Power System Analysis

Chapter 3 Transformer models

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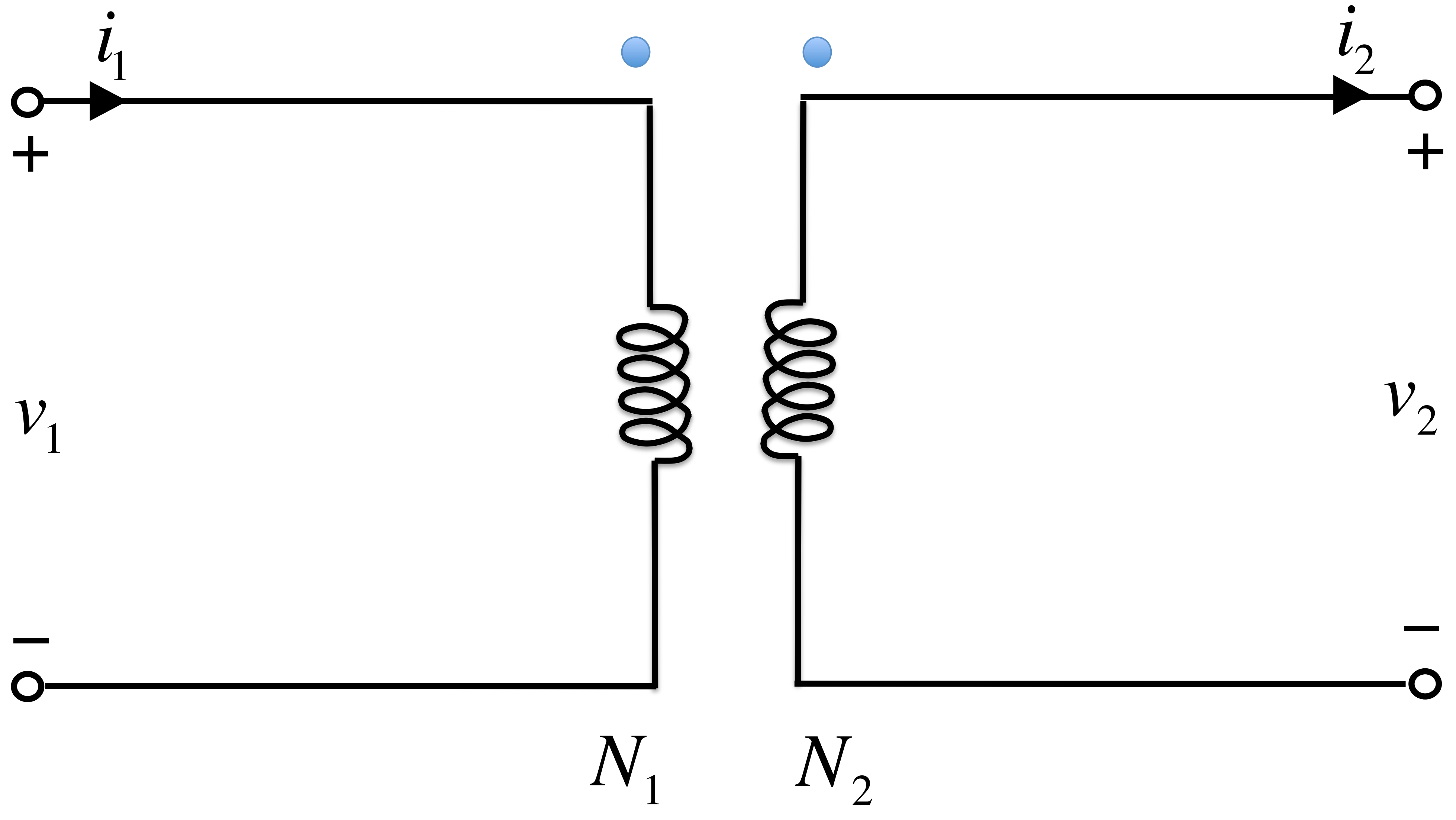
Outline

1. Single-phase transformer
2. Balanced three-phase transformers
3. Equivalent impedance
4. Per-phase analysis
5. Per-unit normalization

Outline

1. Single-phase transformer
    - Ideal transformer
    - Nonideal transformer
    - Circuit models: T eq circuit, simplified circuit, UVN, split-phase
2. Balanced three-phase transformers
3. Equivalent impedance
4. Per-phase analysis
5. Per-unit normalization

Ideal transformer



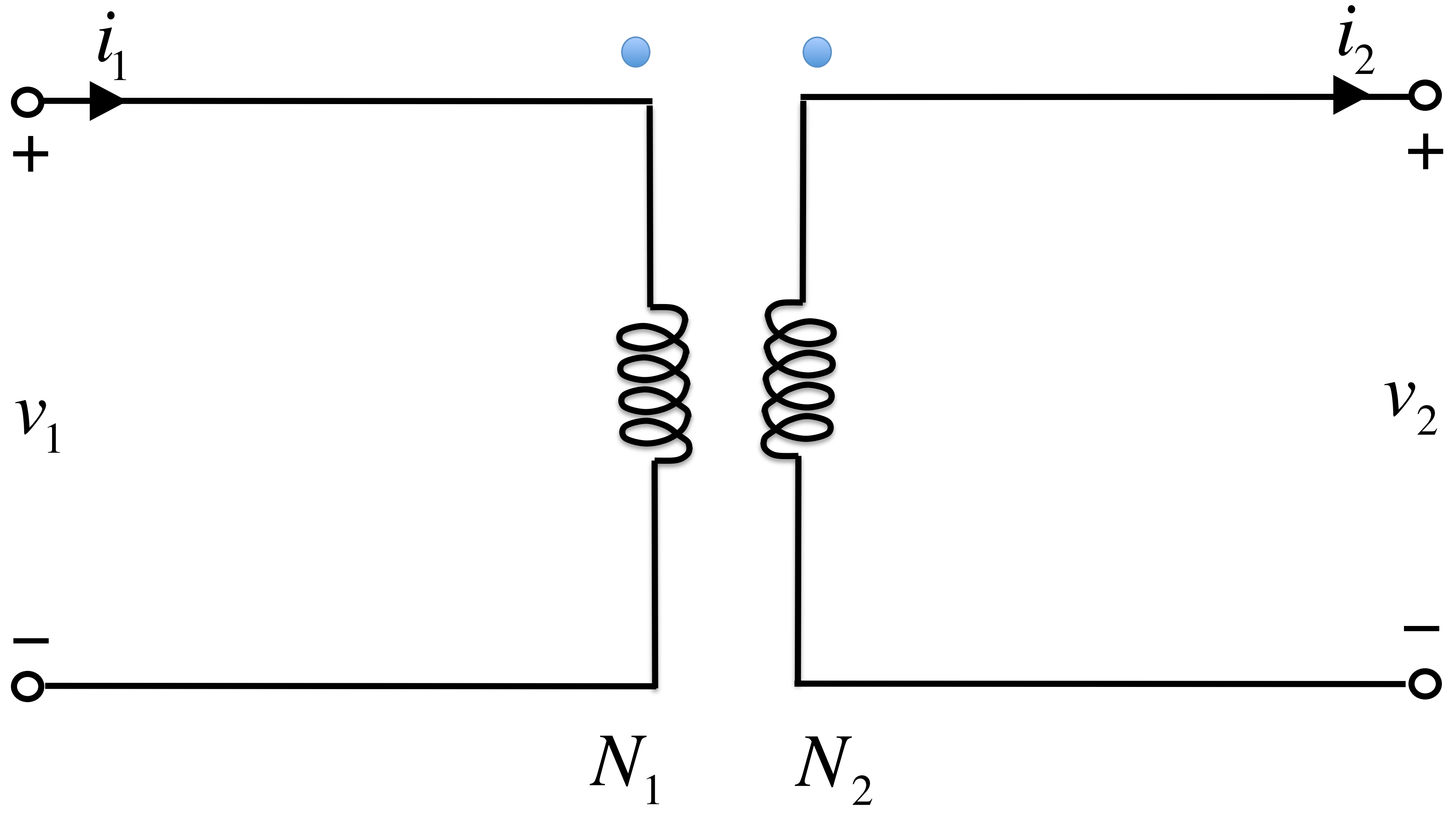
Voltage & current gains

$$\frac{v_2(t)}{v_1(t)} = n \qquad \frac{i_2(t)}{i_1(t)} = a$$

voltage gain $n := \dfrac{N_2}{N_1}$

turns ratio $a := \dfrac{N_1}{N_2}$

Ideal transformer



voltage gain $n := \frac{N_2}{N_1}$

turns ratio $a := \frac{N_1}{N_2}$

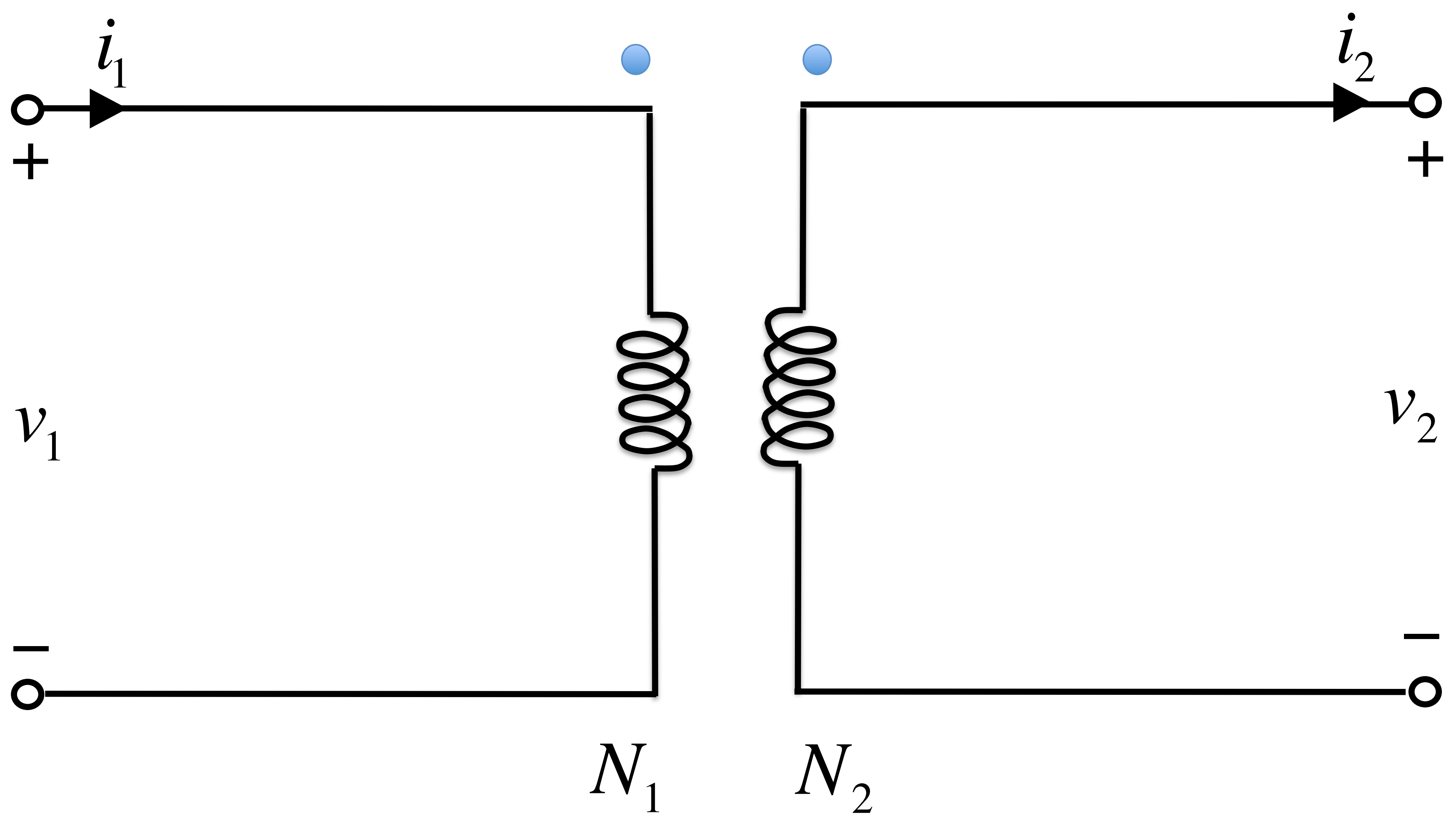
Voltage & current gains

$$\frac{V_2}{V_1} = n \qquad \frac{I_2}{I_1} = a$$

Transmission matrix

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} a & 0 \\ 0 & n \end{bmatrix} \begin{bmatrix} V_2 \\ I_2 \end{bmatrix}$$

Ideal transformer



voltage gain $n := \frac{N_2}{N_1}$

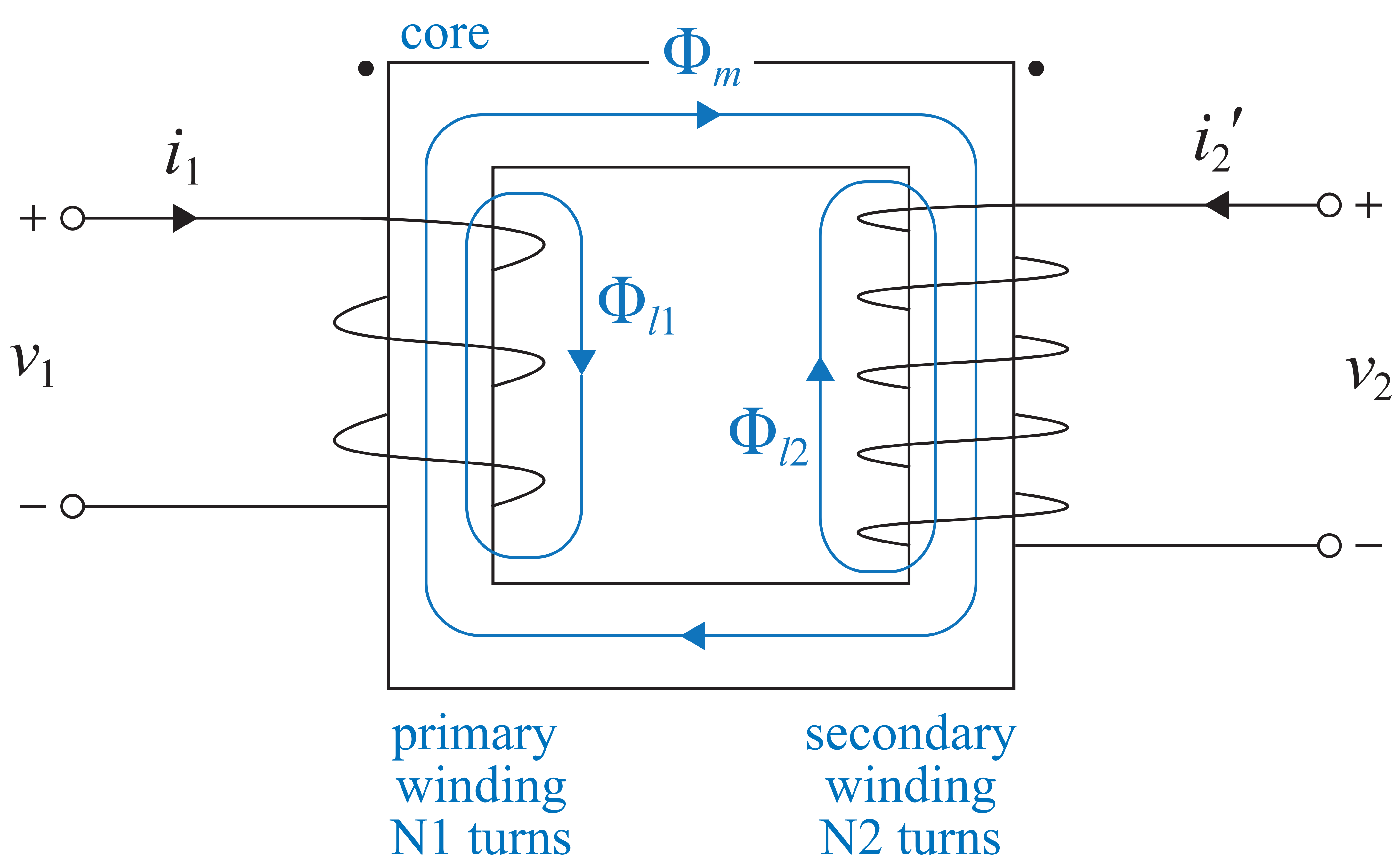
turns ratio $a := \frac{N_1}{N_2}$

Power transfer

$$\frac{-S_{21}}{S_{12}} := \frac{V_2 \bar{I}_2}{V_1 \bar{I}_1} = n \cdot a = 1$$

i.e., deal transformer incurs no power loss

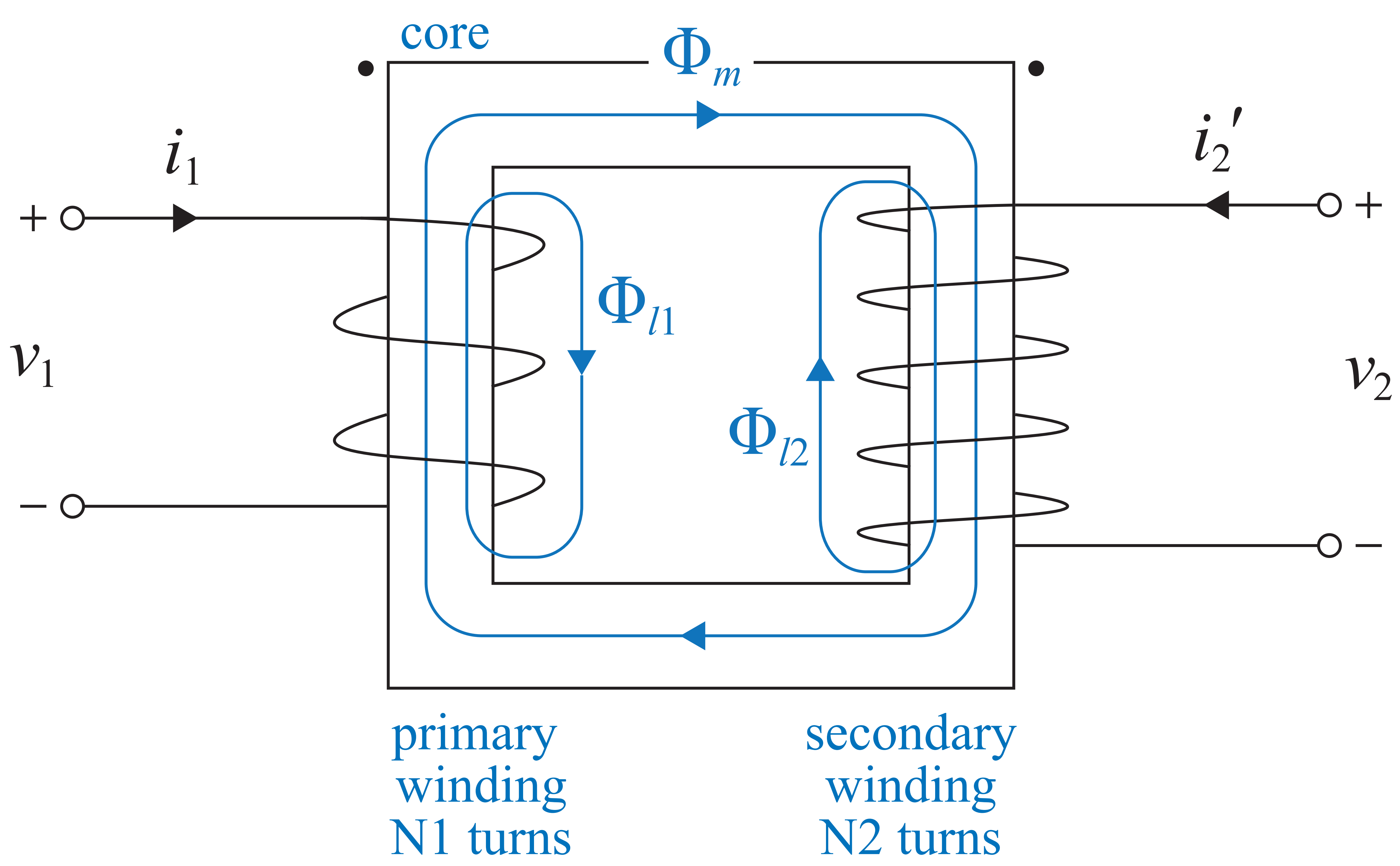
Nonideal transformer



Nonideal behavior

- Power losses (coil resistances, eddy currents, hysteresis losses)
- Leakage magnetic fluxes $\left(\Phi_{l_1}, \Phi_{l_2}\right)$
- Finite permeability of magnetic cores

Nonideal transformer



Voltages

$$v_1 = r_1 i_1 + \frac{d\lambda_1}{dt}, \qquad v_2 = r_2 i_2' + \frac{d\lambda_2}{dt}$$

Total flux linkages

$$\lambda_1 = N_1 \Phi_m + \lambda_{l1}, \qquad \lambda_2 = N_2 \Phi_m + \lambda_{21}$$

$$\lambda_{l1} = L_{l1}\, i_1, \qquad \lambda_{l2} = L_{l2}\, i_2'$$

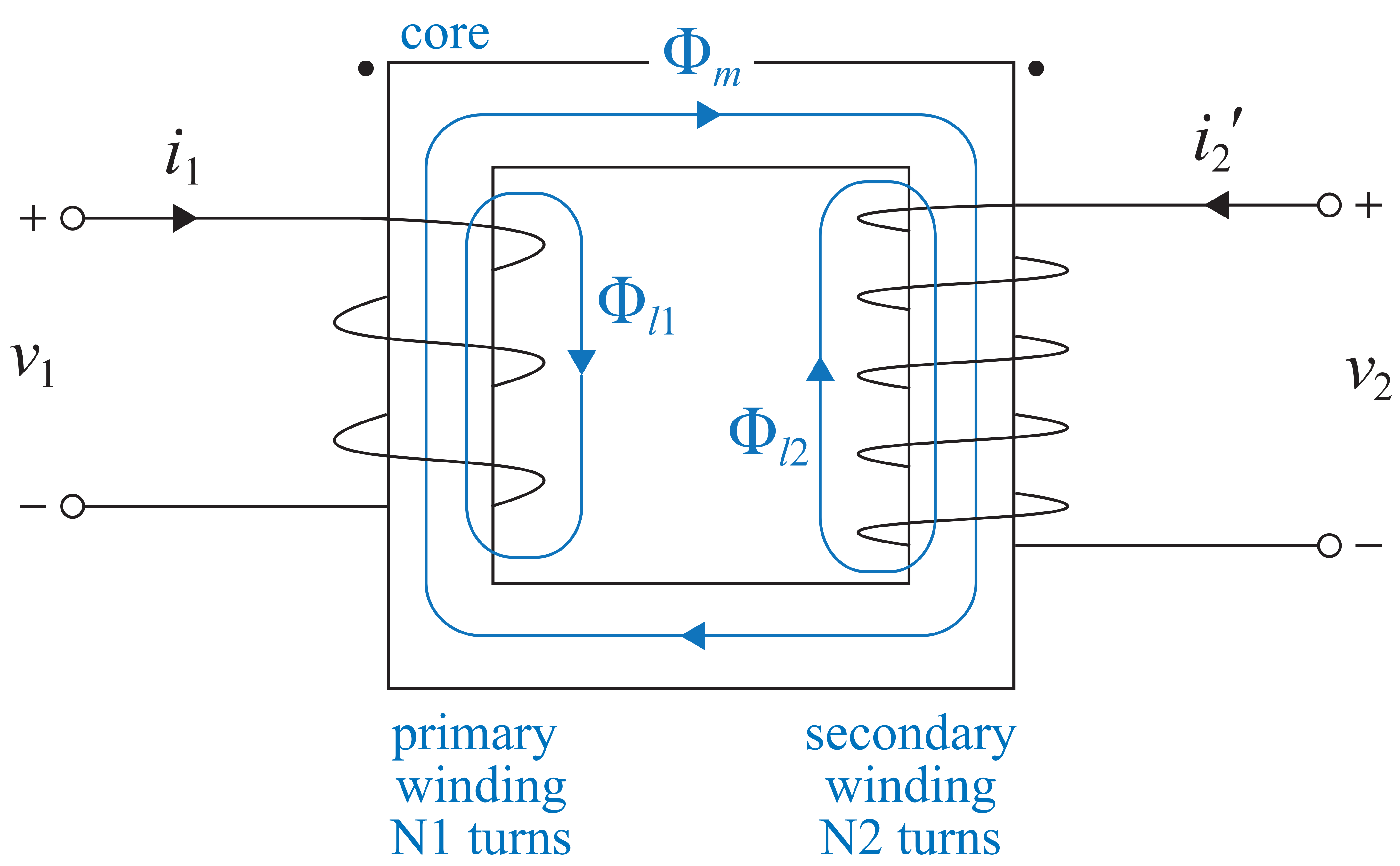
Total magnetomotive force

$$F = N_1 i_1 + N_2 i_2' = R\Phi_m$$

Mutual flux linkages due to mutual flex Φ_m: $\left(N_1\Phi_m, N_2\Phi_m\right)$

Leakage flux linkages due to leakage fluxes $\left(\Phi_{l_1}, \Phi_{l_2}\right)$: $\left(\lambda_{l1},\ \lambda_{l2}\right)$

Nonideal transformer



Voltages

$$v_1 = r_1 i_1 + \frac{d\lambda_1}{dt}, \qquad v_2 = r_2 i_2' + \frac{d\lambda_2}{dt}$$

