally fused |
| 87V Tap | One bottom group |
| 87V Tap PTR | 120:1 |
| 60N CTR | 20:5 |



$$F = \frac{SP}{S-1}\frac{k_{OV}-1}{k_{OV}} = \frac{6 \cdot 15}{6-1} \cdot \frac{1.143-1}{1.143} = 2.25$$

# Analysis and insights

- Some unbalance protection operating signals have identical or proportional values

***Examples***

- Any ungrounded bank

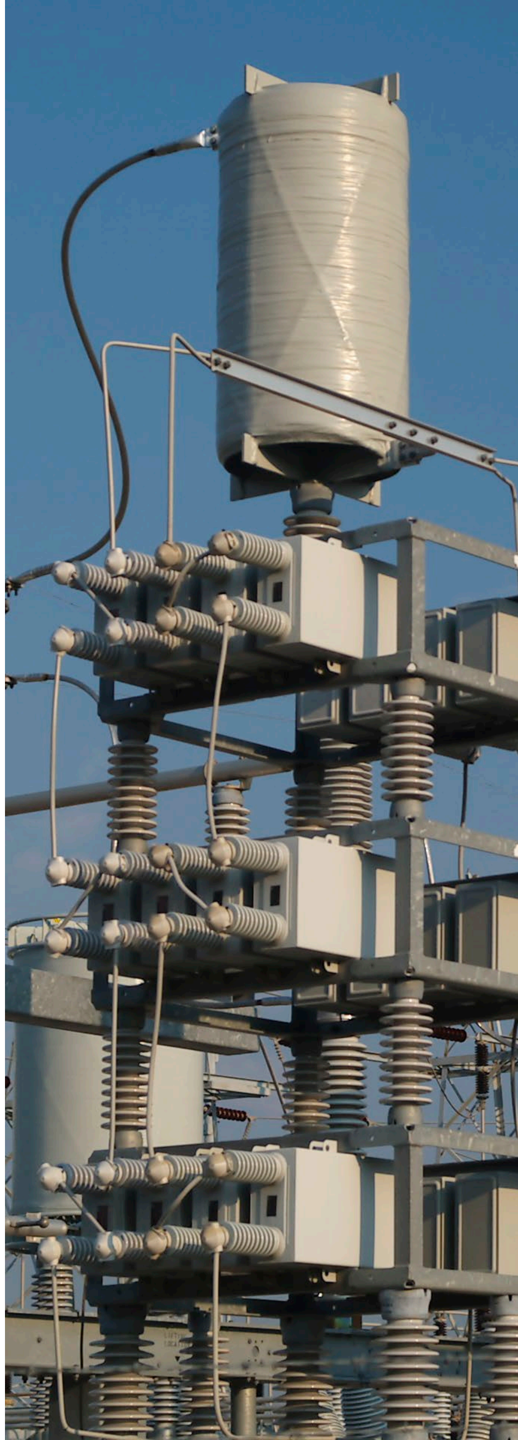
$$V_{59N} = -j\frac{1}{3} \cdot 3I_2$$

- Double-wye grounded bank

$$I_{60P} = I_{60N} = 3I_2$$

- Double-wye ungrounded bank

$$I_{60P} = 3I_2, \qquad I_{60N} = \frac{1}{2} \cdot 3I_2$$



# Analysis and insights

- Some unbalance protection operating signals have identical or proportional values
- All unbalance protection operating signals are very similar in per-unit values