Total flux linkages

$$\lambda_1 = N_1 \Phi_m + \lambda_{l1}, \qquad \lambda_2 = N_2 \Phi_m + \lambda_{21}$$

$$\lambda_{l1} = L_{l1}\, i_1, \qquad \lambda_{l2} = L_{l2}\, i_2'$$

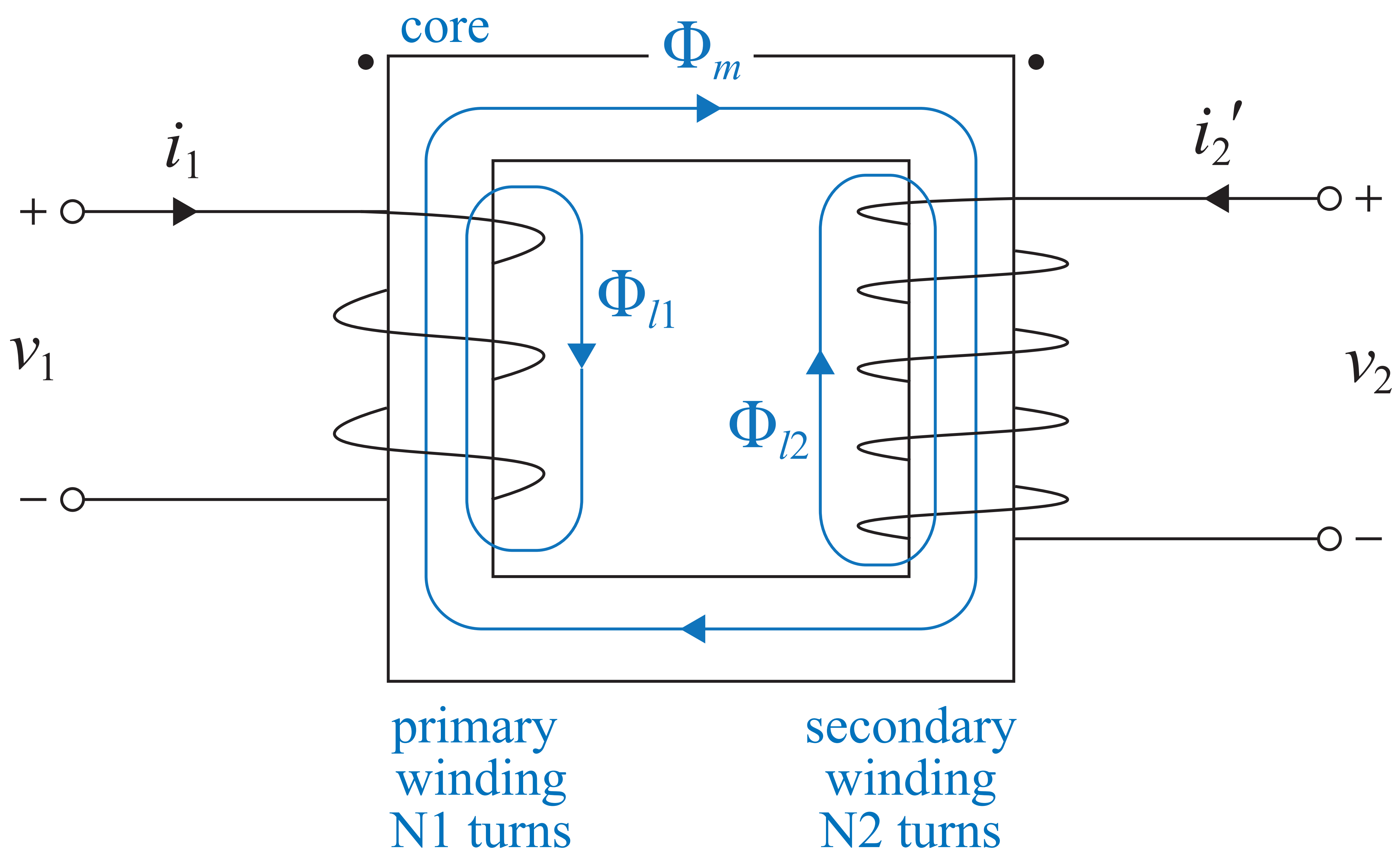
Total magnetomotive force

$$F = N_1 i_1 + N_2 i_2' = R \Phi_m$$

Ideal transformer

- Zero power losses: $r_1 = r_2 = 0$
- Zero leakage flux linkages: $L_{l1} = L_{l2} = 0$ $\Longrightarrow$ $v_1 = N_1 \frac{d\Phi_m}{dt}, \quad v_2 = N_2 \frac{d\Phi_m}{dt}, \quad 0 = N_1 i_1 + N_2 i_2'$
- Infinite permeability: $R = 0$

Nonideal transformer



Voltages

$$v_1 = r_1 i_1 + L_{l1}\frac{di_1}{dt} + N_1\frac{d\Phi_m}{dt}$$

$$v_2 = r_2 i_2' + L_{l2}\frac{di_2'}{dt} + N_2\frac{d\Phi_m}{dt}$$

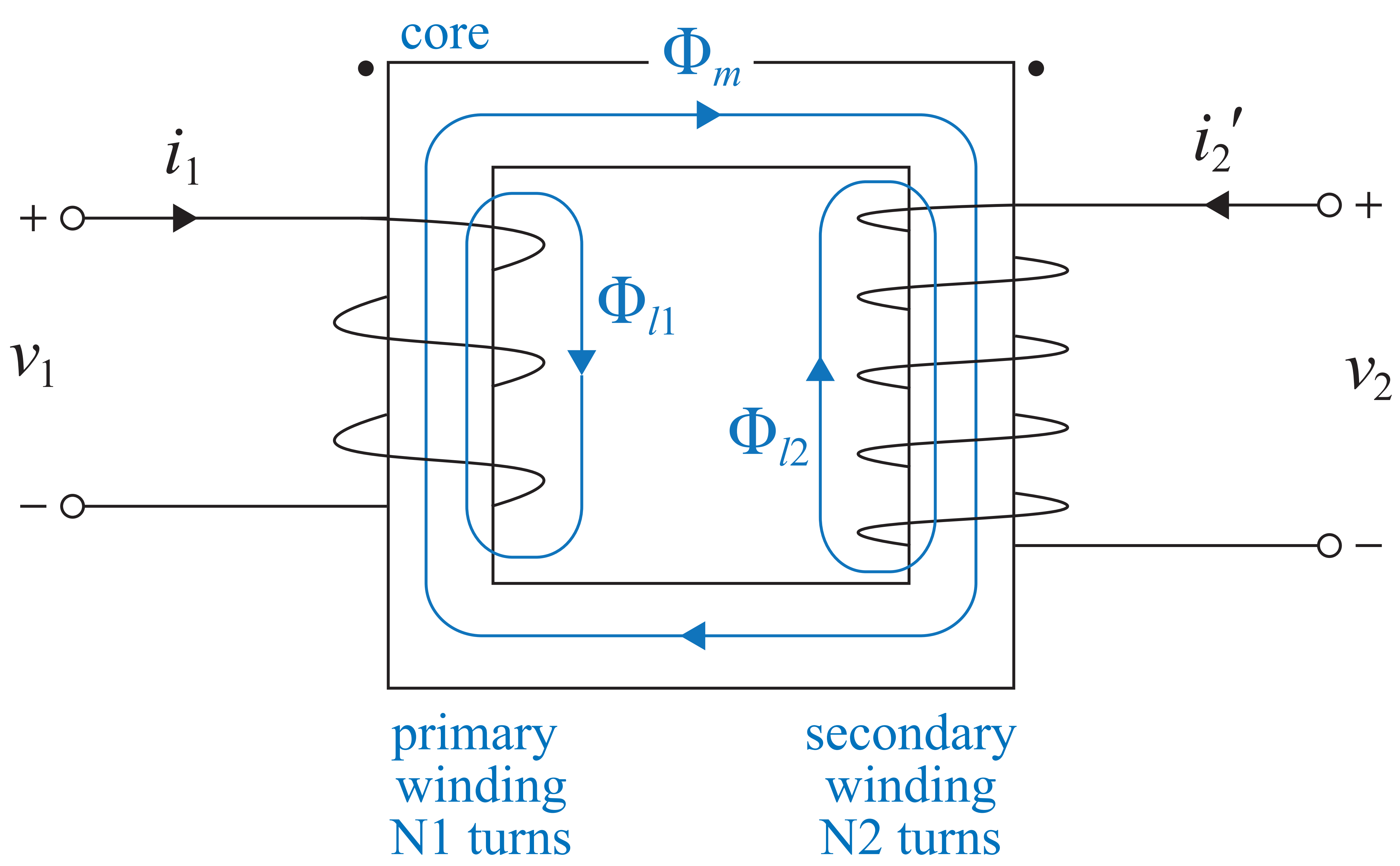
Primary magnetizing current $\hat{i}_m$

- primary current when secondary circuit is open $i_2' := 0$
- $N_1 \hat{i}_m = R\Phi_m$: let $L_m := N_1^2/R$ and

$$\hat{u}_1 := N_1\frac{d\Phi_m}{dt} = L_m\frac{d\hat{i}_m}{dt}$$

$$\hat{u}_2 := N_2\frac{d\Phi_m}{dt} = \frac{N_2}{N_1}\hat{u}_1 \qquad \text{ideal transformer}$$

Nonideal transformer



Nonideal elements

$$v_1 = r_1 i_1 + L_{l1}\frac{di_1}{dt} + \hat{u}_1, \quad \hat{u}_1 = L_m \frac{d\hat{i}_m}{dt}$$

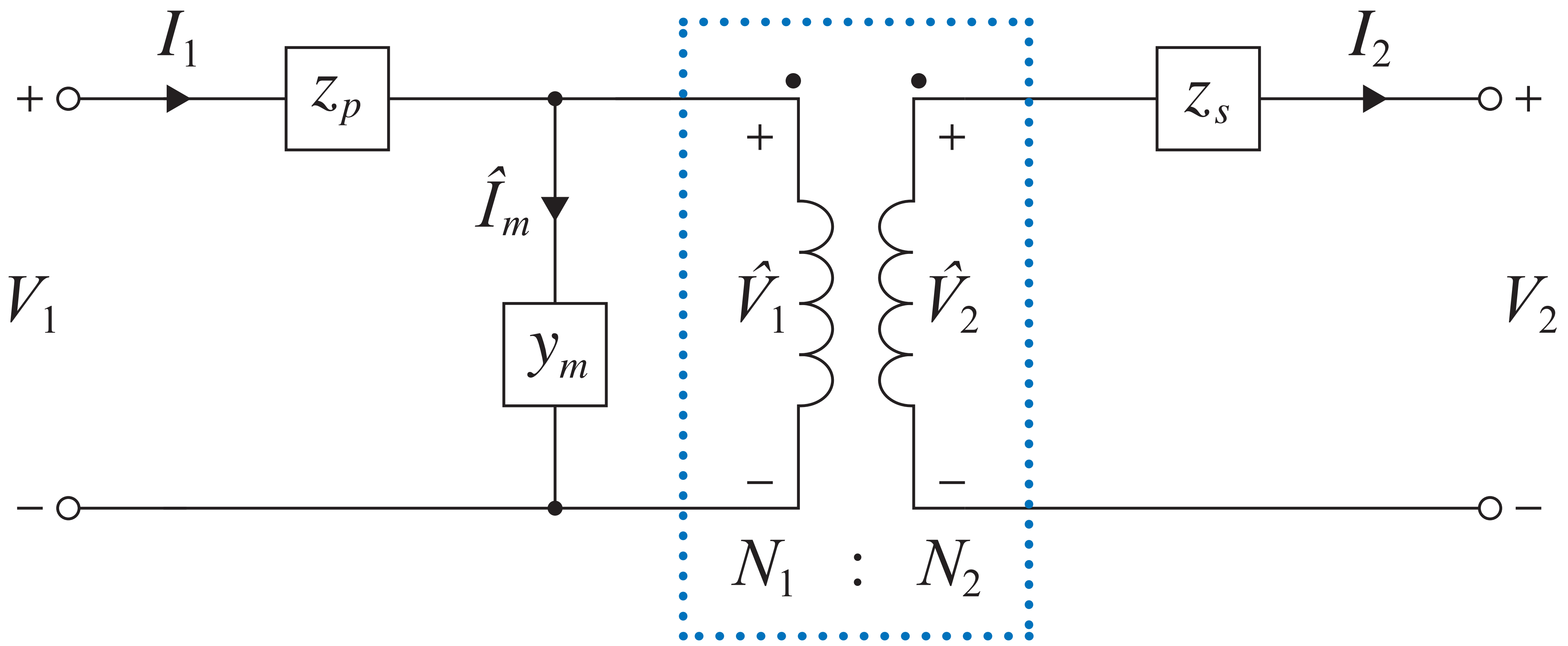
$$v_2 = -r_2 i_2 - L_{l2}\frac{di_2}{dt} + \hat{u}_2$$

Ideal transformer

$$\hat{u}_2 = \frac{N_2}{N_1}\hat{u}_1, \qquad i_2 = \frac{N_1}{N_2}\left(i_1 - \hat{i}_m\right)$$

Nonideal transformer

Circuit model



Nonideal elements (phasor domain)

$$V_1 = z_p I_1 + \hat{U}_1, \qquad \hat{I}_m = y_m \hat{U}_1$$

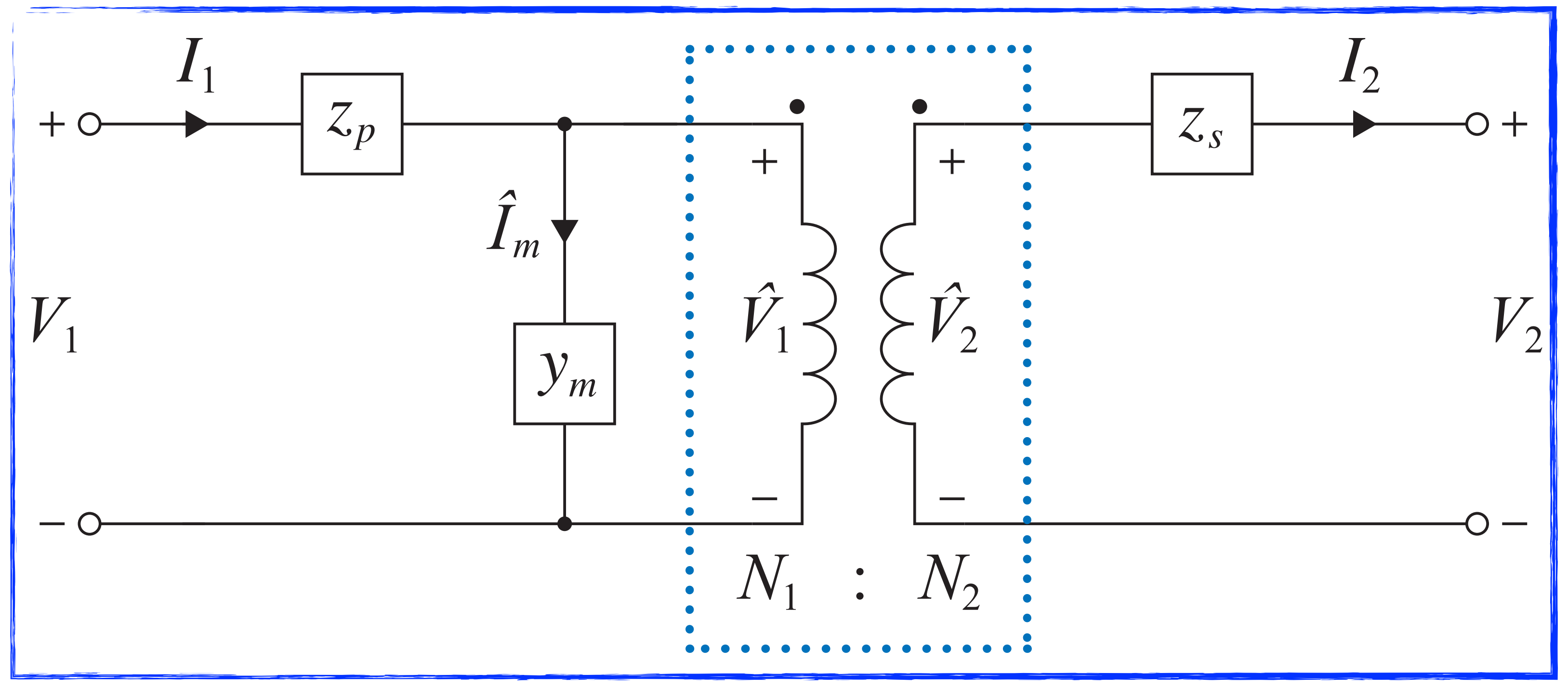
$$\hat{U}_2 = z_s I_2 + V_2$$

Ideal transformer (phasor domain)

$$\hat{U}_2 = \frac{N_2}{N_1} \hat{U}_1, \qquad I_2 = \frac{N_1}{N_2} \left(I_1 - \hat{I}_m \right)$$

Nonideal transformer

Circuit models



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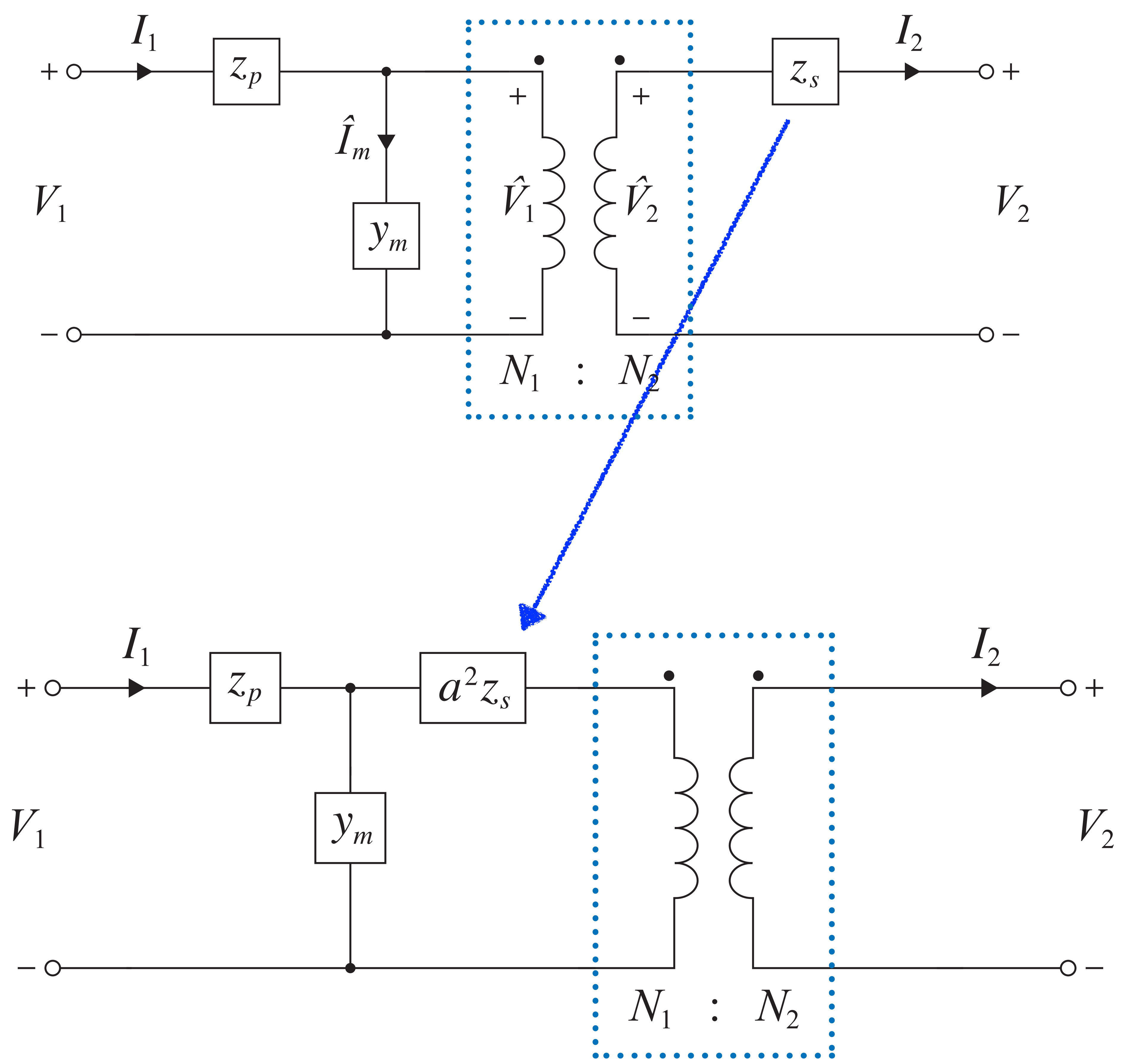
T equivalent circuit $\equiv$ unitary voltage network

$\wr\wr$

simplified model

T equivalent circuit



Refer series impedance z_s to the primary side $\longrightarrow$ T equivalent circuit

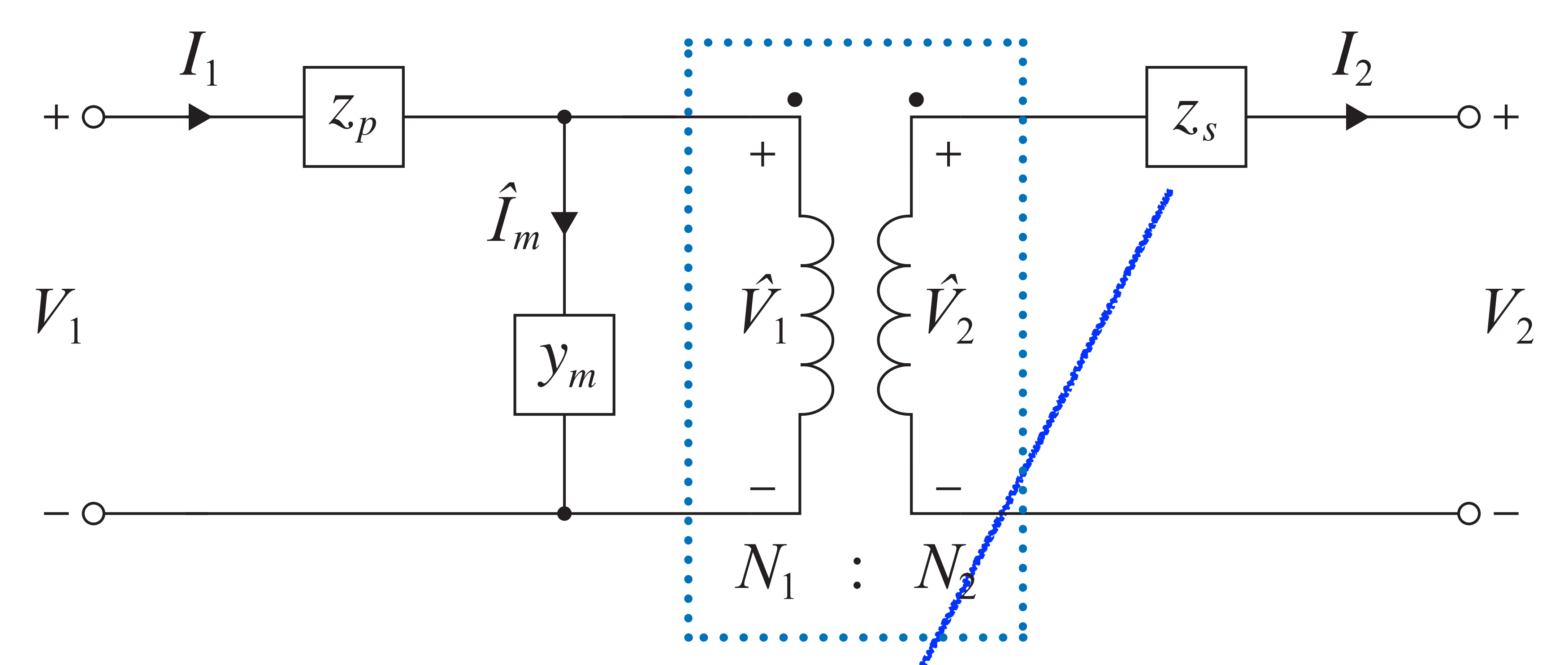
$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} a\left(1 + z_p y_m\right) & a z_s (1 + z_p y_m) + n z_p \\ a y_m & n + a z_s y_m \end{bmatrix} \begin{bmatrix} V_2 \\ I_2 \end{bmatrix}$$

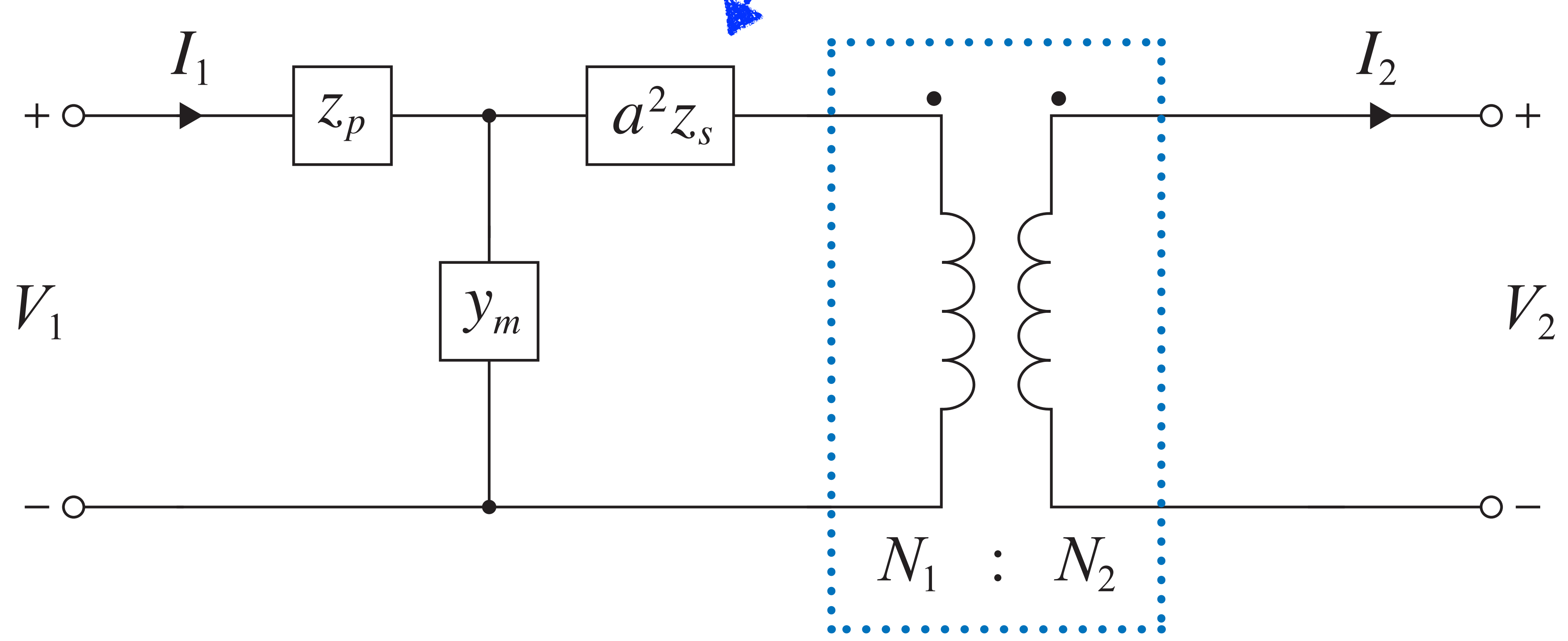
where $n := N_2/N_1, \; a := 1/n$

"Equivalent model" means

- Same end-to-end behavior, e.g., transmission matrix, or admittance matrix;
- Internal variables may be different

T equivalent circuit





Refer series impedance z_s to the primary side $\longrightarrow$ T equivalent circuit

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} a\left(1 + z_p y_m\right) & a z_s(1 + z_p y_m) + n z_p \\ a y_m & n + a z_s y_m \end{bmatrix} \begin{bmatrix} V_2 \\ I_2 \end{bmatrix}$$

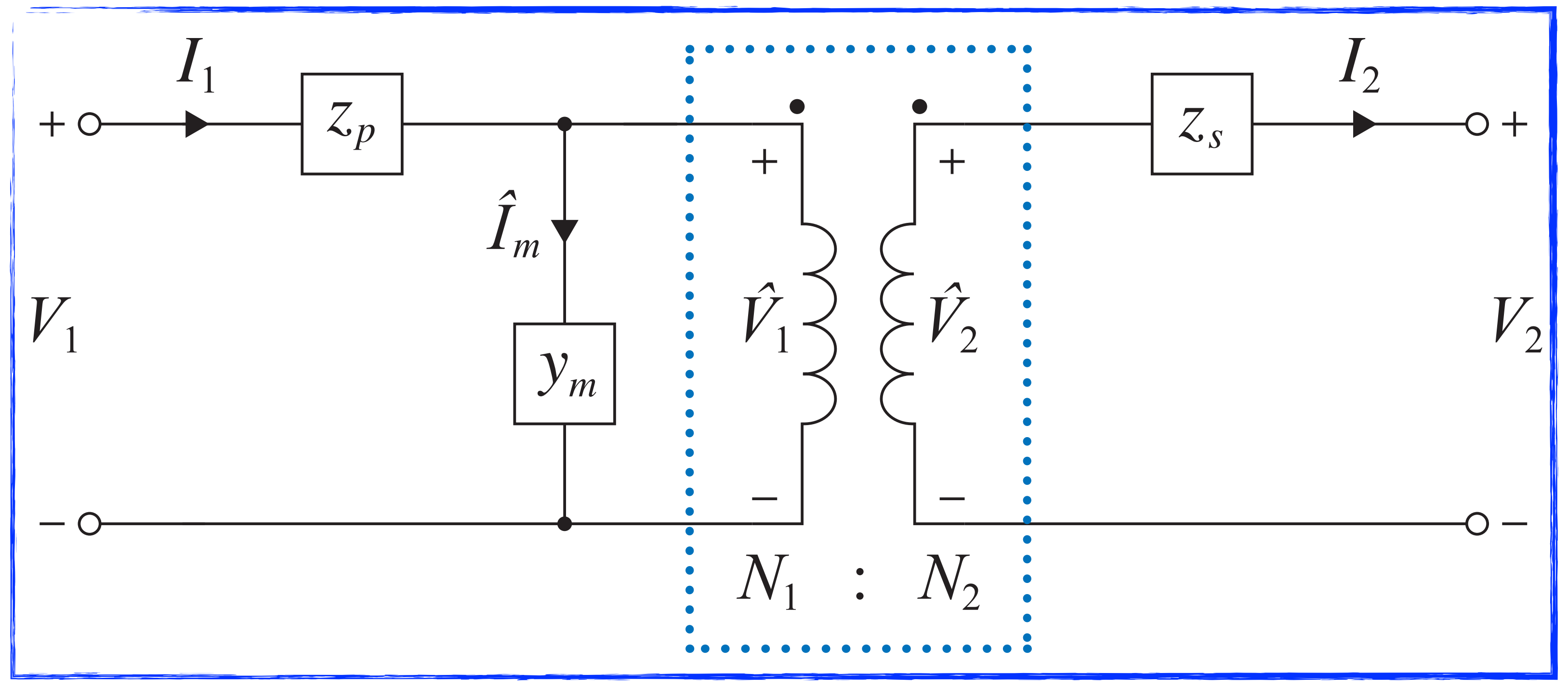
where $n := N_2/N_1,\ a := 1/n$

Model parameters (z_p, z_s, y_m) cannot be uniquely determined from just short-circuit & open-circuit tests

- Additional tests are needed

Nonideal transformer

Circuit models



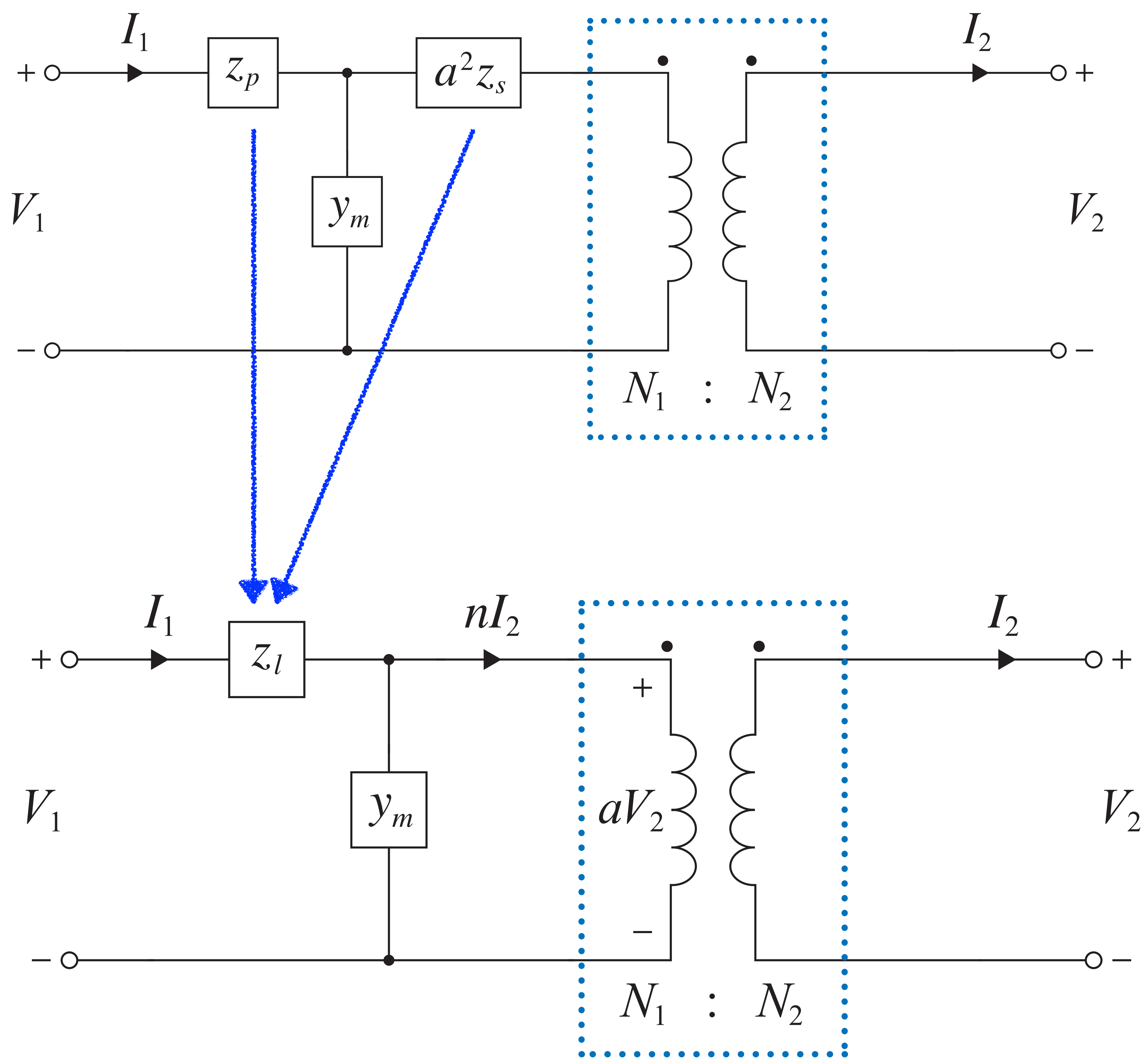
$\equiv$

T equivalent circuit $\equiv$ unitary voltage network

$\approx$

simplified model

Simplified circuit



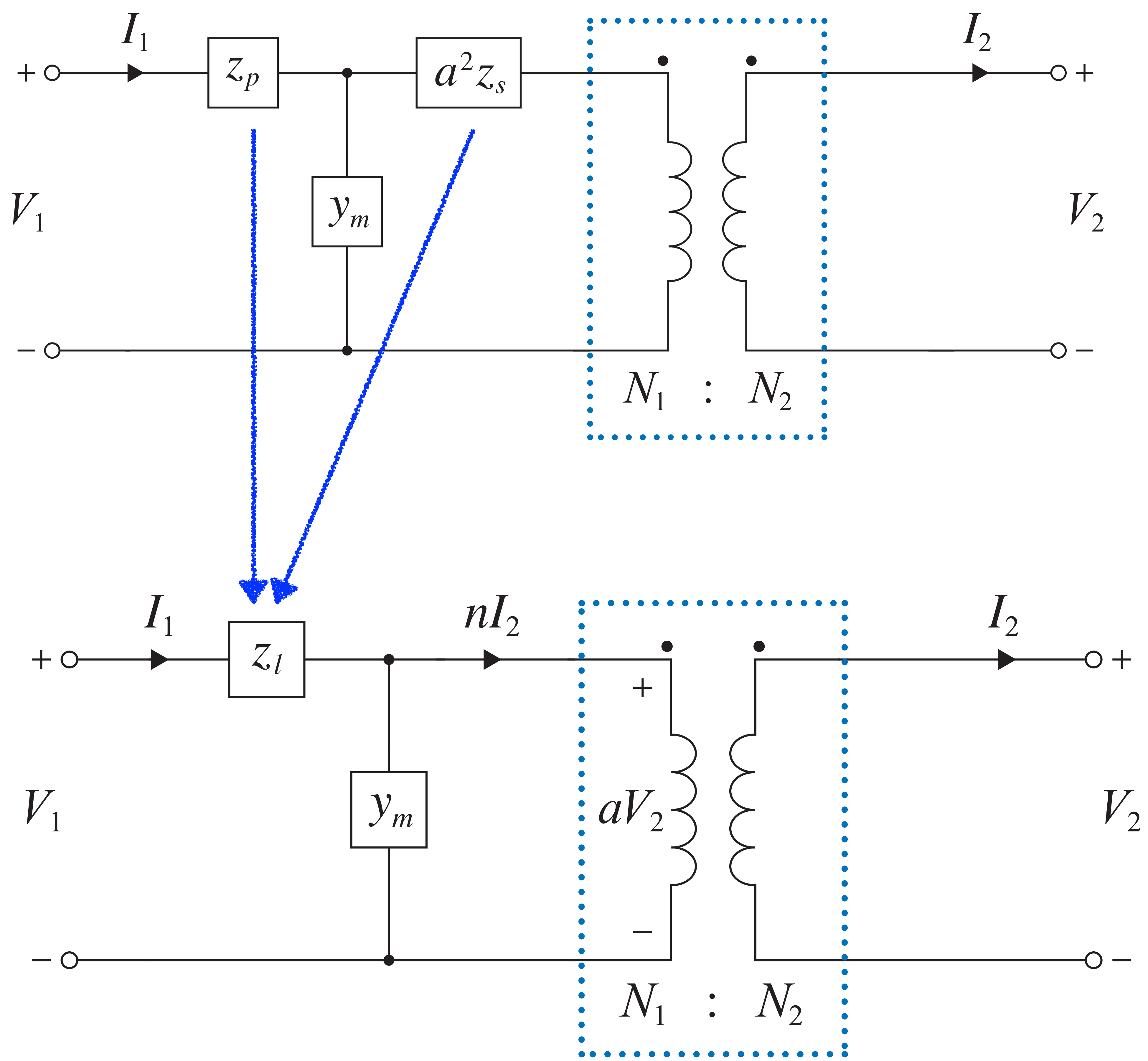
Interchange $a^2 z_s$ and y_m and combine with z_p :

$z_l := z_p + a^2 z_s$

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} a\left(1 + z_l y_m\right) & n z_l \\ a y_m & n \end{bmatrix} \begin{bmatrix} V_2 \\ I_2 \end{bmatrix}$$

where $n := N_2/N_1,\ a := 1/n$

Simplified circuit



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where $n := N_2/N_1, \ a := 1/n$

Good approximation of T equivalent circuit when $|y_m| \ll 1/|a^2 z_s|$

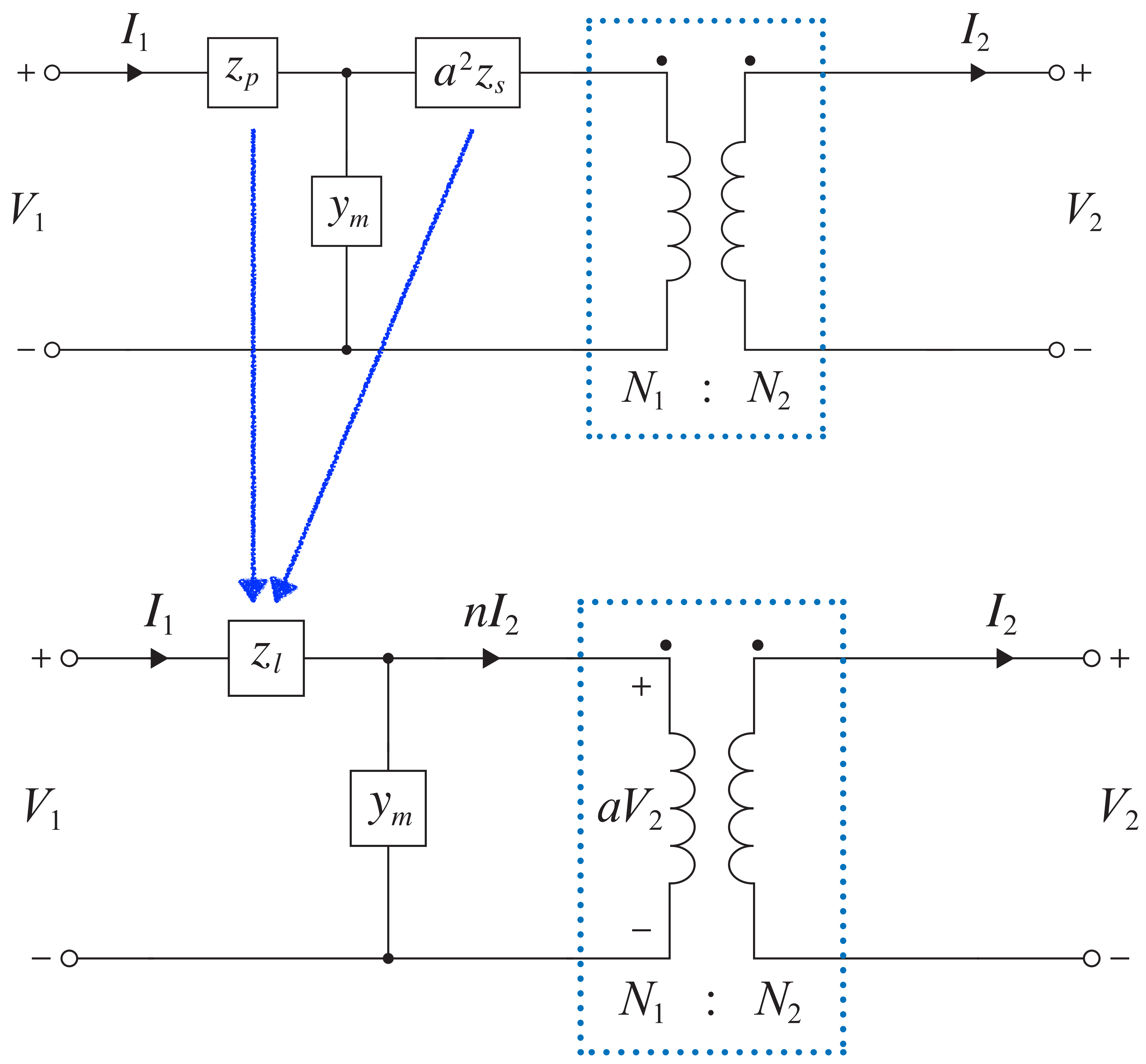
$$\frac{\|M - T\|}{\|T\|} < |\epsilon| \ll 1$$

M : transmission matrix of simplified model

T : transmission matrix of simplified model

$\epsilon := a^2 z_s y_m$

Simplified circuit



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where $n := N_2 / N_1, \; a := 1/n$

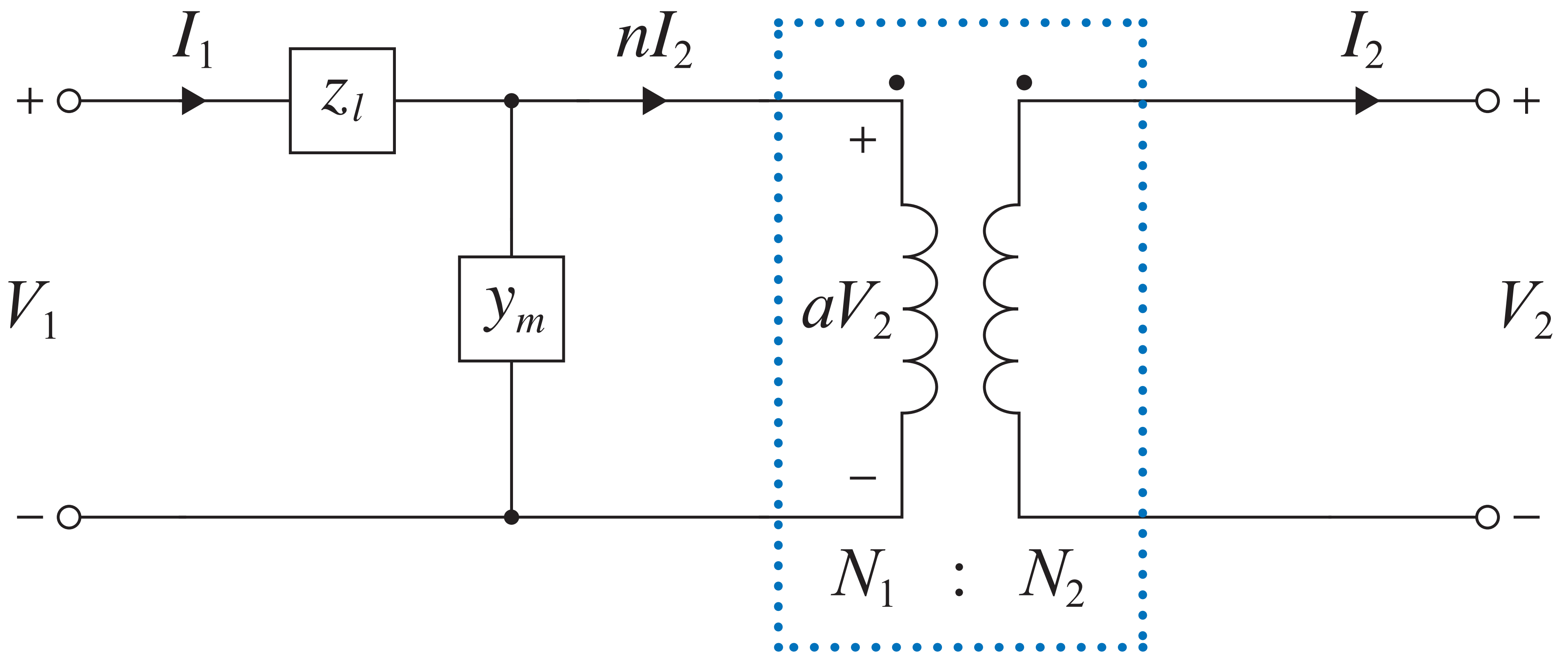
Good approximation when $|y_m| \ll 1/|a^2 z_s|$

$$\frac{\|M - T\|}{\|T\|} < |\epsilon| \ll 1$$

If $y_m = 0$: T equivalent circuit and simplified model are equivalent, $M = T$

Parameter determination

Short & open-circuit tests



Most popular model
(at least for transmission systems)

Parameters (z_l, y_m) can be determined from open and short-circuit tests

- Short-circuit test $(V_2 := 0)$:

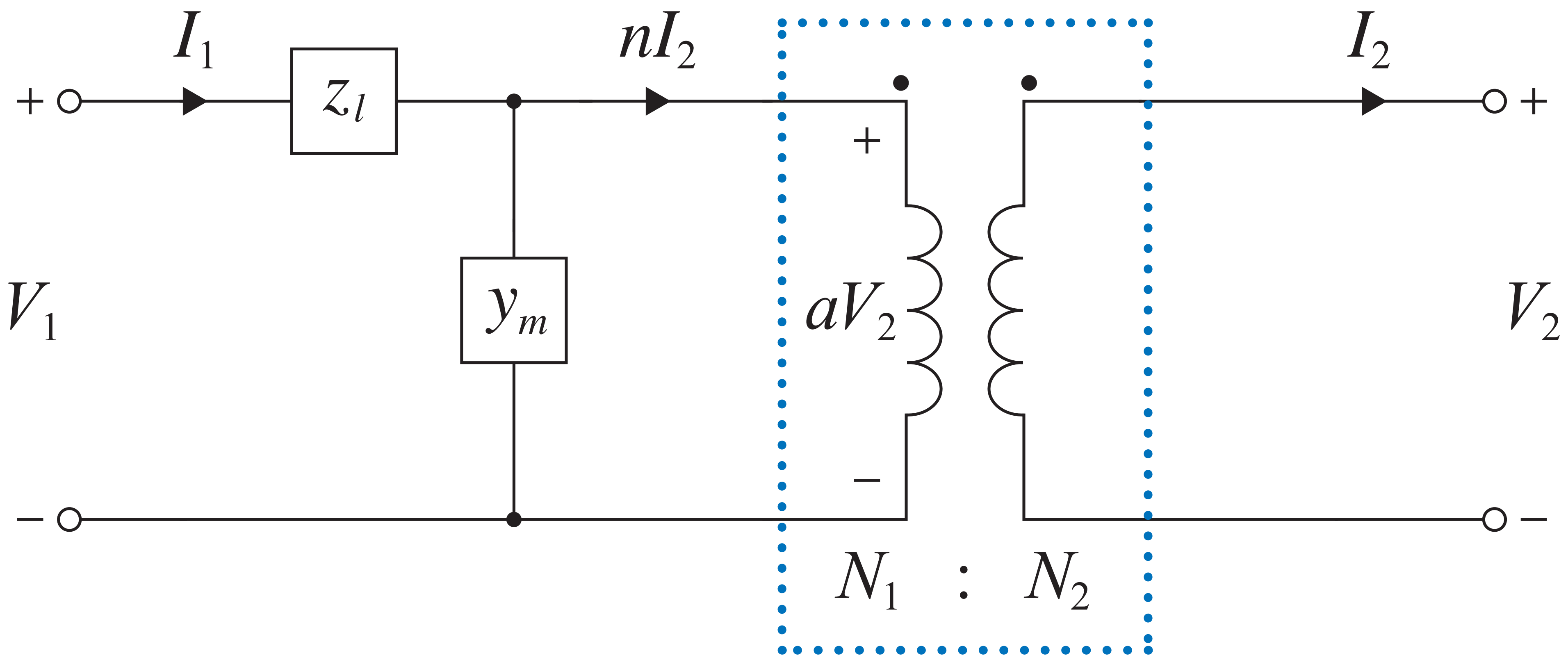
$$z_l = \frac{V_{sc}}{I_{sc}}$$

- Open-circuit test $(I_2 := 0)$:

$$\frac{1}{y_m} = \frac{V_{oc}}{I_{oc}} - \frac{V_{sc}}{I_{sc}}$$

Parameter determination

Short & open-circuit tests



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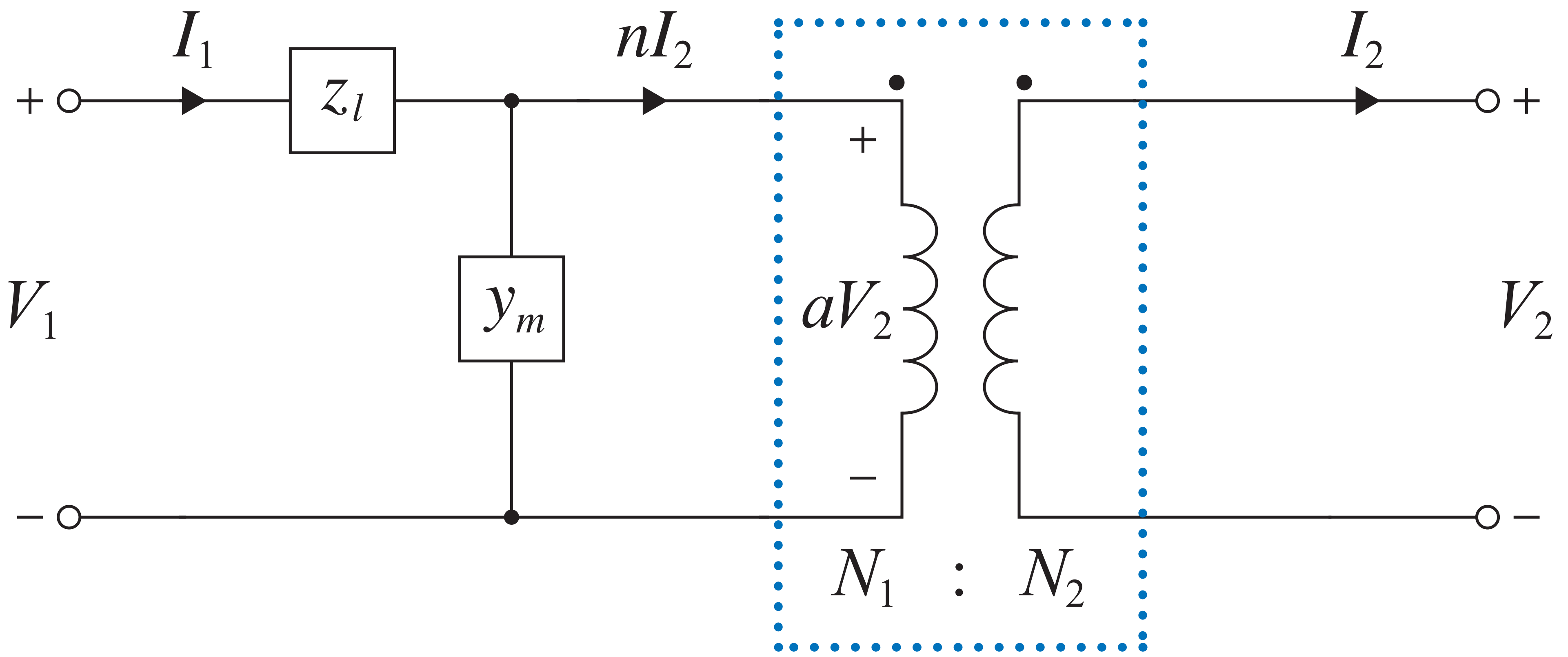
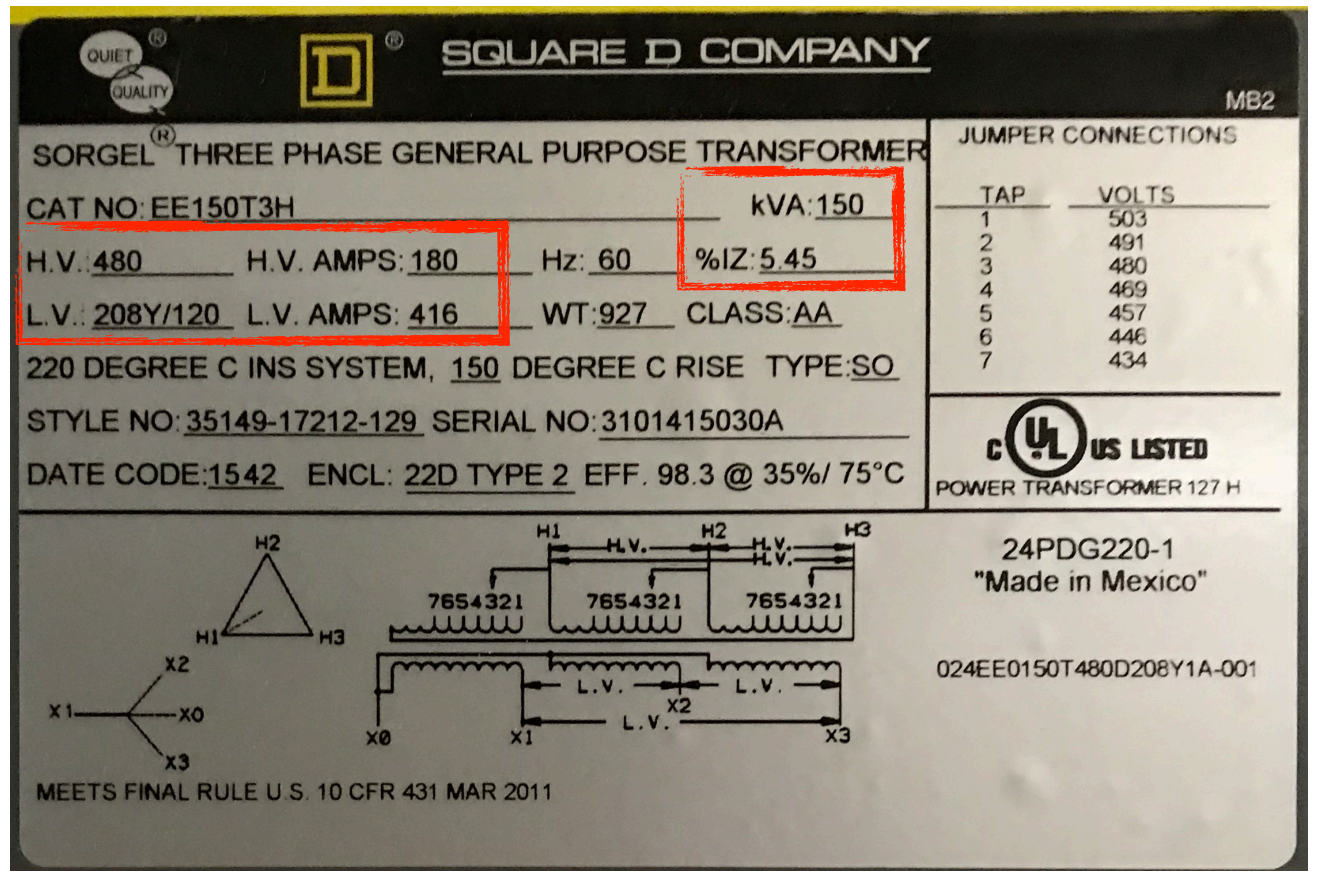
- Open-circuit test $(I_2 := 0)$:

$$\frac{1}{y_m} = \frac{V_{oc}}{I_{oc}} - \frac{V_{sc}}{I_{sc}}$$

Parameter determination

Zero shunt admittance $y_m = 0$





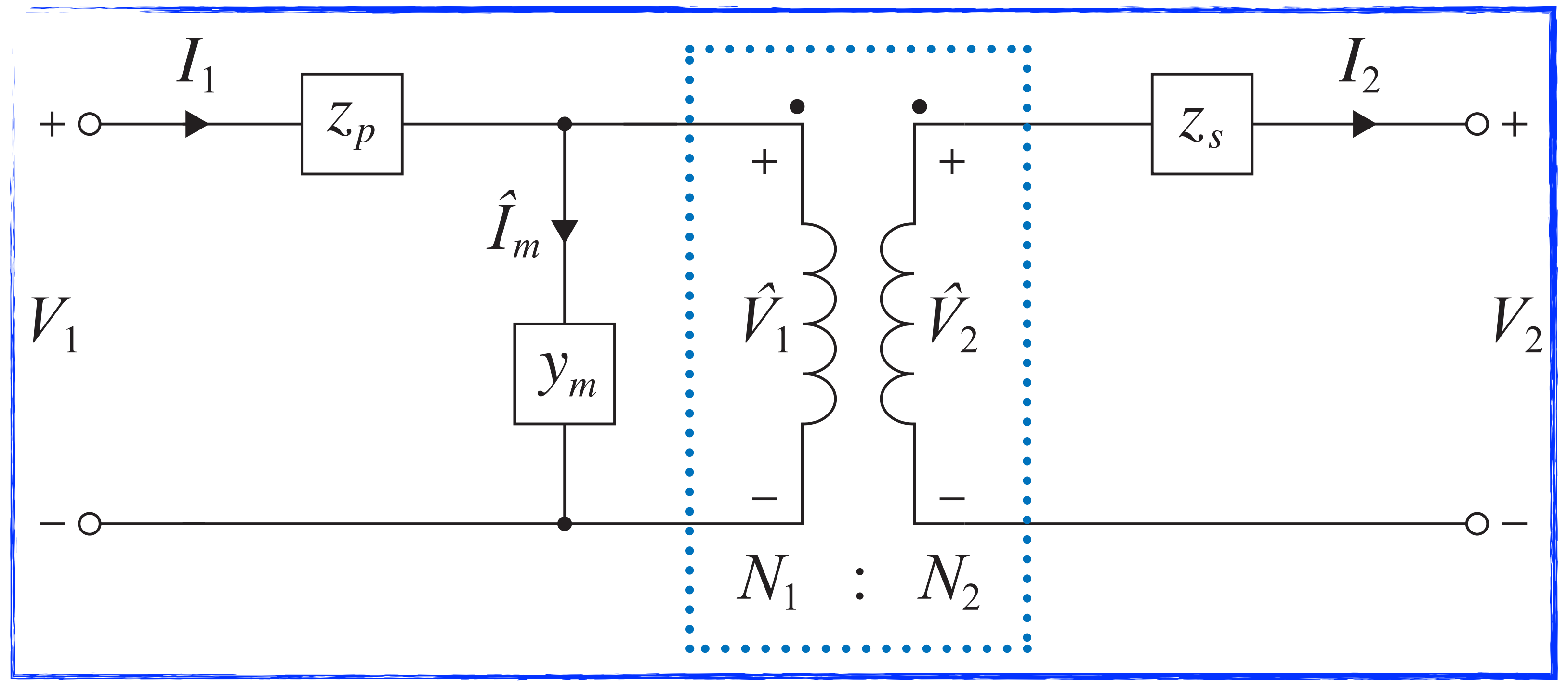
When $y_m = 0$, parameter z_l can be determined from standard 3-phase transformer ratings:

- Rated primary line-to-line voltage $\left|V_{\text{pri}}\right|$
- Rated primary line current $\left|I_{\text{pri}}\right|$
- Impedance voltage β on the primary side, per phase, as % of rated primary voltage

β : voltage needed on the primary side to produce rated primary current across each single-phase transformer is $\beta \times$ rated primary voltage

Nonideal transformer

Circuit models

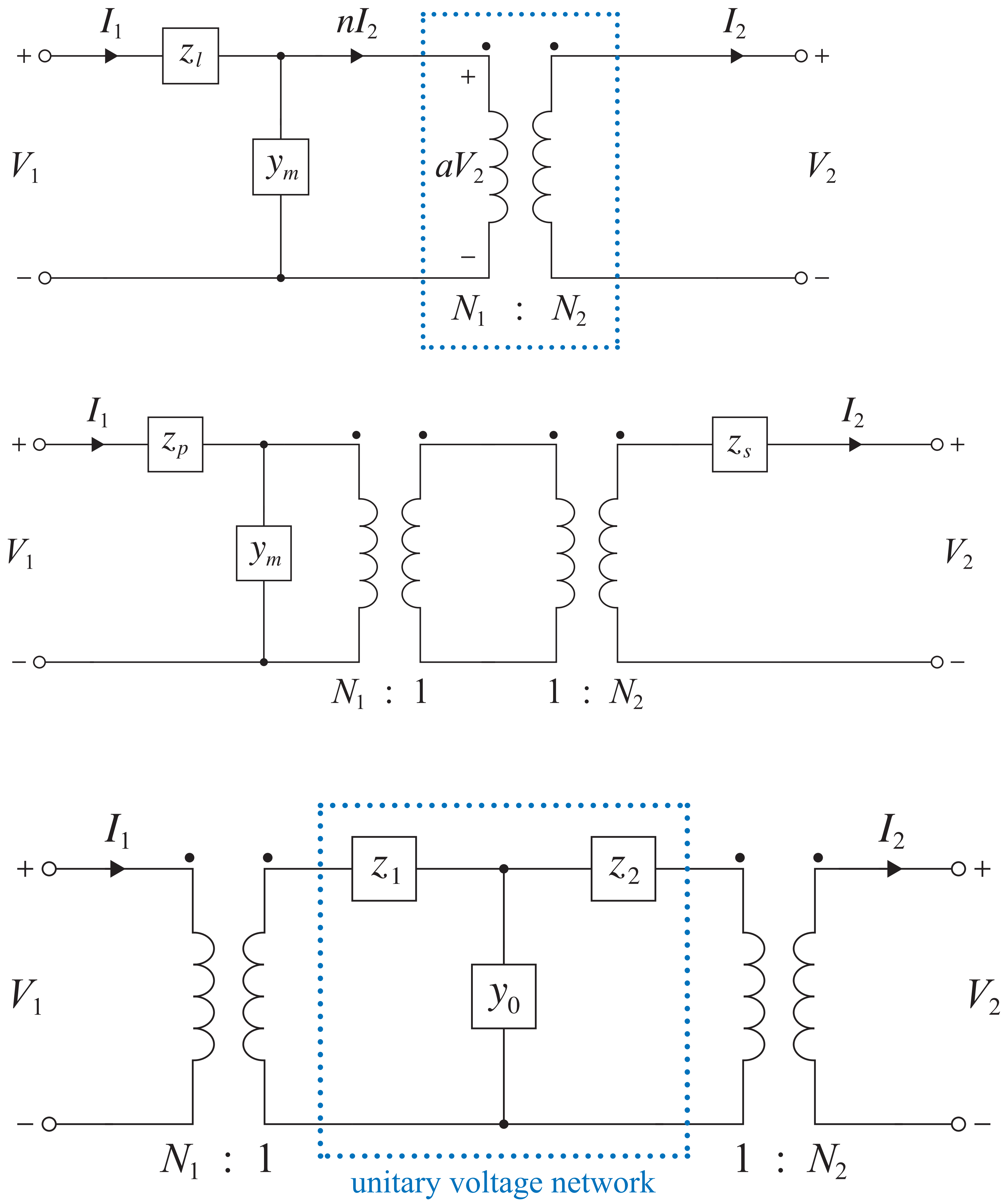


T equivalent circuit ≡ unitary voltage network

simplified model

Unitary voltage network

Single-phase 2-winding transformer



equivalent to 2 ideal transformers in series

ref imp & adm across ideal transformers

UVN-based model

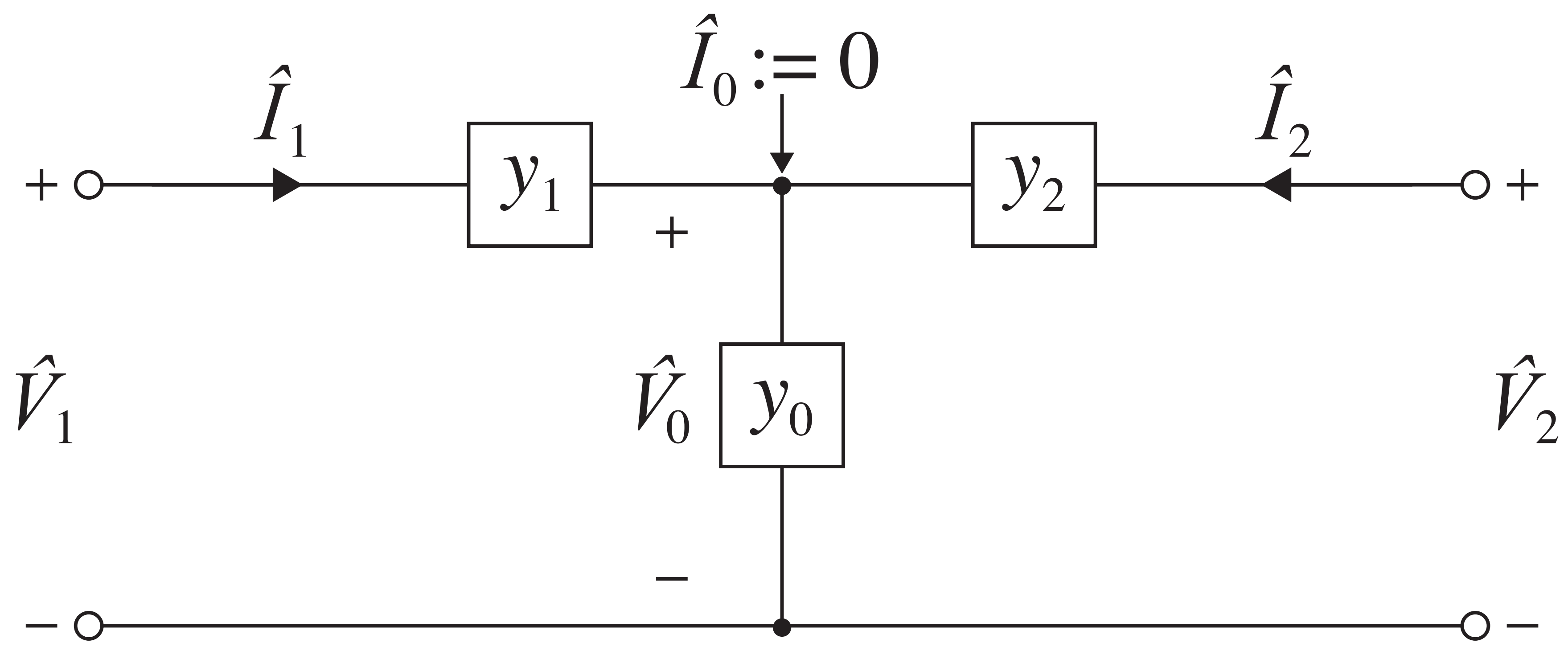
- Unitary voltage network (UVN) connecting 2 ideal transformers
- Equivalent to T equivalent circuit
- Simplified model is an approximation

Advantages

- UVN can be generalized to incorporate multiple windings, e.g., split-phase transformers
- Ideal transformers on both ends can be connected in various ways, e.g., 3-phase transformers in Y/Δ configurations, non-standard transformers

Single-phase transformer

Unitary voltage network



$$\hat{I}_1 = y_1(\hat{V}_1 - \hat{V}_0), \qquad \hat{I}_2 = y_2(\hat{V}_2 - \hat{V}_0)$$

$$y_0\hat{V}_0 = \hat{I}_0 + \hat{I}_1 + \hat{I}_2$$

Admittance matrix

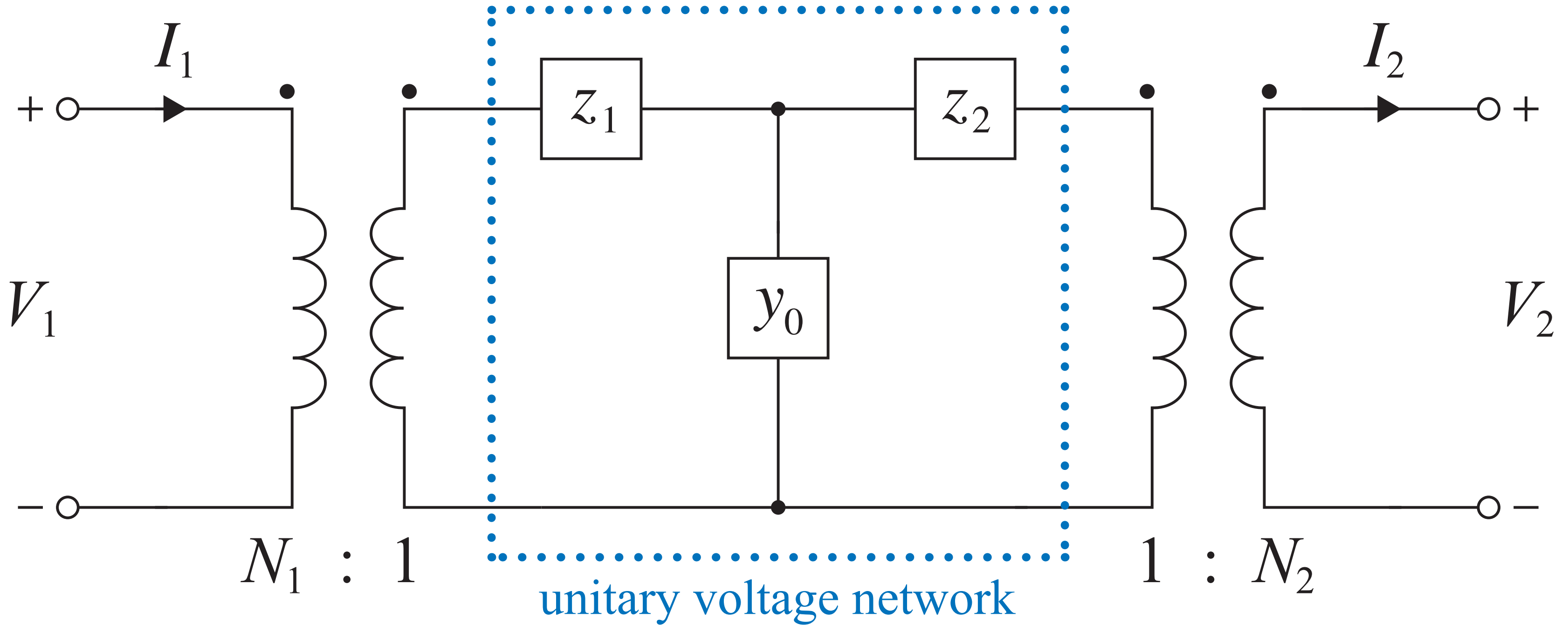
$$\begin{bmatrix} \hat{I}_0 \\ \hat{I}_1 \\ \hat{I}_2 \end{bmatrix} = \begin{bmatrix} y_0 + y_1 + y_2 & -y_1 & -y_2 \\ -y_1 & y_1 & 0 \\ -y_2 & 0 & y_2 \end{bmatrix} \begin{bmatrix} \hat{V}_0 \\ \hat{V}_1 \\ \hat{V}_2 \end{bmatrix}$$

Since $\hat{I}_0 = 0$, can eliminate $\hat{U}_0$ to obtain Kron reduced admittance matrix

$$\begin{bmatrix} \hat{I}_1 \\ \hat{I}_2 \end{bmatrix} = \underbrace{\frac{1}{\sum_i y_i} \begin{bmatrix} y_1(y_0 + y_2) & -y_1 y_2 \\ -y_1 y_2 & y_2(y_0 + y_1) \end{bmatrix}}_{Y_{\text{uvn}}} \begin{bmatrix} \hat{V}_1 \\ \hat{V}_2 \end{bmatrix}$$

Single-phase transformer

External model: admittance matrix



$$\begin{bmatrix} \hat{I}_1 \\ \hat{I}_2 \end{bmatrix} = \underbrace{\frac{1}{\sum_i y_i} \begin{bmatrix} y_1(y_0 + y_2) & -y_1 y_2 \\ -y_1 y_2 & y_2(y_0 + y_1) \end{bmatrix}}_{Y_{\text{uvn}}} \begin{bmatrix} \hat{V}_1 \\ \hat{V}_2 \end{bmatrix}$$

Let

$$I := \begin{bmatrix} I_1 \\ -I_2 \end{bmatrix}, \quad V := \begin{bmatrix} V_1 \\ V_2 \end{bmatrix}$$

$$M := \begin{bmatrix} 1/N_1 & 0 \\ 0 & 1/N_2 \end{bmatrix}$$

Conversion between internal vars & terminal vars across ideal transformers

$$\hat{U} = MV, \quad \hat{J} = M^{-1} I$$

Hence, external model:

$$I = \left(M Y_{\text{uvn}} M \right) V$$

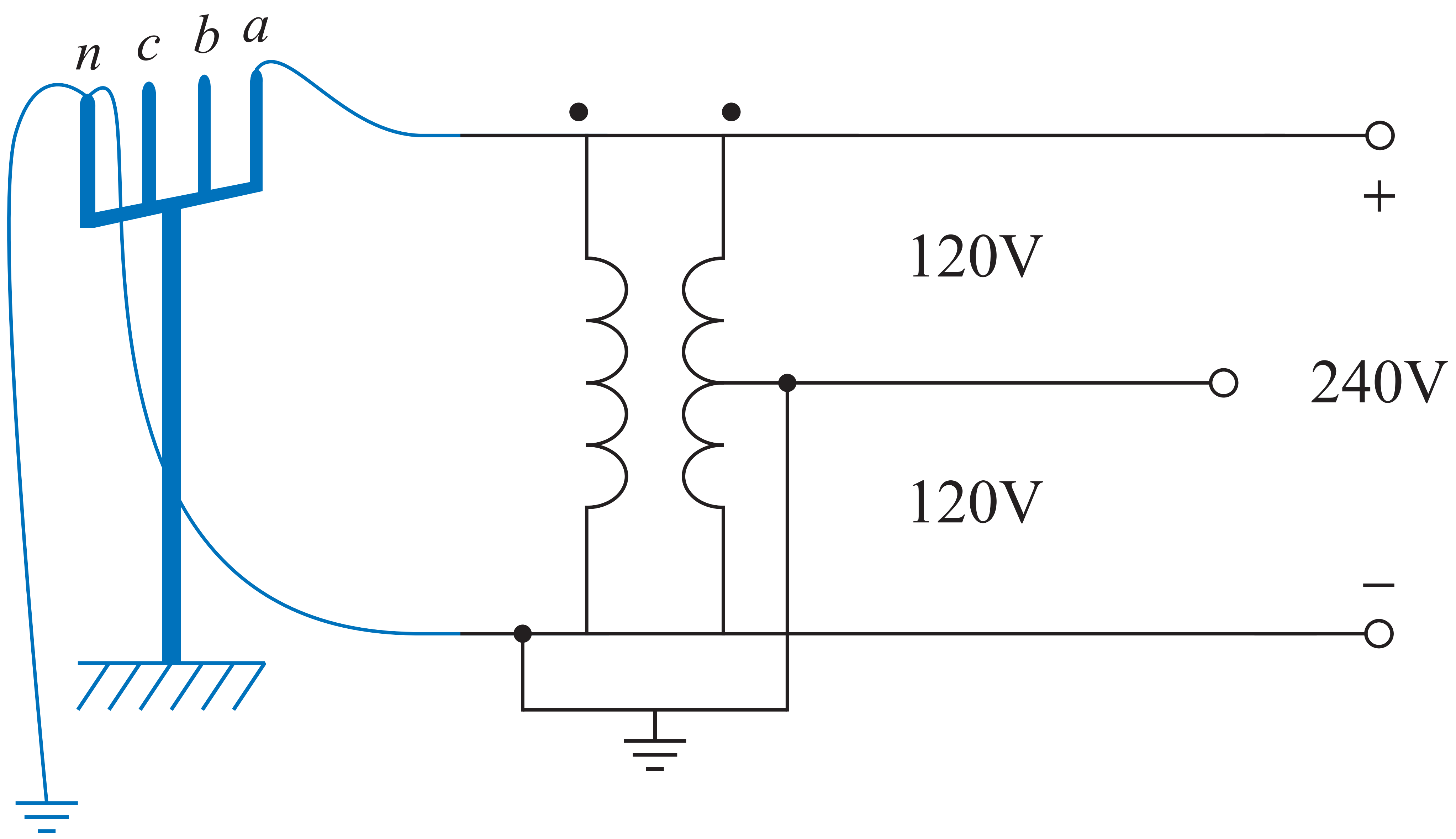
Application of UVN model

Common distribution transformers

line-to-line voltage (kV) $\lvert V_{ab} \rvert$	phase voltage (kV) $\lvert V_{an} \rvert$	total power (MVA) $\lvert S_{3\phi} \rvert$
4.8	2.8	3.3
12.47	7.2	8.6
22.9	13.2	15.9
34.5	19.9	23.9