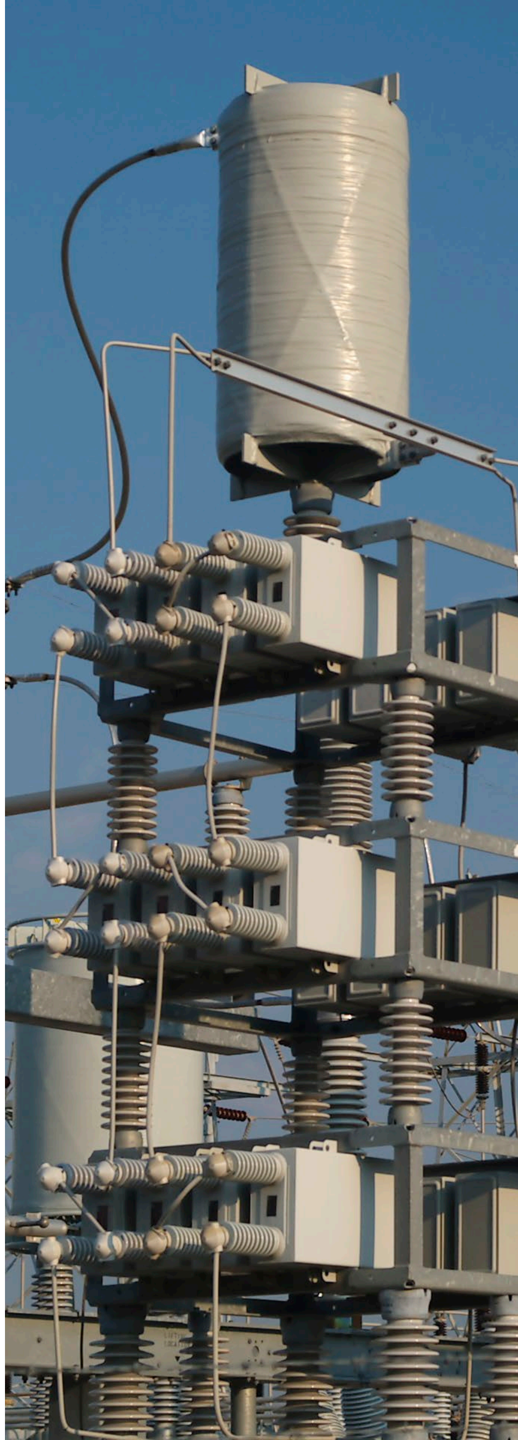
***Example***

Grounded single-wye bank, fail open:

$$|3I_2| = \frac{F}{S \cdot R \cdot P - F \cdot (S \cdot R - R)}$$

$$|\Delta X| = \frac{F}{S \cdot R \cdot P - F \cdot (S \cdot R - R \mathbf{+ 1})}$$