Distribution transformer

Example: split-phase

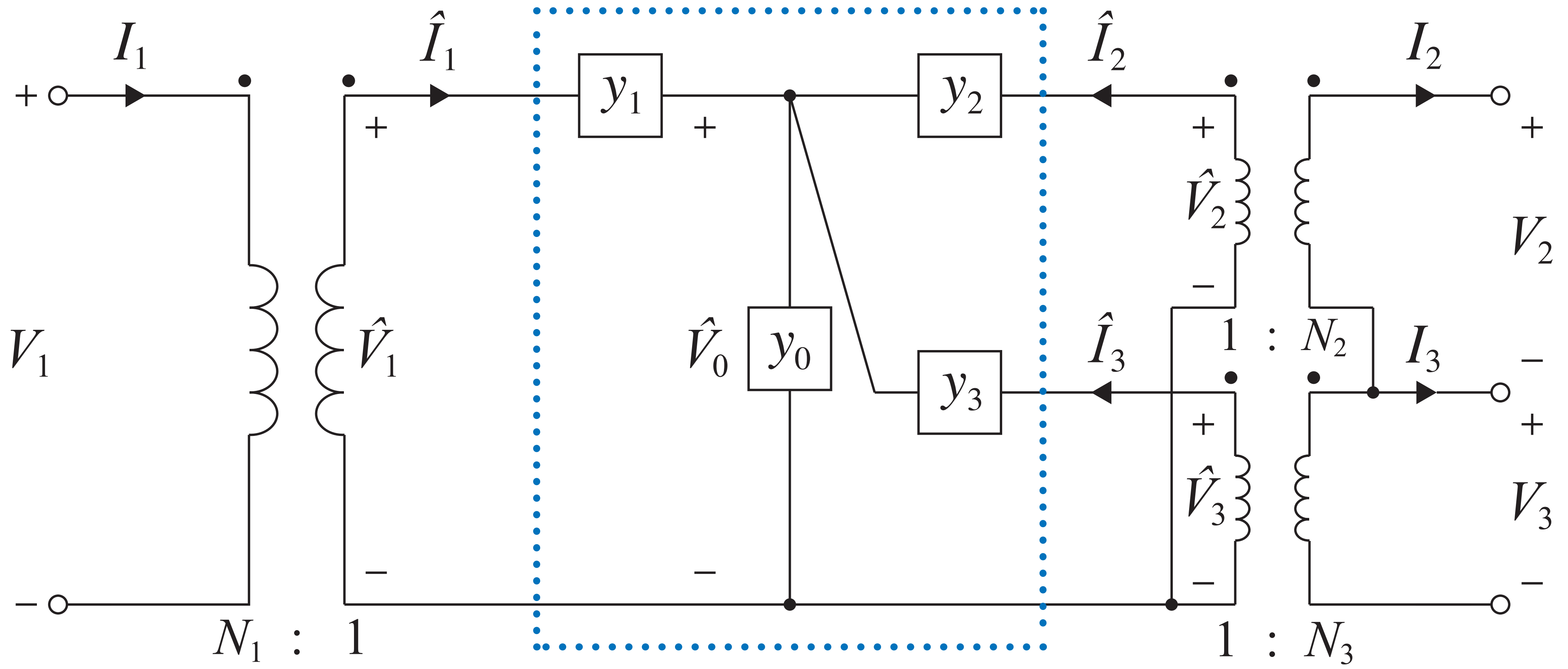


Common deployment in US

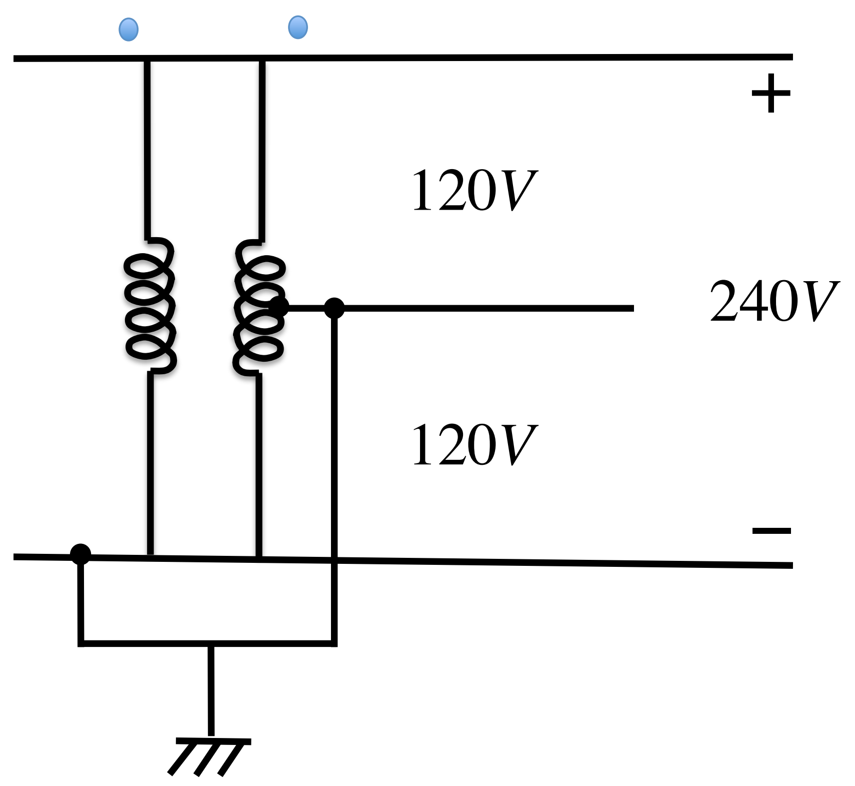
- Single phase
- Split-phase 120/240 V

Multi-winding transformers

Example: split-phase



$$\begin{bmatrix} \hat{I}_0 \\ \hat{I}_1 \\ \hat{I}_2 \\ \hat{I}_3 \end{bmatrix} = \begin{bmatrix} \sum_{i=0}^{3} & -y_1 & -y_2 & -y_3 \\ -y_1 & y_1 & 0 & 0 \\ -y_2 & 0 & y_2 & 0 \\ -y_3 & 0 & 0 & y_3 \end{bmatrix} \begin{bmatrix} \hat{V}_0 \\ \hat{V}_1 \\ \hat{V}_2 \\ \hat{V}_3 \end{bmatrix}$$

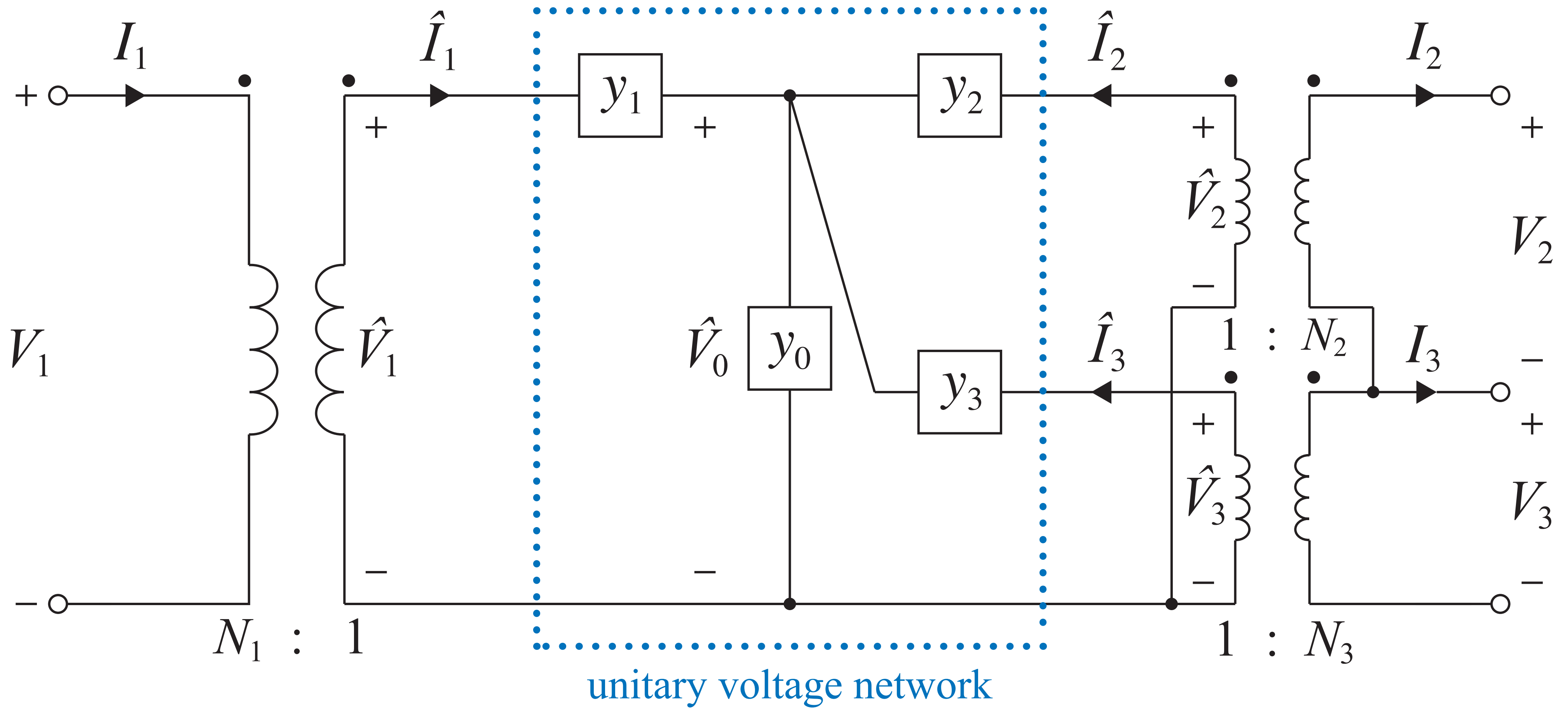


UVN: Kron-reduced admittance matrix

$$\begin{bmatrix} \hat{I}_1 \\ \hat{I}_2 \\ \hat{I}_3 \end{bmatrix} = \underbrace{\frac{1}{\sum_i y_i} \begin{bmatrix} y_1(y_0 + y_2 + y_3) & -y_1 y_2 & -y_1 y_3 \\ -y_2 y_1 & y_2(y_0 + y_1 + y_3) & -y_2 y_3 \\ -y_3 y_1 & -y_3 y_2 & y_3(y_0 + y_1 + y_2) \end{bmatrix}}_{Y_{\text{uvn}}} \begin{bmatrix} \hat{V}_1 \\ \hat{V}_2 \\ \hat{V}_3 \end{bmatrix}$$

Multi-winding transformers

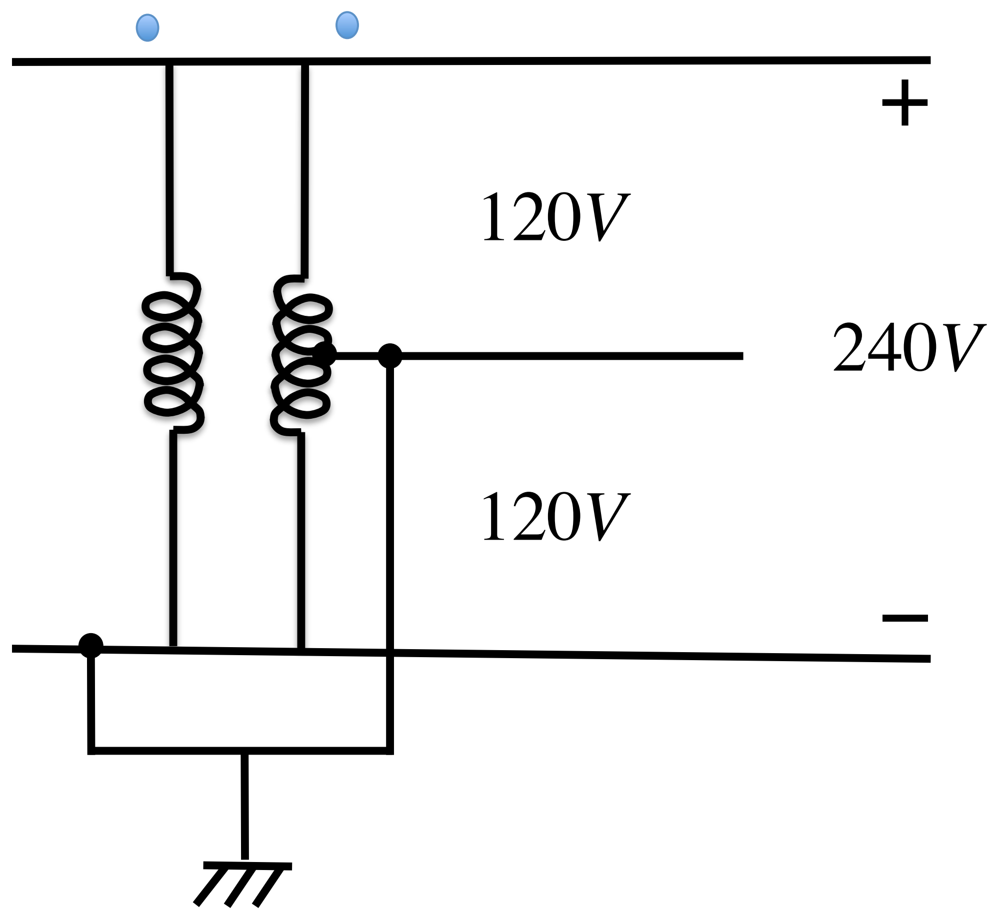
Example: split-phase transformer



Let

$$I \;:=\; \begin{bmatrix} I_1 \\ -I_2 \\ -I_3 \end{bmatrix}, \quad V \;:=\; \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix}$$

$$M \;:=\; \begin{bmatrix} 1/N_1 & 0 & 0 \\ 0 & 1/N_2 & 0 \\ 0 & 0 & 1/N_3 \end{bmatrix}$$

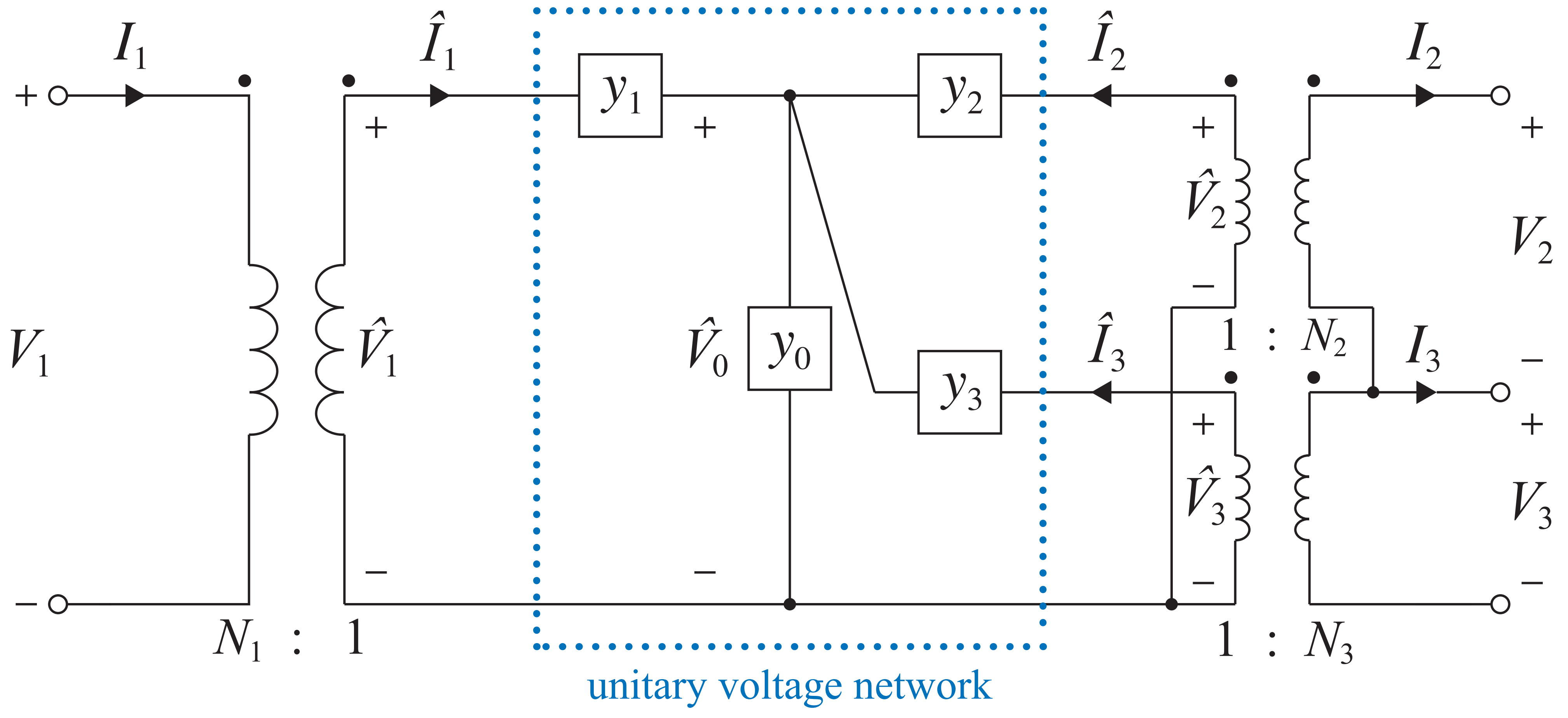


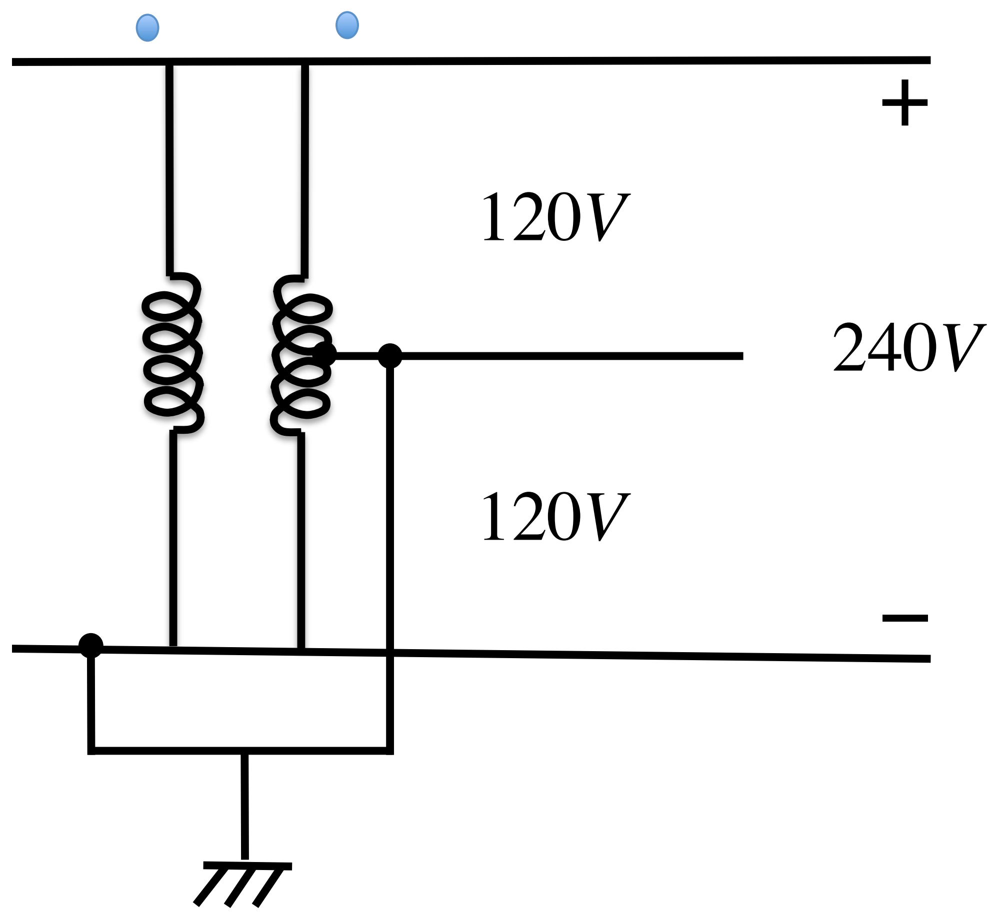
Conversion between internal vars & terminal vars across ideal transformers: $\hat{V} = MV$ and

$$\hat{I} \;=\; M^{-1} \begin{bmatrix} I_1 \\ -I_2 \\ -I_2 - I_3 \end{bmatrix} \;=:\; M^{-1}AI \quad \text{where } A := \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 1 & 1 \end{bmatrix}$$

Multi-winding transformers

Example: split-phase transformer





Let

$$I := \begin{bmatrix} I_1 \\ -I_2 \\ -I_3 \end{bmatrix}, \quad V := \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix}$$

$$M := \begin{bmatrix} 1/N_1 & 0 & 0 \\ 0 & 1/N_2 & 0 \\ 0 & 0 & 1/N_3 \end{bmatrix}$$

Eliminate internal vars $(\hat{I}, \hat{V})$ from

$$\hat{V} = Y_{\text{uvn}}\hat{I}, \quad \hat{V} = MV, \quad \hat{I} = M^{-1}AI$$

External model:

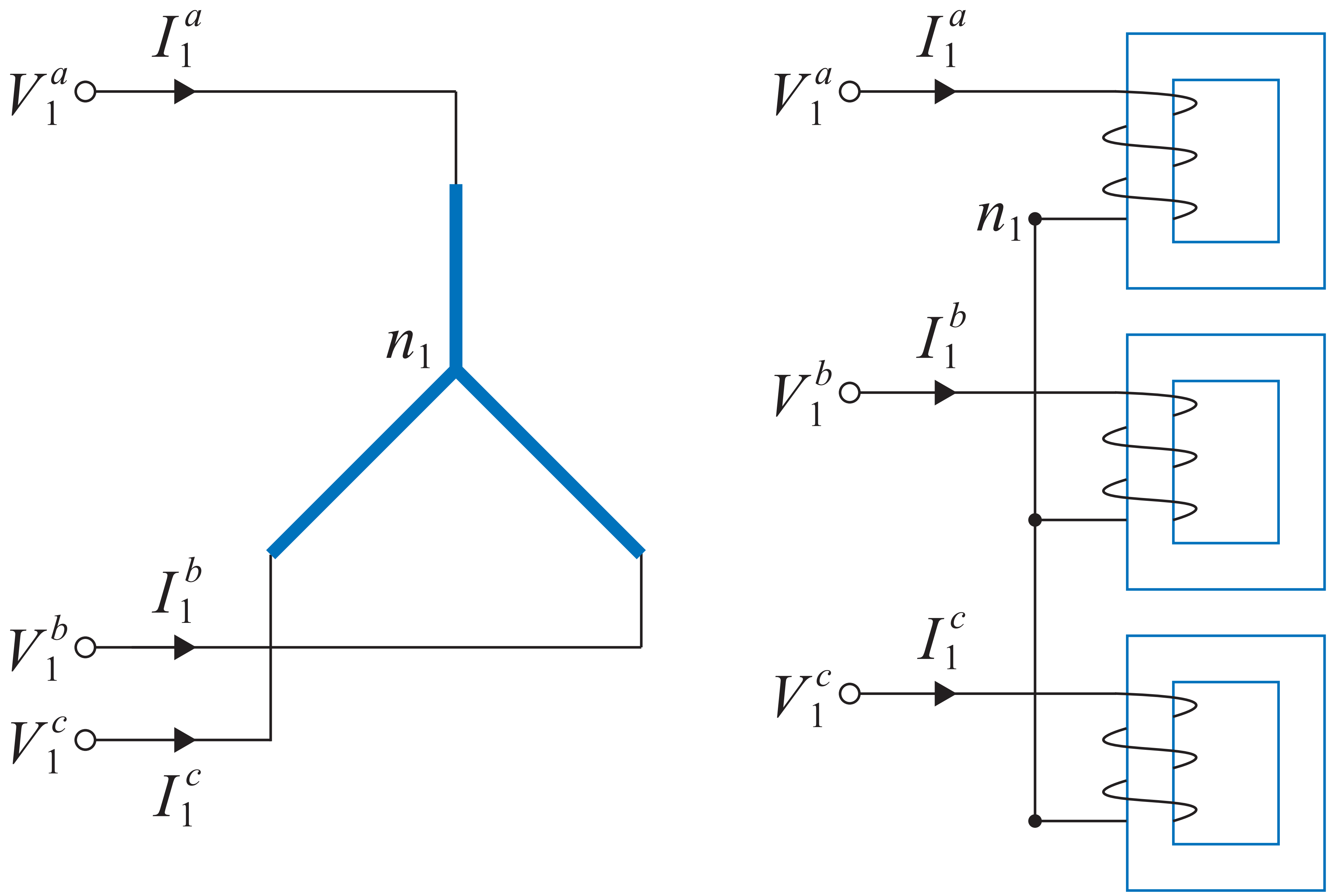
$$I \ = \ A^{-1}\left(MY_{\text{uvn}}M\right) V$$

Outline

1. Single-phase transformer
2. Balanced three-phase transformers
    - Ideal transformers
    - Nonideal transformers
3. Equivalent impedance
4. Per-phase analysis
5. Per-unit normalization

Ideal transformers

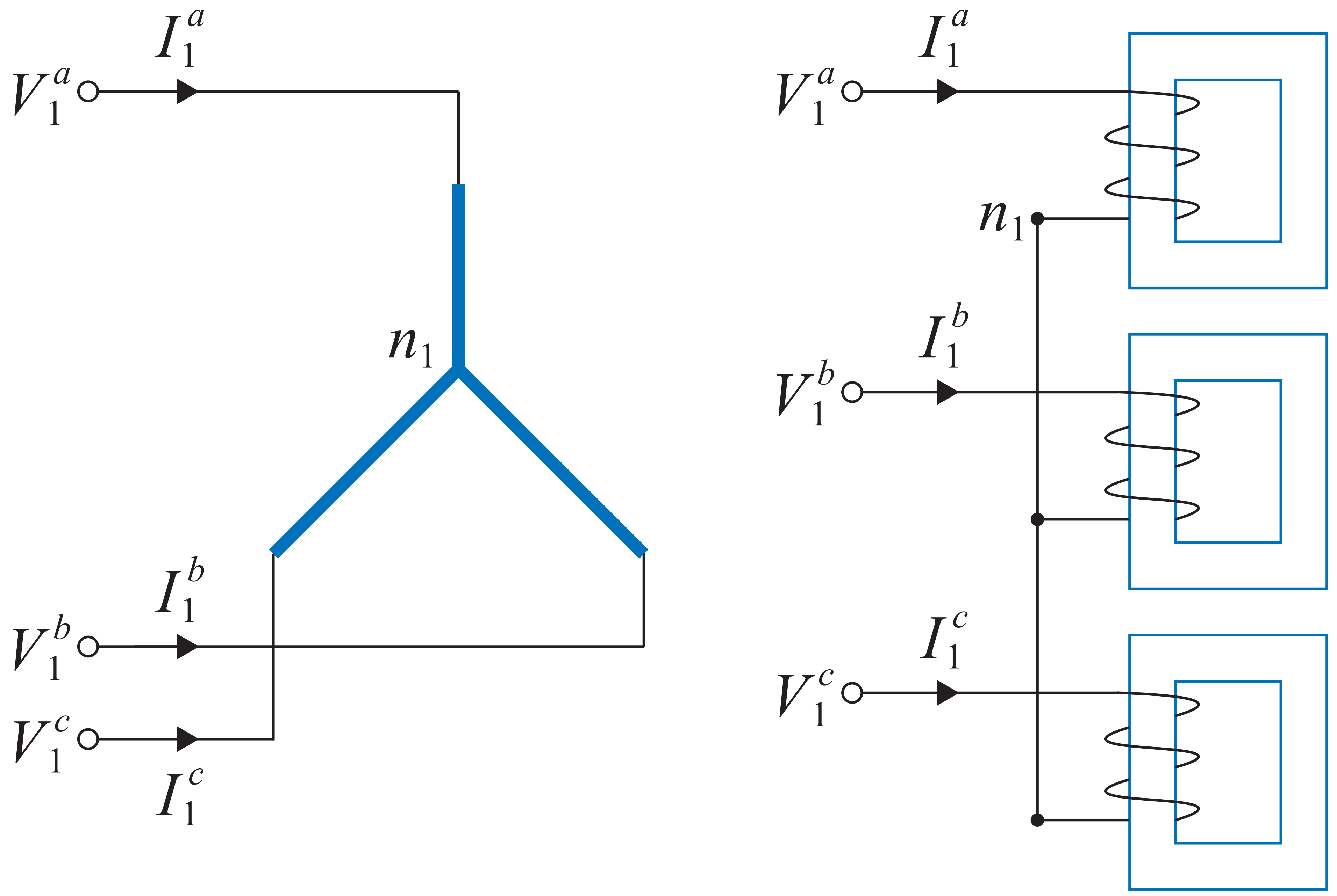
Connectivity



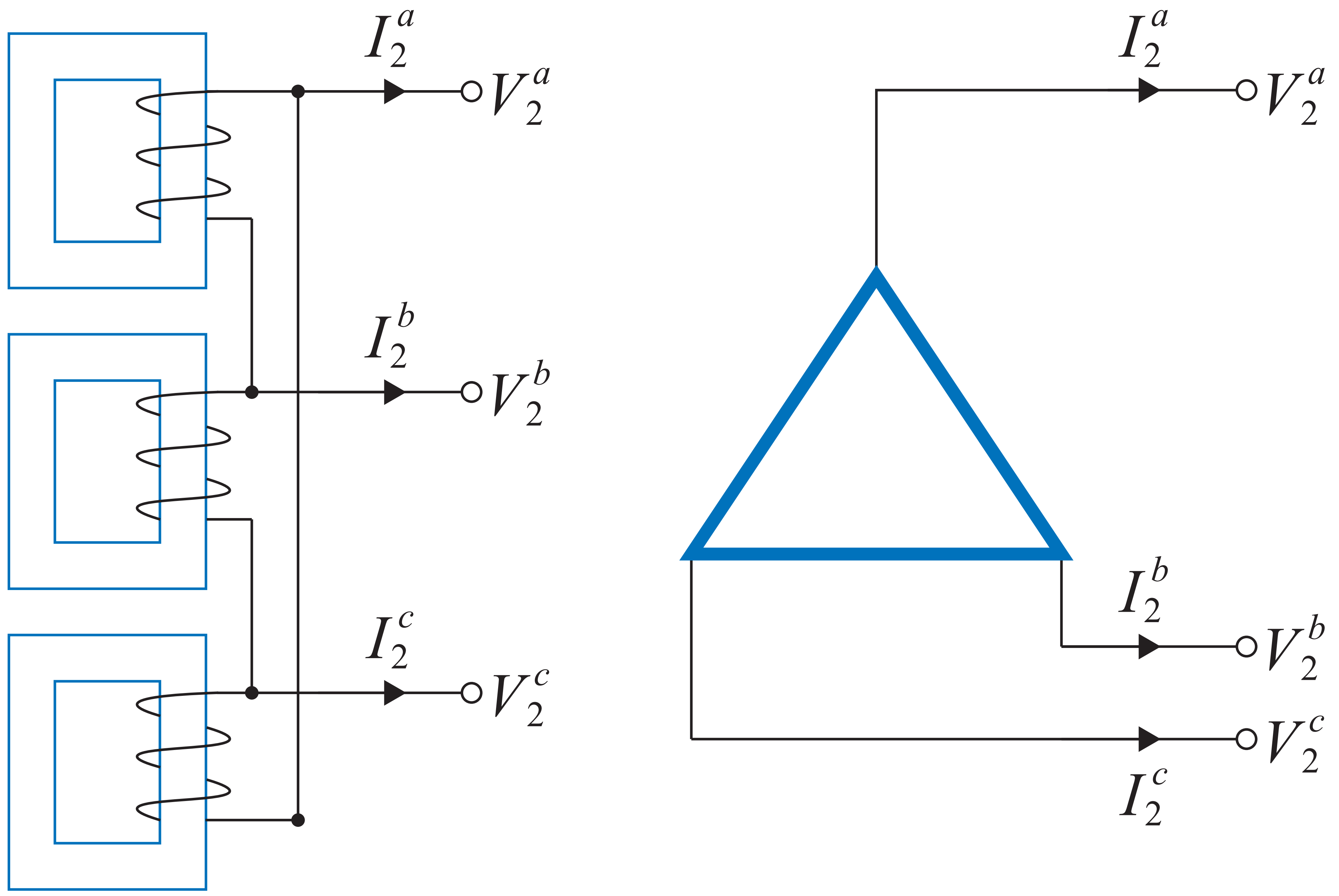
(a) Primary winding in Y configuration

Ideal transformers

Connectivity



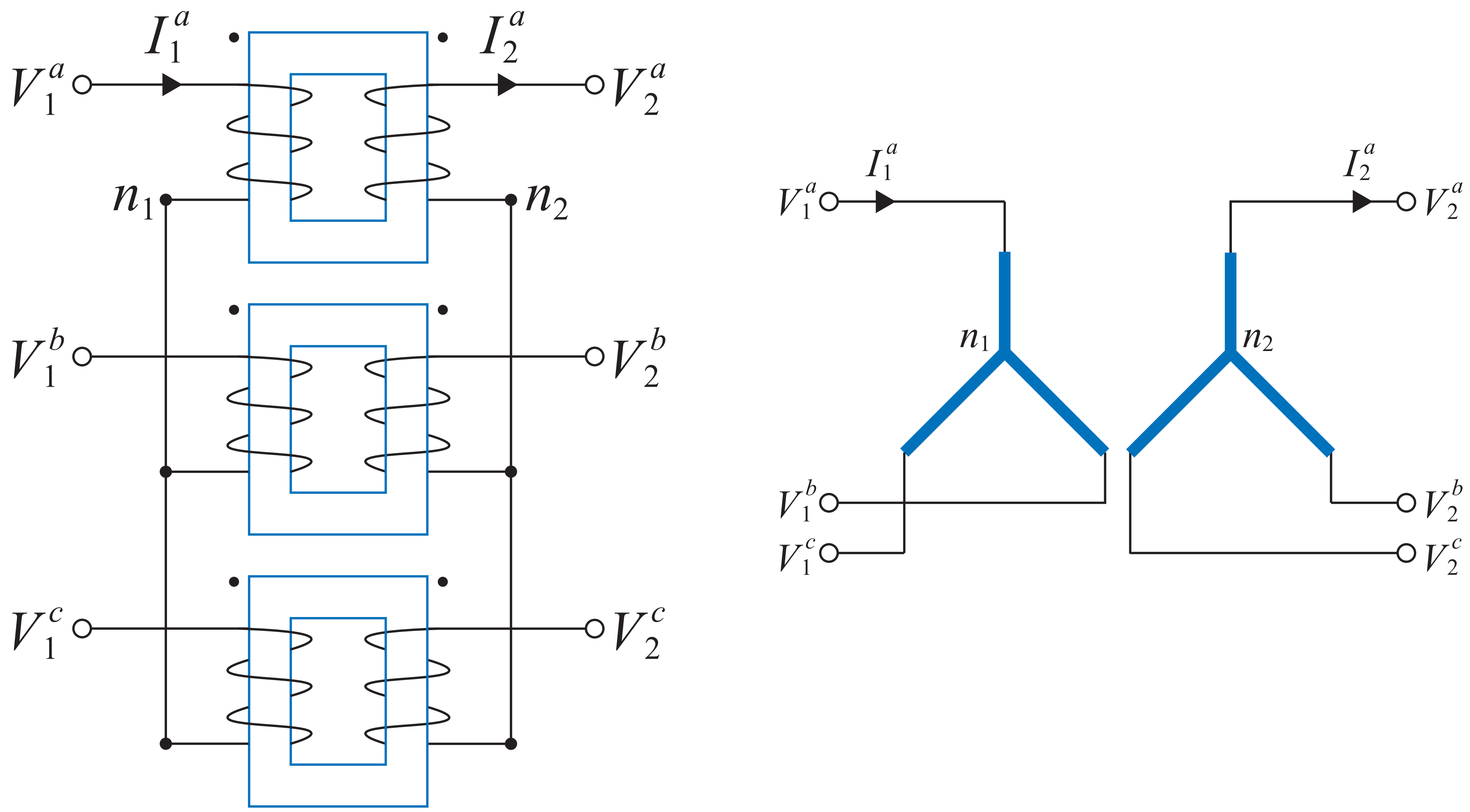
(a) Primary winding in Y configuration



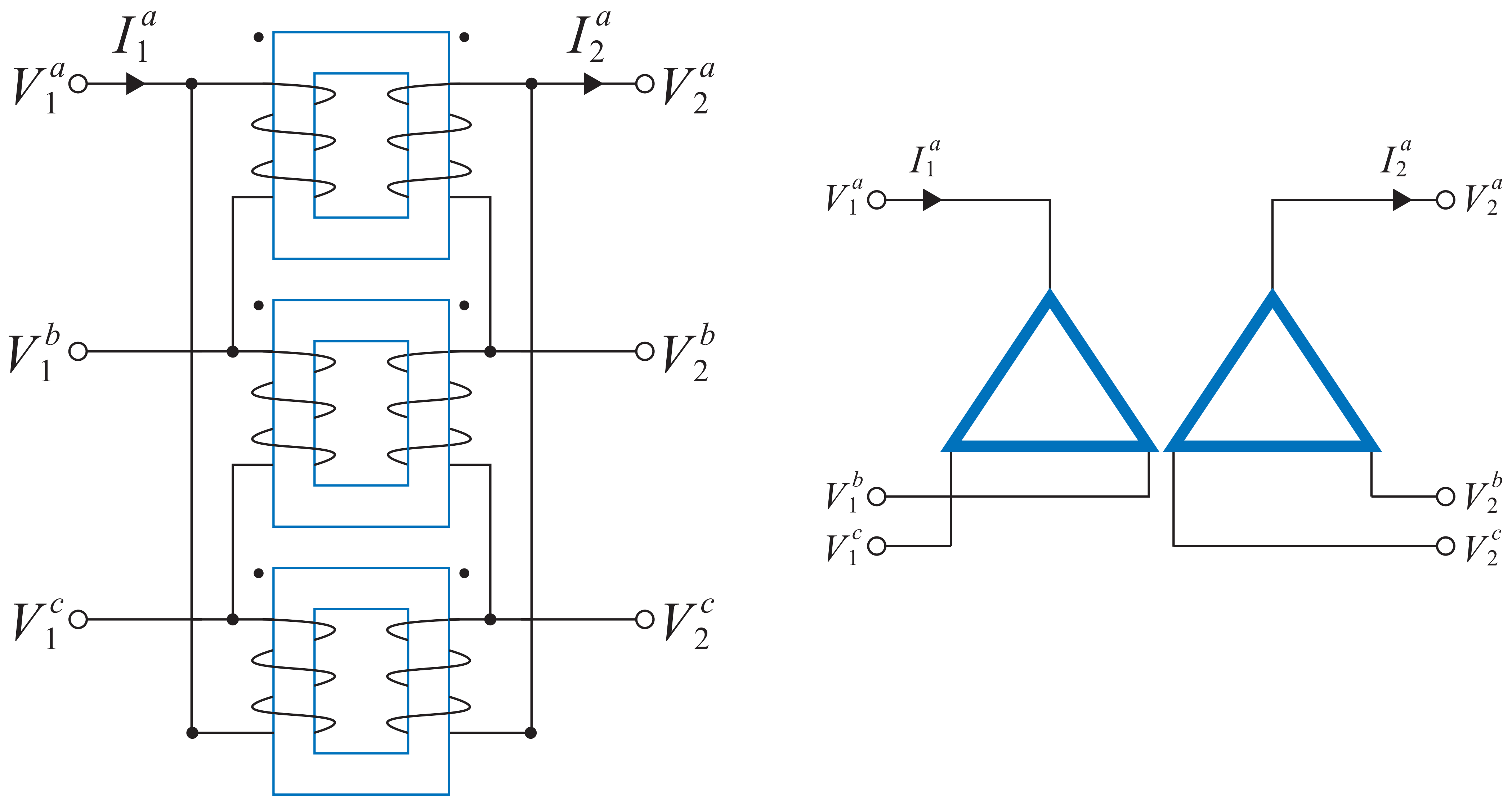
(b) Secondary winding in Δ configuration

Ideal transformers

Configurations



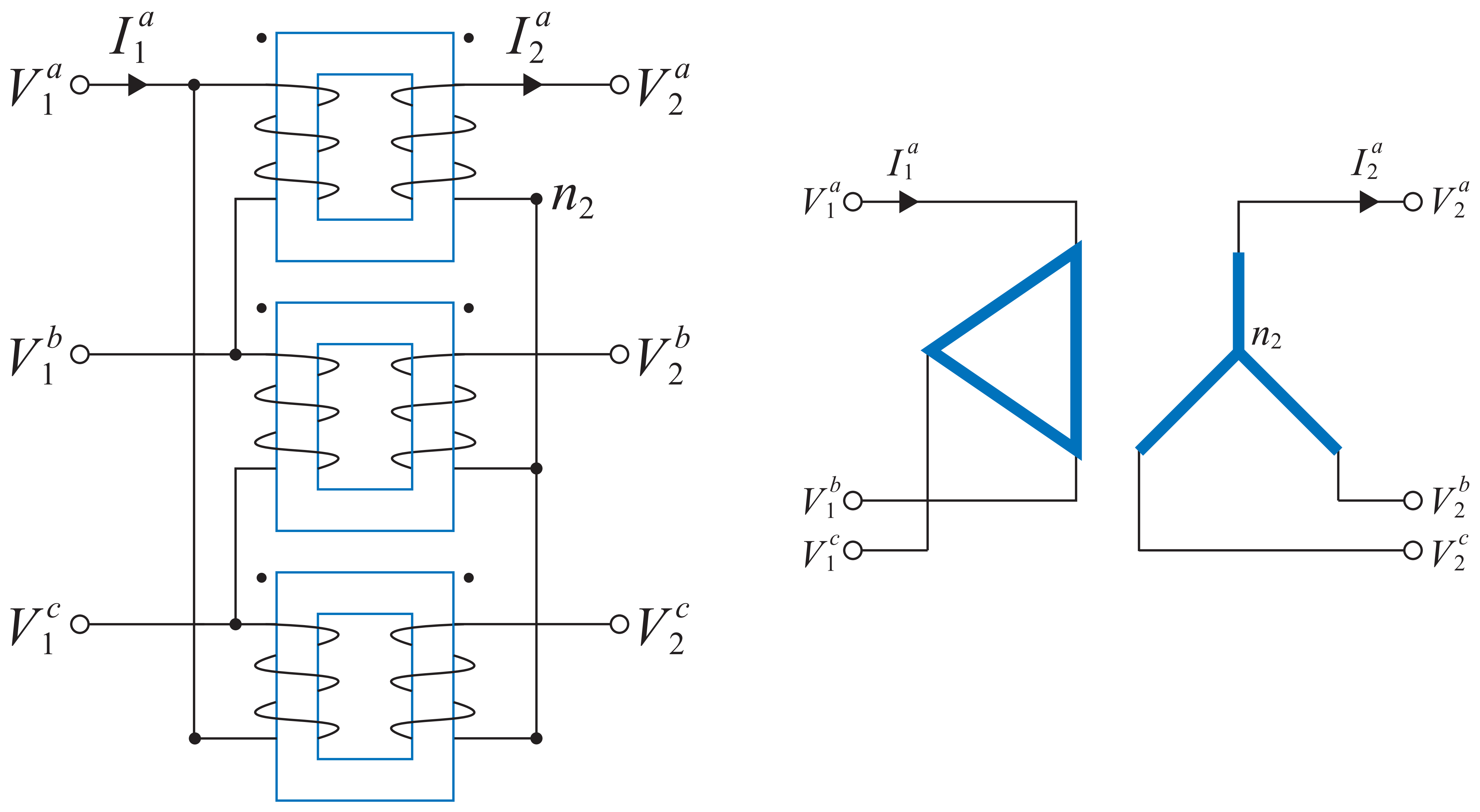
YY



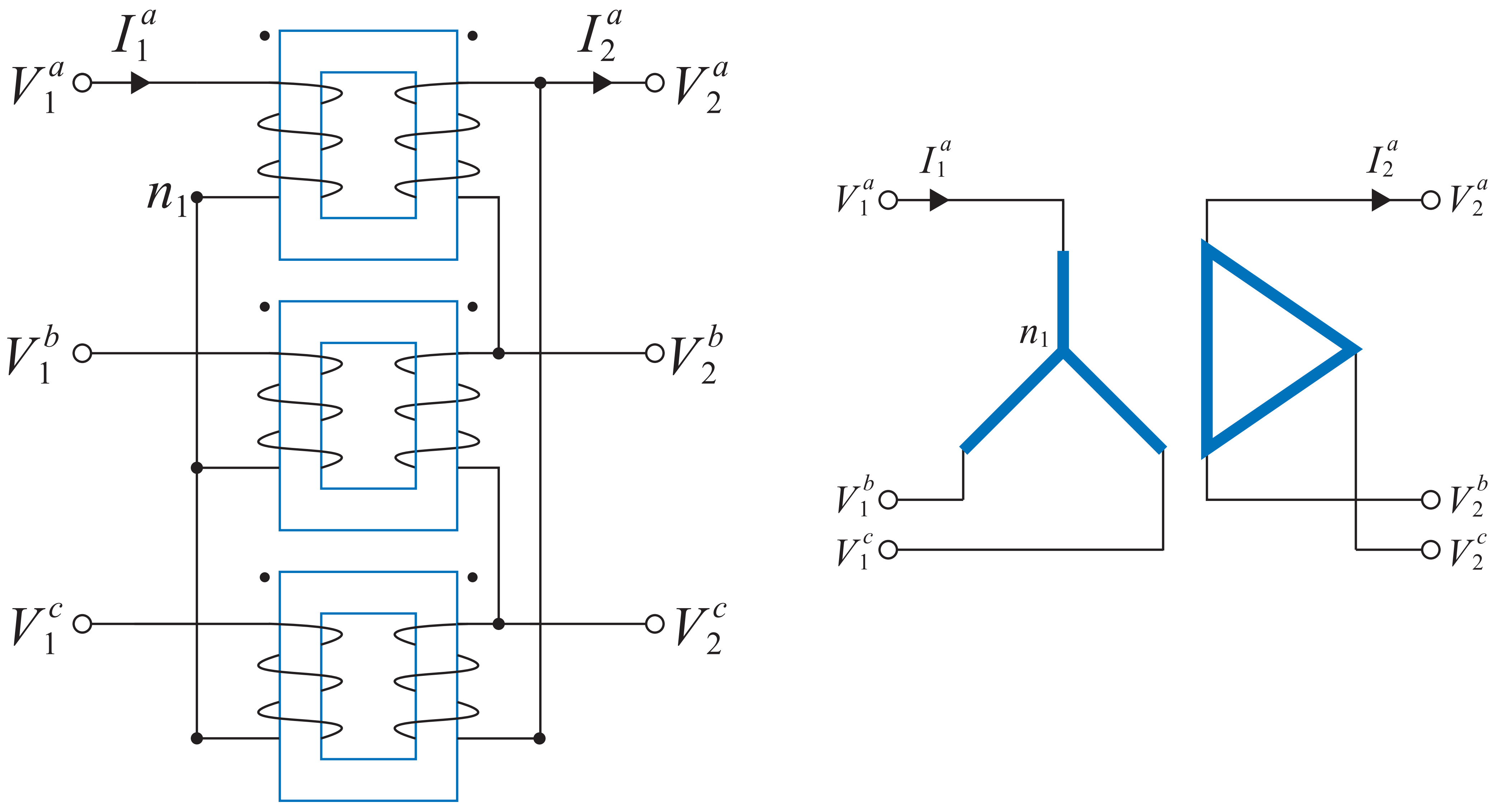
$\Delta\Delta$

Ideal transformers

Configurations



ΔY



$Y\Delta$

Ideal transformers

Summary

Property	Gain
Voltage gain	$K(n)$
Current gain	$\frac{1}{\bar{K}(n)}$
Power gain	1
Sec z_l referred to pri	$\frac{z_l}{\lvert K(n)\rvert^2}$

Configuration	Gain
YY	$K_{YY}(n) := n$
$\Delta\Delta$	$K_{\Delta\Delta}(n) := n$
ΔY	$K_{\Delta Y}(n) := \sqrt{3}n\ e^{\mathbf{i}\pi/6}$
$Y\Delta$	$K_{Y\Delta}(n) := \frac{n}{\sqrt{3}}\ e^{-\mathbf{i}\pi/6}$

Per-phase equivalent

YY-equivalent of a balanced 3-phase transformer: balanced YY transformer with same external model, i.e., same voltage gain $K(n)$

- Single-phase equivalent: phase a model of YY-equivalent

$$YY: \qquad V_2^{\text{line}} = (1-\alpha)V_2^Y = nV_1^{\text{line}}, \qquad I_2 = aI_1^Y \qquad \Rightarrow \qquad K_{YY}(n) := n$$

$$\Delta\Delta: \qquad V_2^{\text{line}} = V_2^{\Delta} = nV_1^{\text{line}}, \qquad I_2 = aI_1^Y \qquad \Rightarrow \qquad K_{\Delta\Delta}(n) := n$$