$$|\Delta X| \cong |3I_2|$$

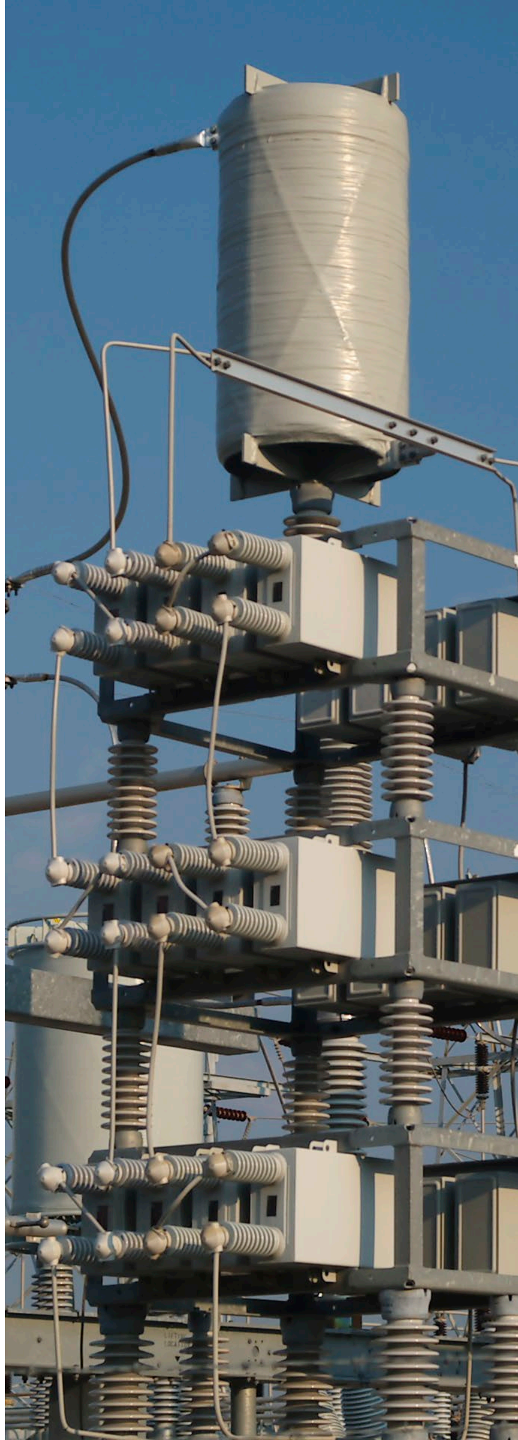


# Analysis and insights

- Some unbalance protection operating signals have identical or proportional values
- All unbalance protection operating signals are very similar in per-unit values
- All unbalance equations have a common format

***Example***

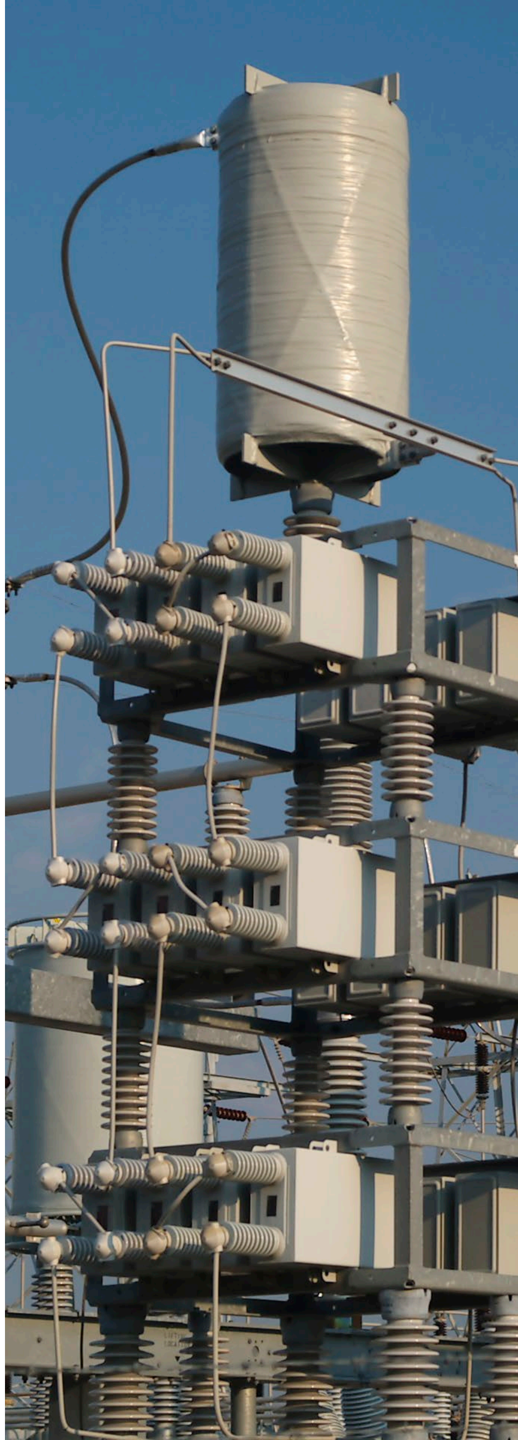
$$\left.\begin{aligned}|V_{59N}| &= \frac{F}{3 \cdot S \cdot P \cdot R - F \cdot (3 \cdot S \cdot R - 3 \cdot R + 1)} \\ |3I_2| &= \frac{1}{2} \cdot \frac{F}{S \cdot R - F \cdot R}\end{aligned}\right\} \Rightarrow Y = \frac{k \cdot F}{A - B \cdot F}$$