ΔY:

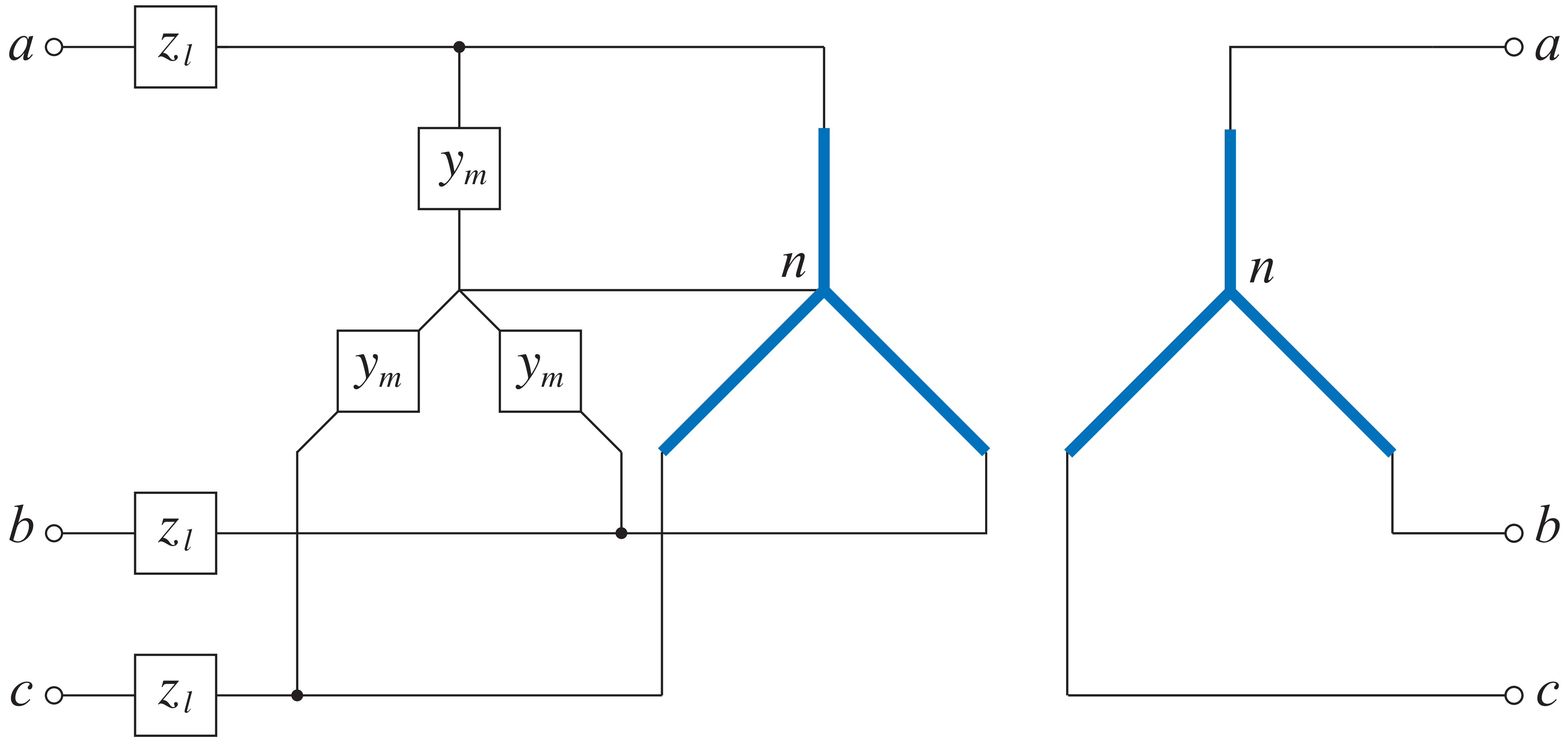
$$V_2^{\text{line}} = (1-\alpha)V_2^Y = (1-\alpha)nV_1^{\text{line}}, \qquad I_2 = \frac{a}{1-\bar{\alpha}}I_1 \qquad \Rightarrow \qquad K_{\Delta Y}(n) := (1-\alpha)n$$

$\Delta\Delta$:

$$V_2^{\text{line}} = V_2^{\Delta} = \frac{n}{1-\alpha}V_1^{\text{line}}, \qquad I_2 = -(1-\alpha^2)I_2^{\Delta} = (1-\bar{\alpha})aI_1 \qquad \Rightarrow \qquad K_{Y\Delta}(n) := n/(1-\alpha)$$