# Analysis and insights

- Some unbalance protection operating signals have identical or proportional values
- All unbalance protection operating signals are very similar in per-unit values
- All unbalance equations have a common format
- Unbalance protection operating signals can be approximated as follows

$$Y_{(PU)} \approx k \cdot \frac{\text{Number of Lost Units}}{\text{Number of Units per Phase}}$$



# Grounded double-wye bank example

## Alarm thresholds (single unit failure)

| PARAMETER | VALUE |
|---|---|
| Voltage (kV LL) | 138 |
| Bus Voltage PTR | 1200:1 |
| Bank Nominal Power (MVAr) | 100 |
| Breaker CTR | 2000:5 |
| Units in a Group, P | 15 |
| Groups in a String, S | 6 |
| Strings in a Phase, R | 1 |
| Unit Voltage Rating, kV | 13.8 |
| Unit Type | Externally fused |
| 87V Tap | One bottom group |
| 87V Tap PTR | 120:1 |
| 60N CTR | 20:5 |

$$3I_2 = I_{60N} = \frac{1}{2}\frac{F}{SPR - F(SR - R)} = \cdots$$

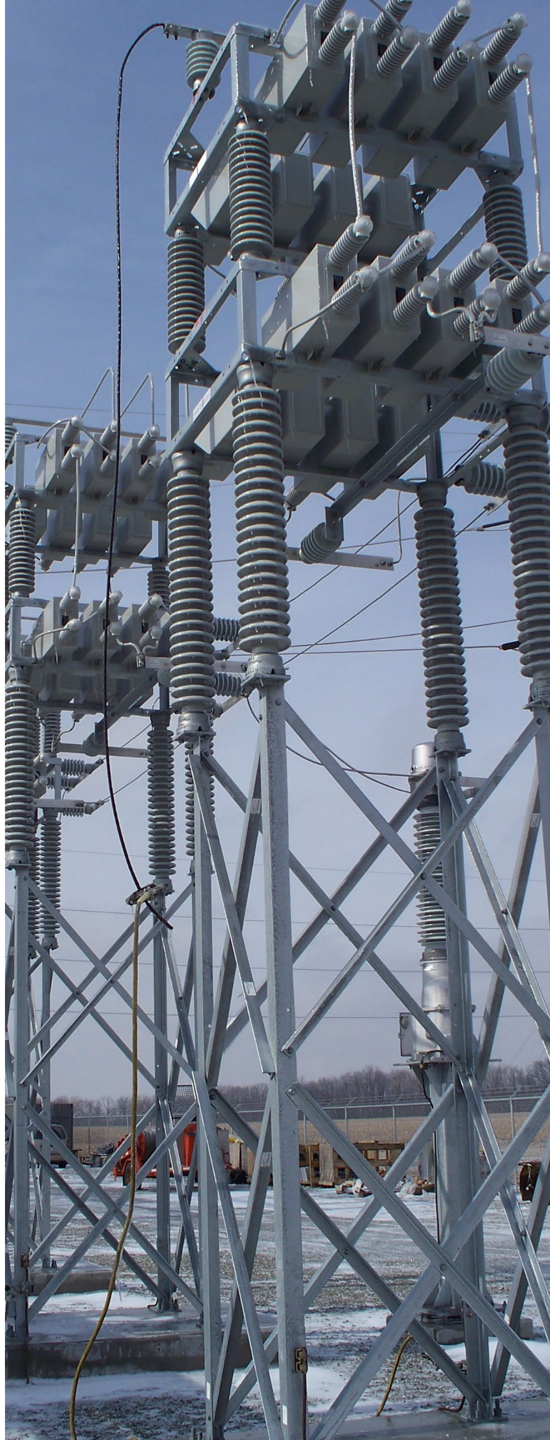
$$\ldots = \frac{1}{2} \cdot \frac{1}{6 \cdot 15 \cdot 1 - 1 \cdot (6 \cdot 1 - 1)} = \frac{1}{170} = 0.0059 \text{ pu}$$

$$Y_{(PU)} \approx \frac{1}{6 \cdot 15 \cdot 2} = \frac{1}{180} = 0.0056 \text{ pu}$$

The approximation is accurate within 6 percent

# Additional material in the paper

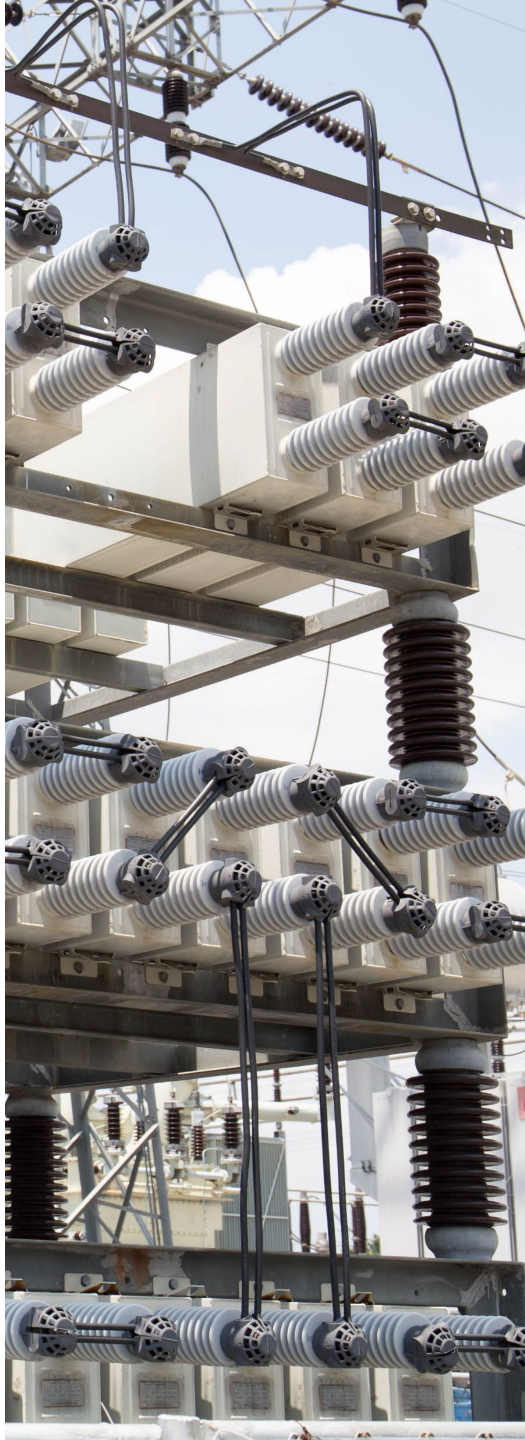
- Calculations for multiple capacitor unit failures
- Calculations for partial capacitor unit failures (capacitor element failures)
- Optimizing for more sensitive unbalance protection
  - Unit arrangement
  - Tap and bridge position
- Discussion on self-canceling failures and redundancy of unbalance protection



# Conclusions

## Calculations and analysis

- Capacitor unbalance calculations can be done in one step (single-equation calculations)
  - Simpler and faster
  - Less prone to errors
- Calculating in per unit allows greater insights and helps spot errors
- Unbalance signals can be easily approximated based on the count of failed units
- Calculations for multiple failures can be done by using the superposition principle



# Conclusions

## Protection

- The paper teaches simple one-step calculations for both alarm and trip thresholds
- Setting trip thresholds based on the overvoltage factor is an elegant solution
- In per unit, all unbalance protection elements have near-identical sensitivities
  - Ease of measurement favors one element vs. others
  - Using multiple elements protects against multiple self-canceling failures