Nonideal transformers

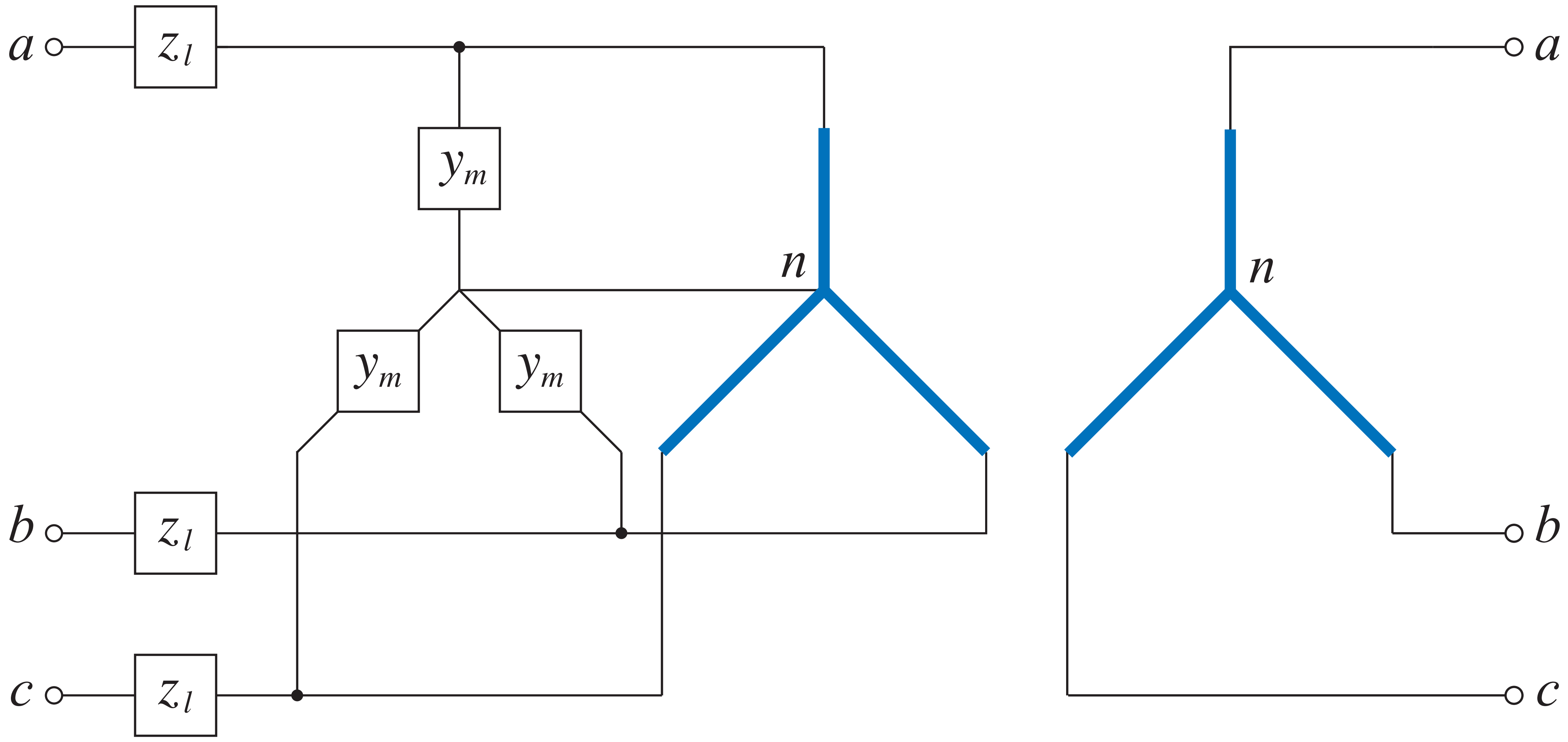
YY configuration



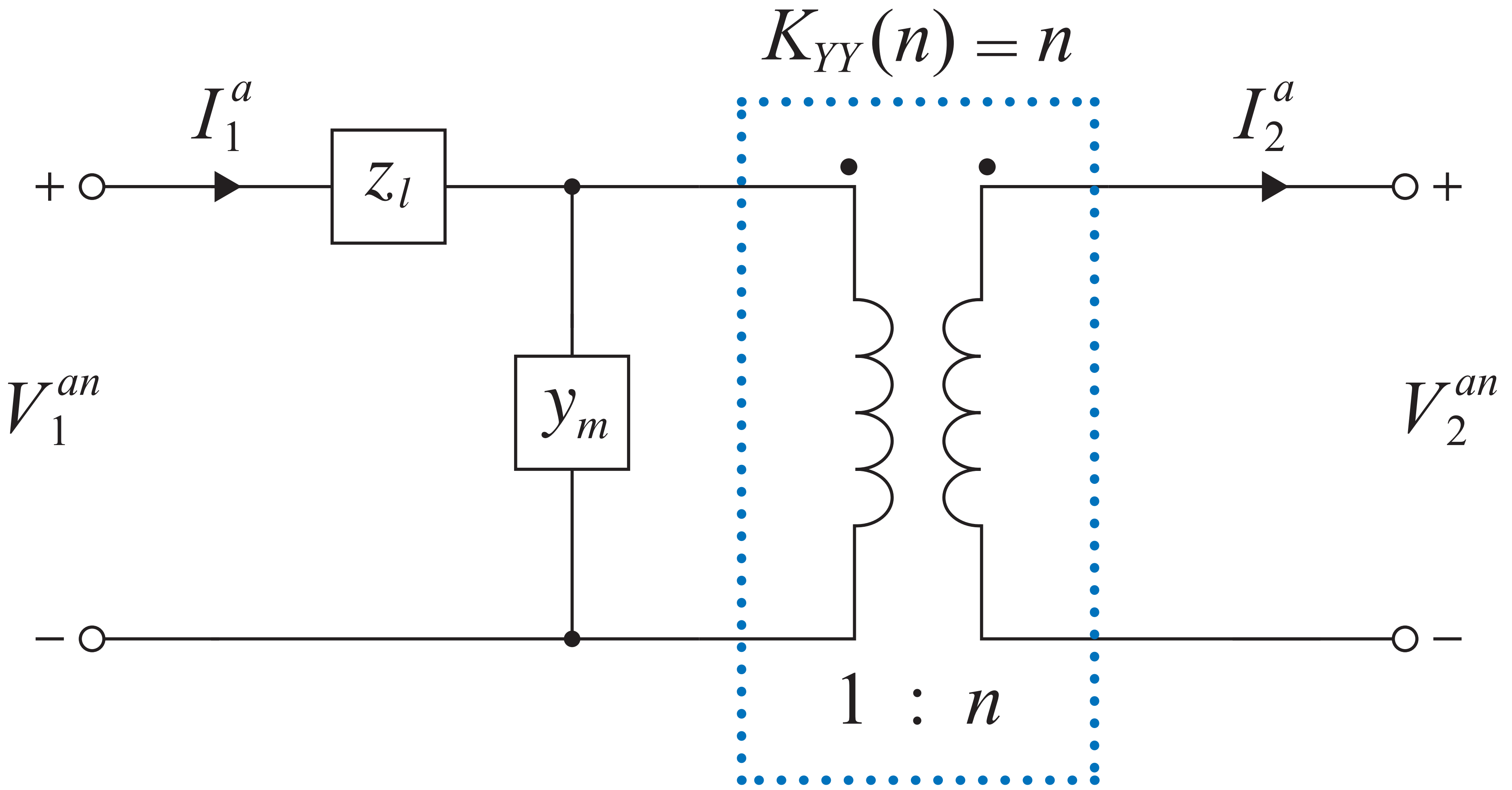
(a) YY configuration

Nonideal transformers

YY configuration



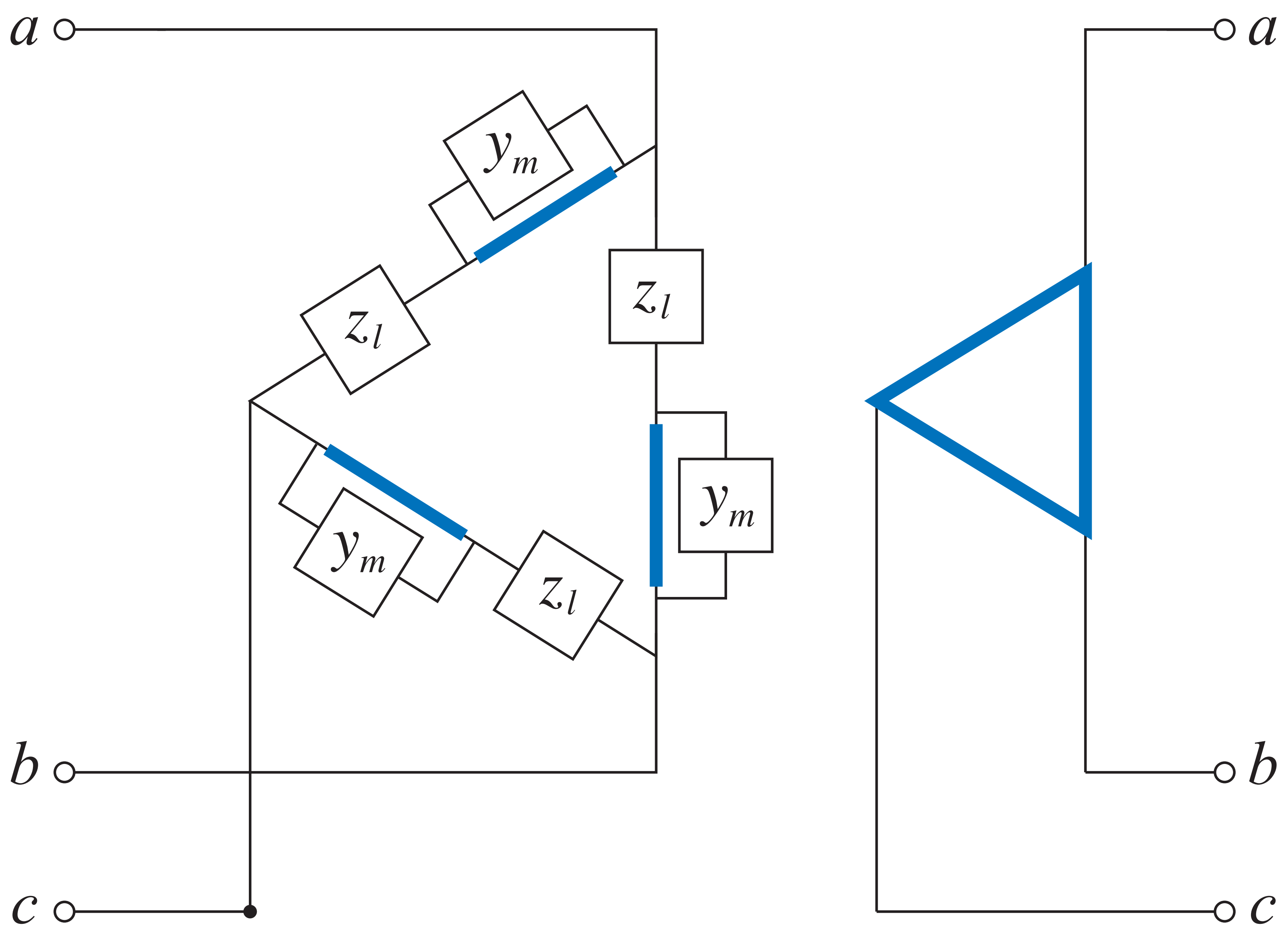
(a) YY configuration



(b) Per-phase circuit

Nonideal transformers

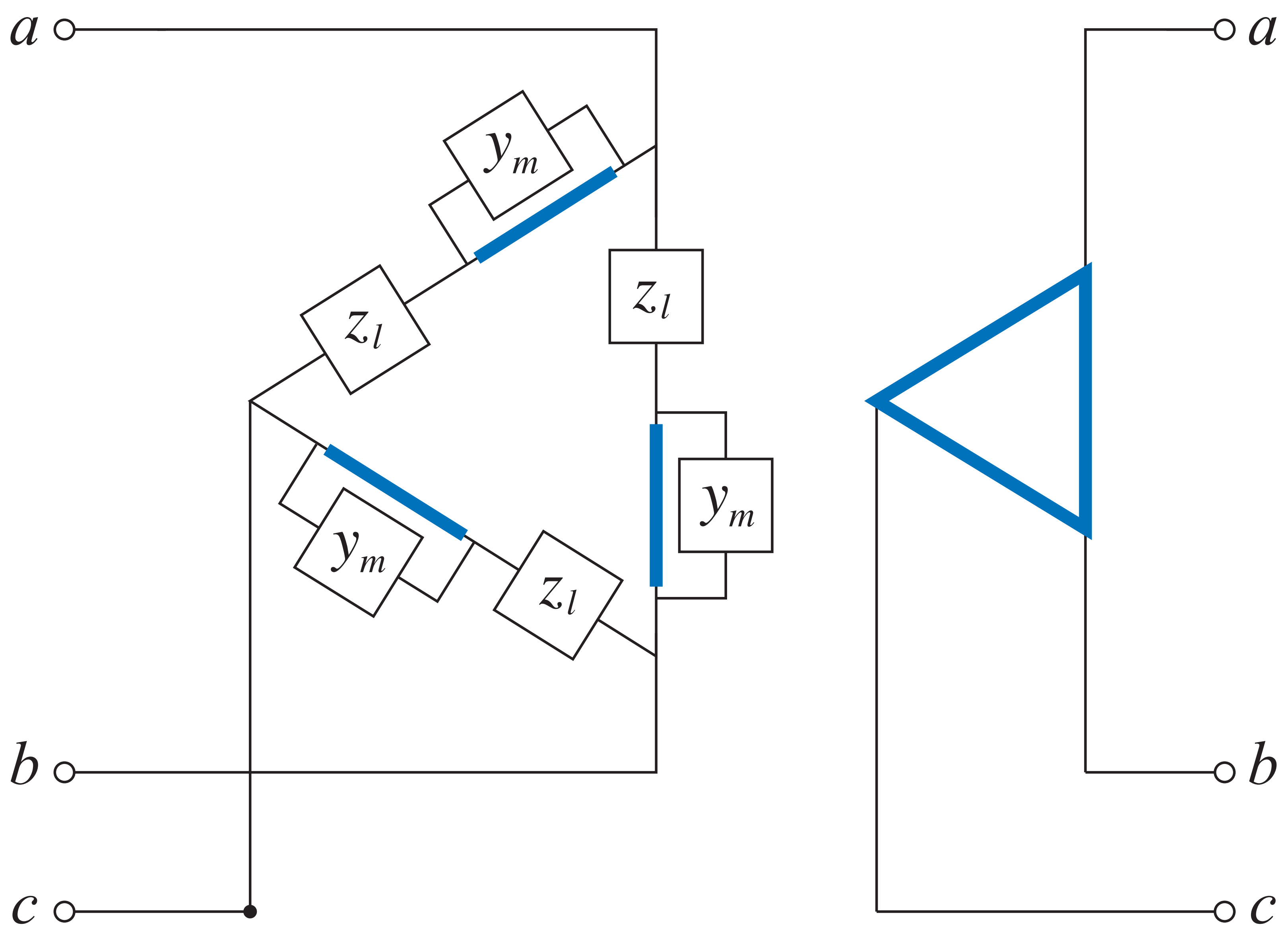
ΔΔ configuration



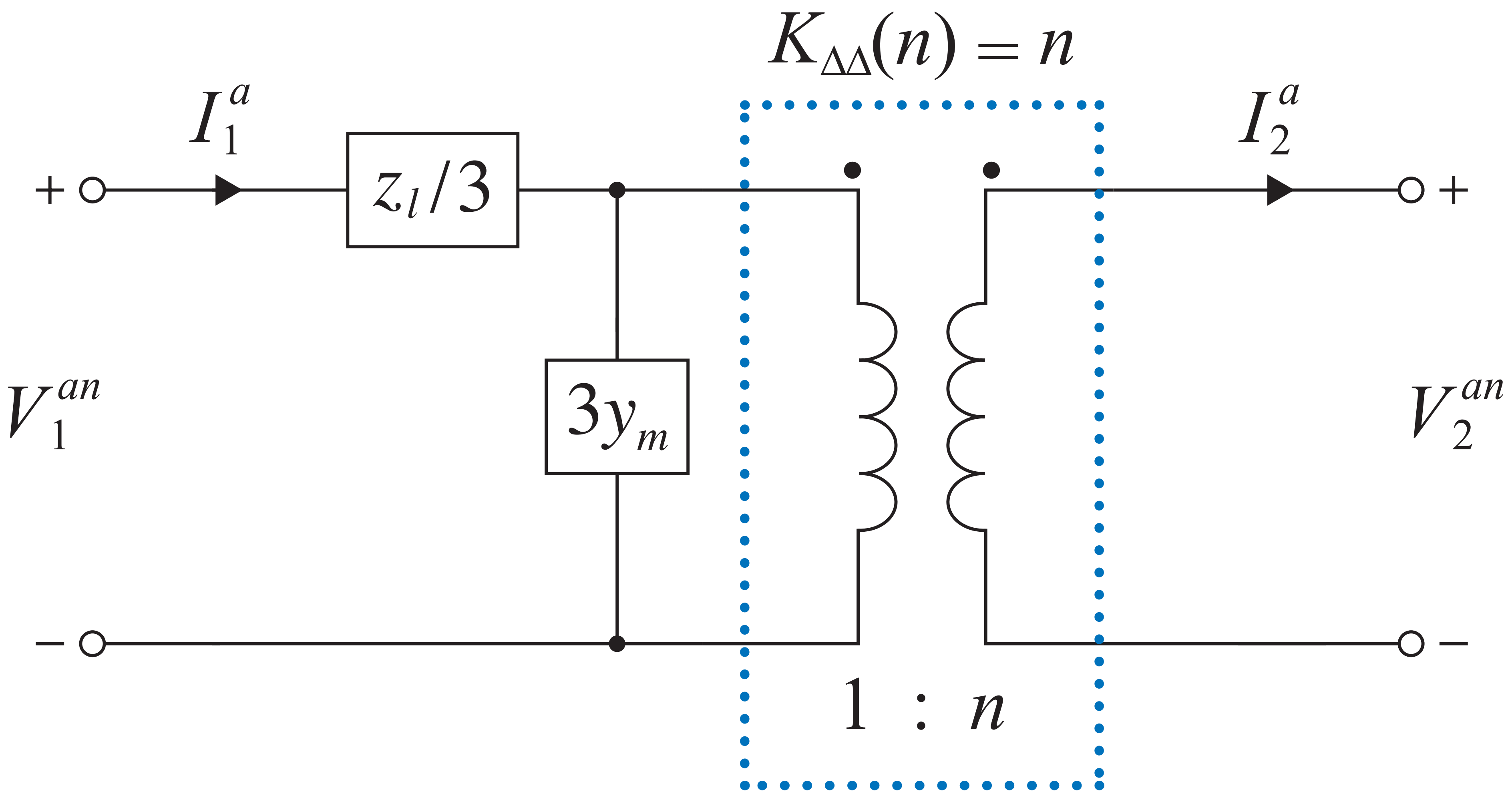
(a) ΔΔ configuration

Nonideal transformers

ΔΔ configuration



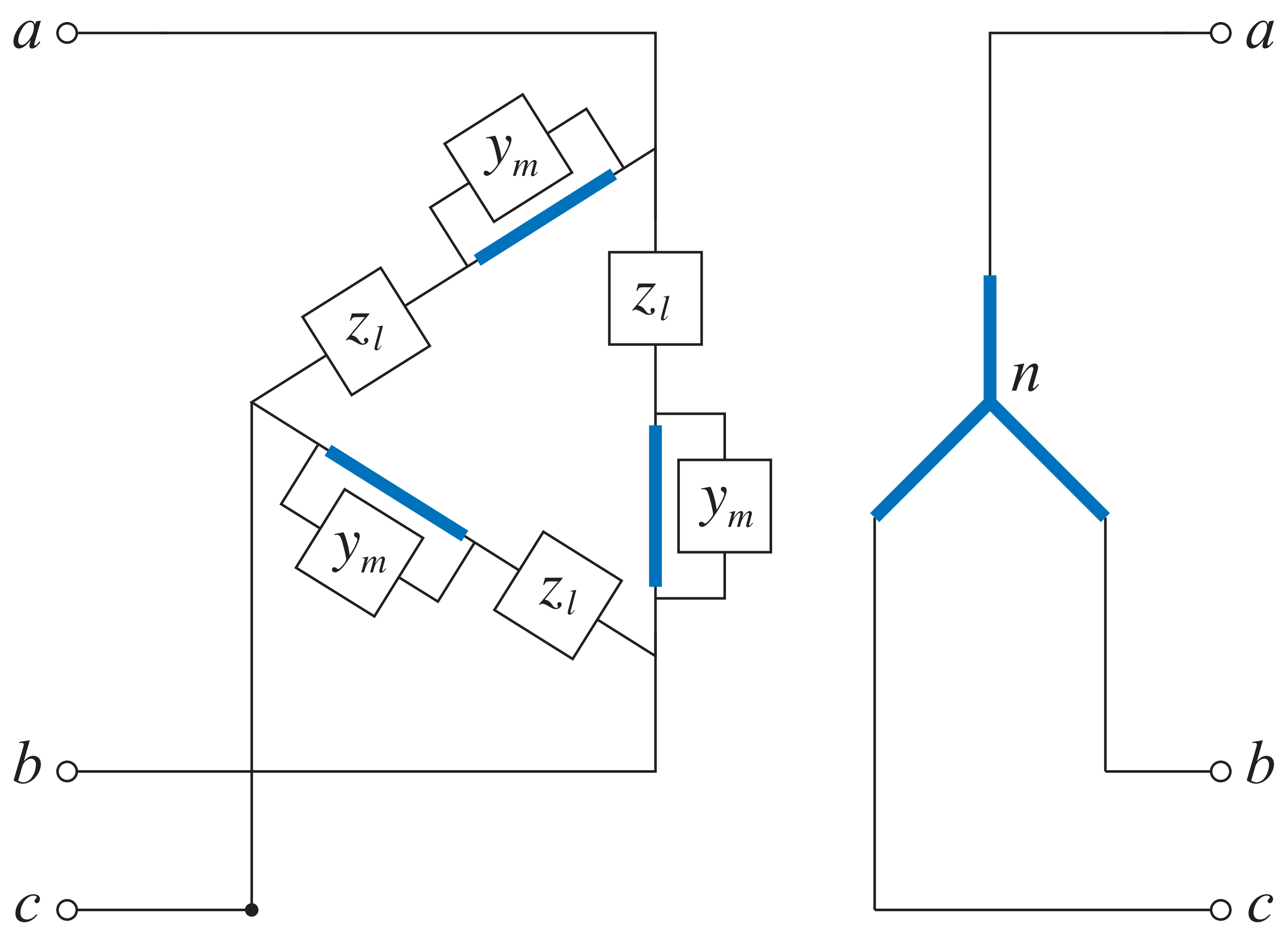
(a) ΔΔ configuration



(b) Per-phase circuit

Nonideal transformers

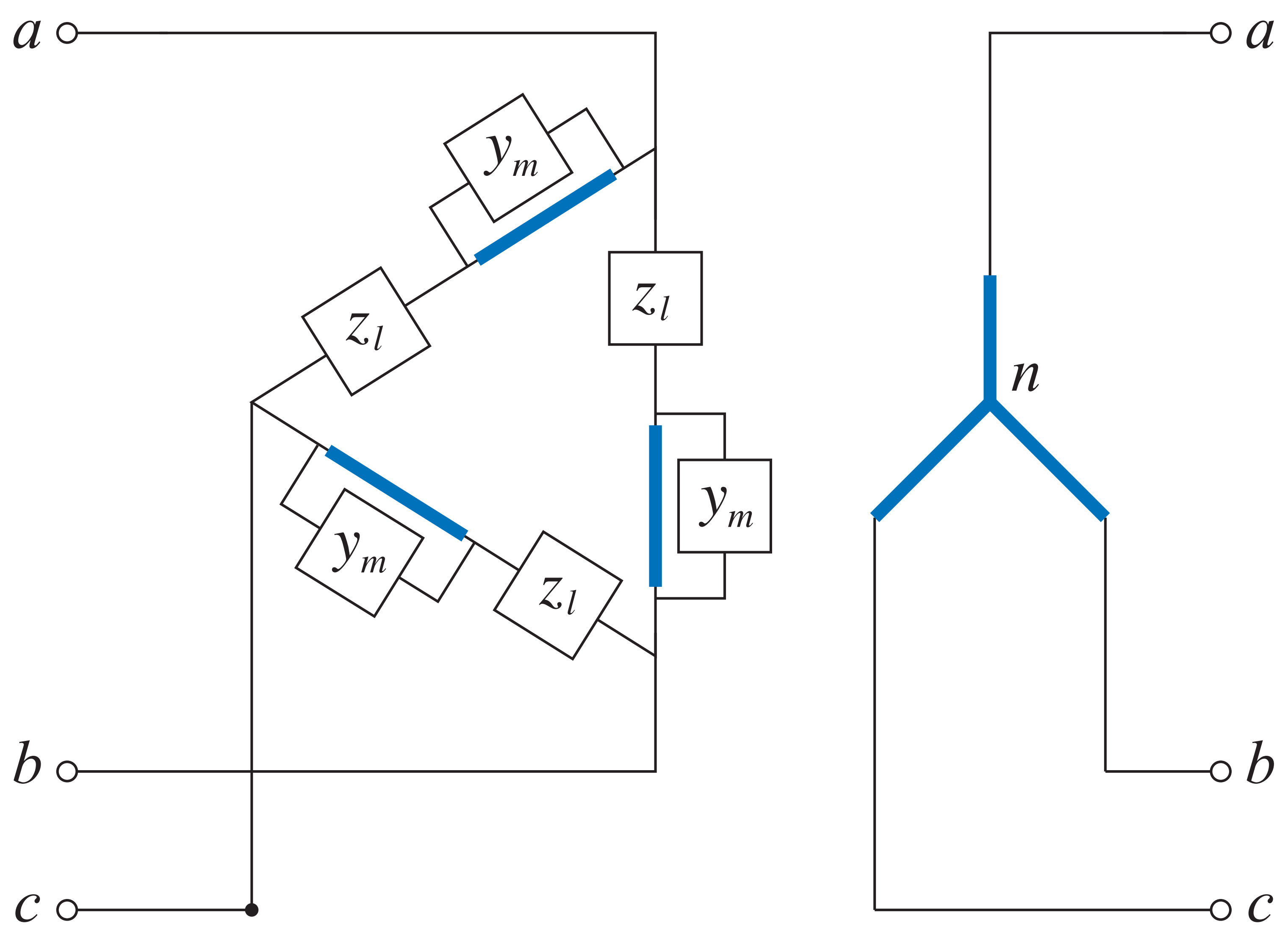
ΔY configuration



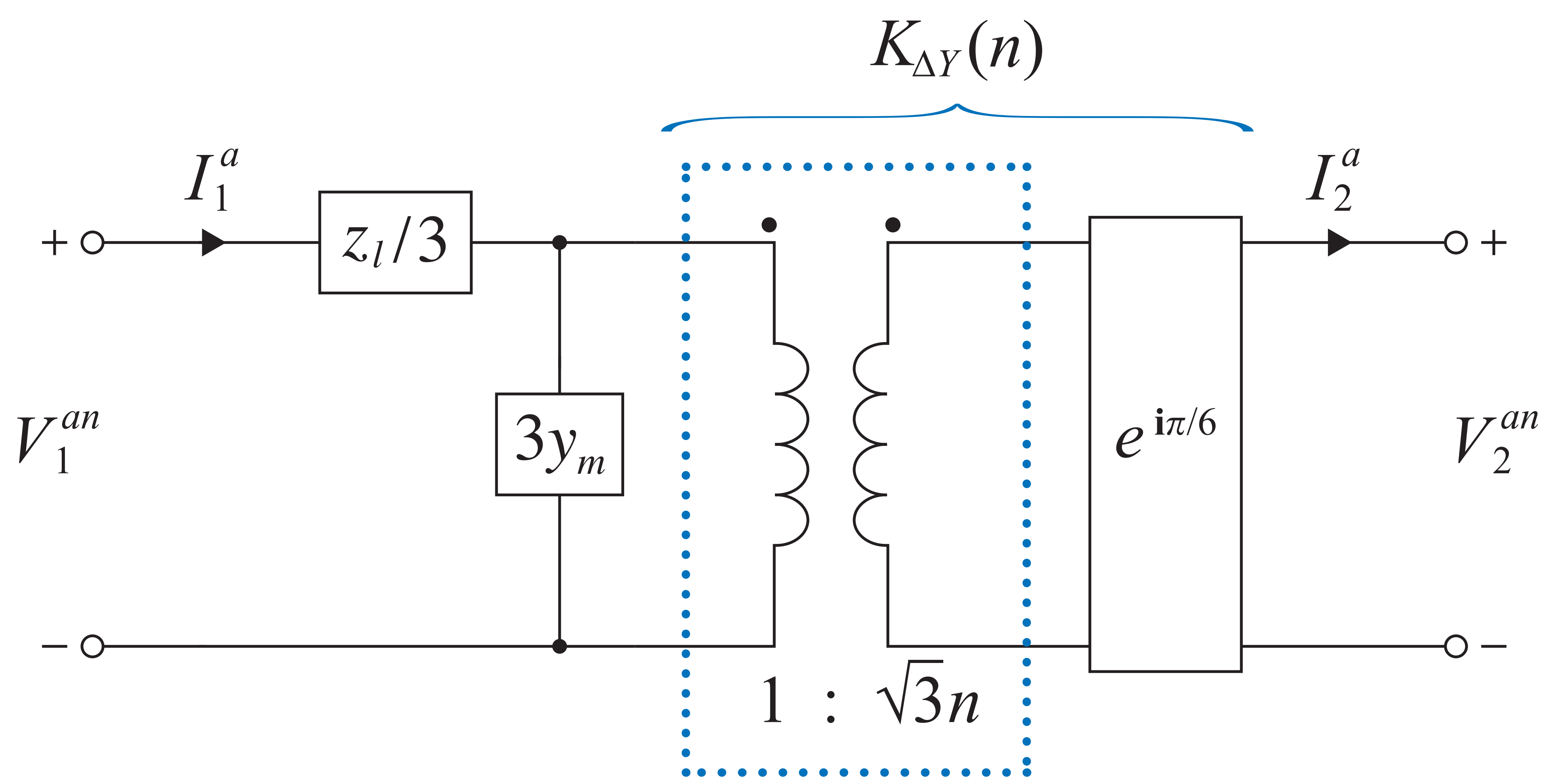
(a) ΔY configuration

Nonideal transformers

ΔY configuration



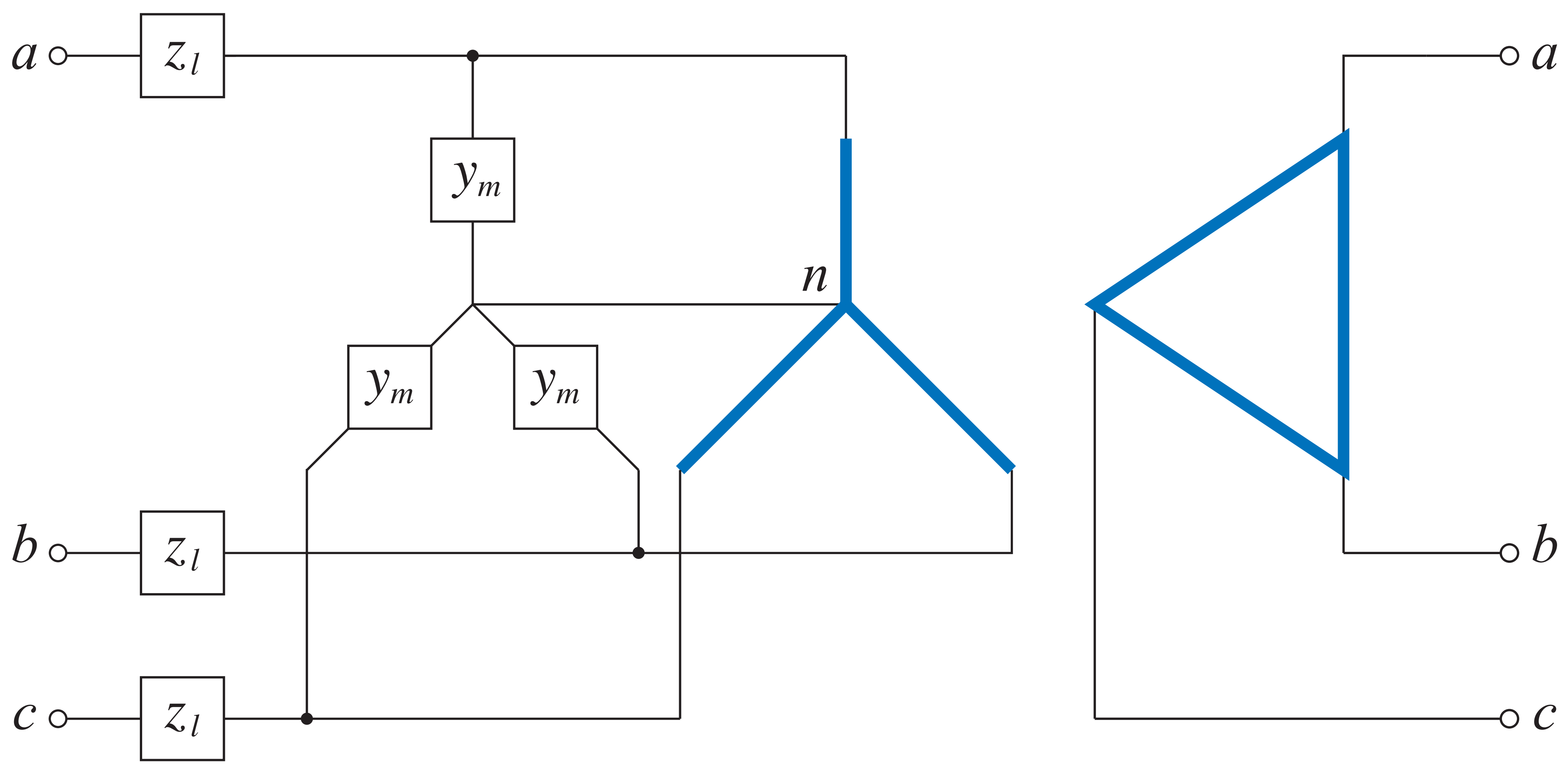
(a) ΔY configuration



(b) Per-phase circuit

Nonideal transformers

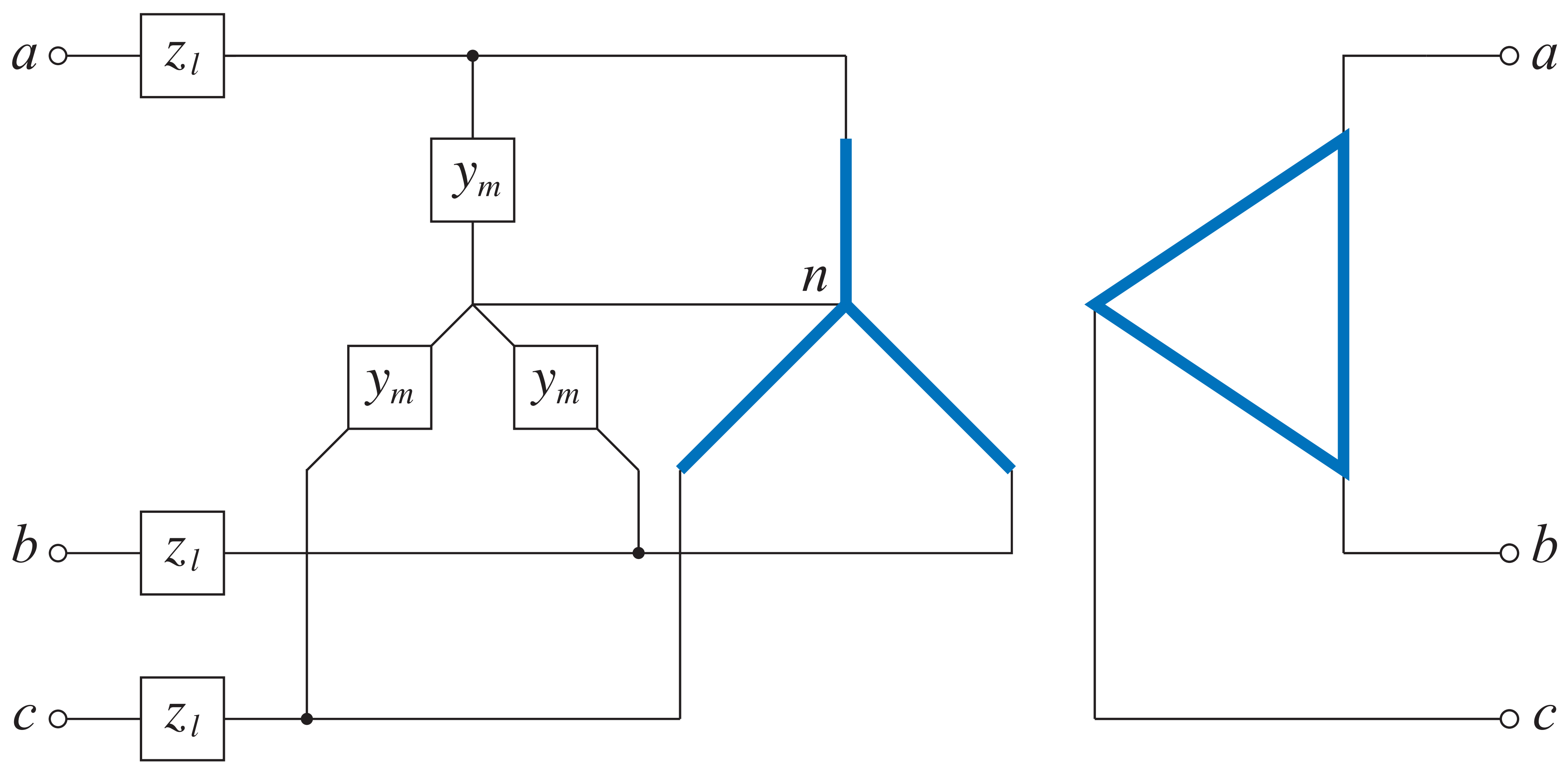
$Y\Delta$ configuration



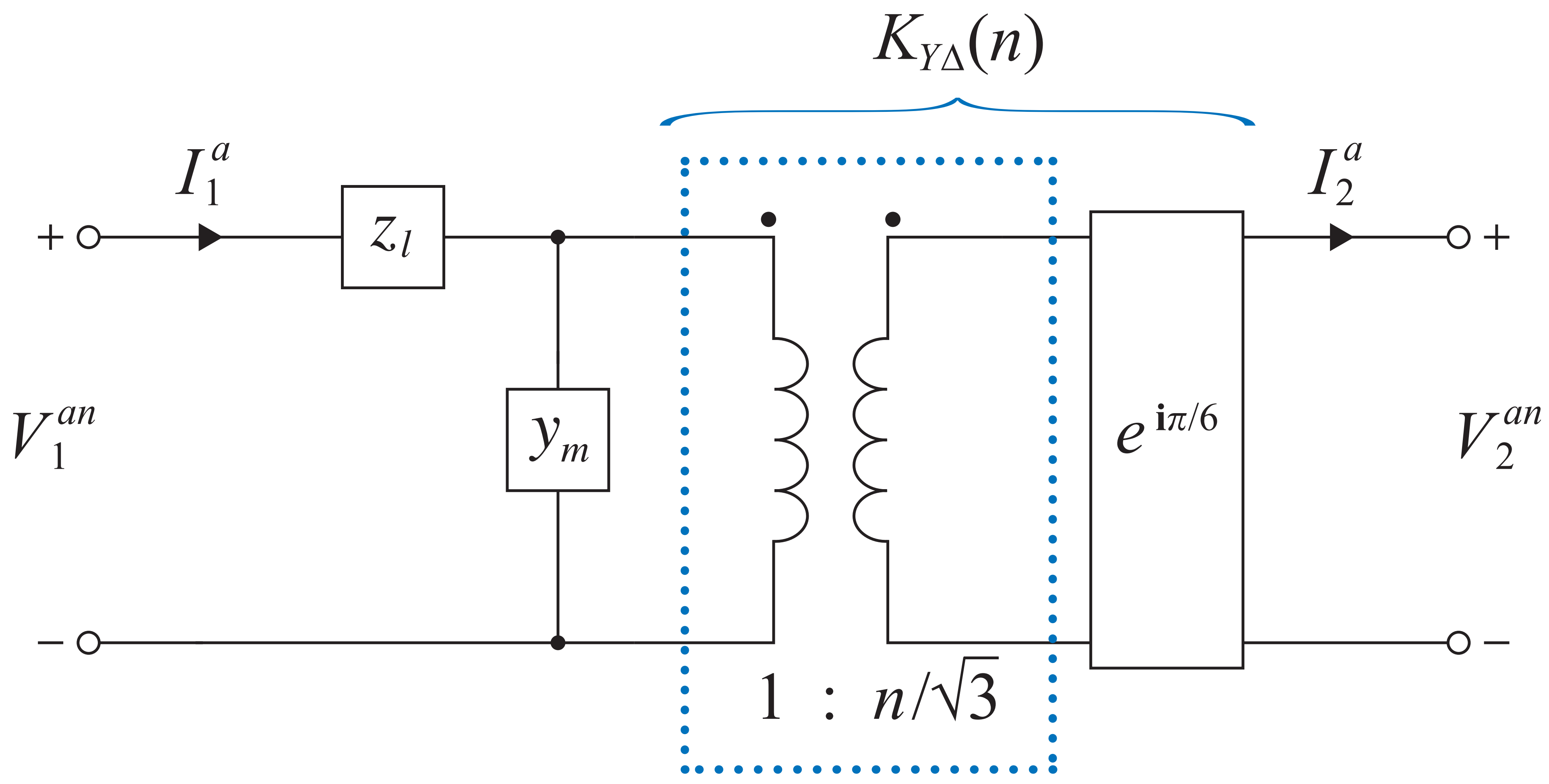
(a) $Y\Delta$ configuration

Nonideal transformers

$Y\Delta$ configuration



(a) $Y\Delta$ configuration



(b) Per-phase circuit

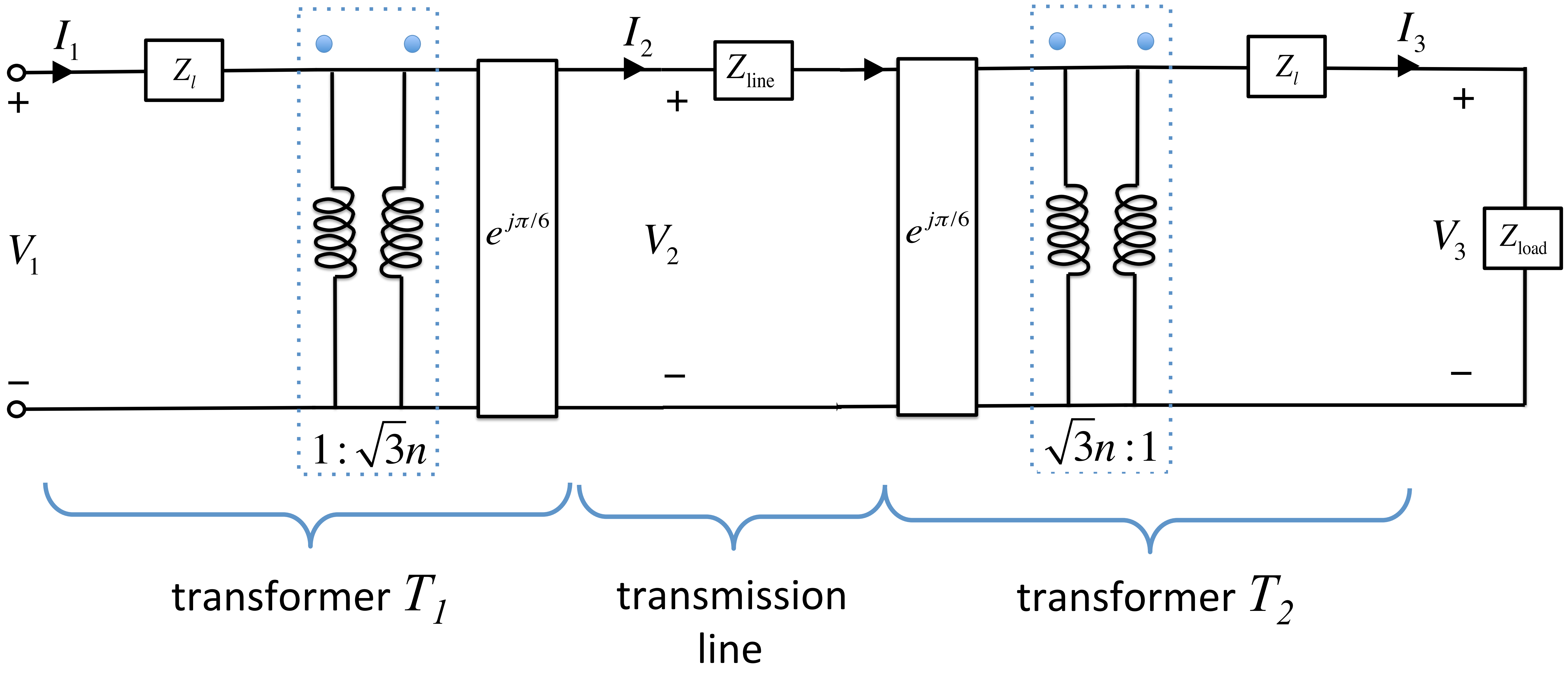
Outline

1. Single-phase transformer
2. Balanced three-phase transformers
3. Equivalent impedance
    - Transmission matrix
    - Driving-point impedance
4. Per-phase analysis
5. Per-unit normalization

Motivation

Short cut in analyzing circuits containing transformers

- Thevenin equivalent of impedances in series and in parallel
- Equivalent impedances in primary or secondary circuits



Equivalent impedances

- referring Z_s in secondary to primary

$$Z_p = \frac{Z_s}{|K(n)|^2}$$

"It is equivalent to replace Z_s in the secondary circuit by Z_p in the primary circuit"

- referring Z_p in primary to secondary

$$Z_s = |K(n)|^2 Z_p$$

"It is equivalent to replace Z_p in the primary circuit by Z_s in the secondary circuit"

Equivalent admittances

- referring Y_s in secondary to primary

$$Y_p \;=\; |K(n)|^2 \; Y_s$$

"It is equivalent to replace Y_s in the secondary circuit by Y_p in the primary circuit"

- referring Y_p in primary to secondary

$$Y_s \;=\; \frac{Y_p}{|K(n)|^2}$$

"It is equivalent to replace Y_p in the primary circuit by Y_s in the secondary circuit"

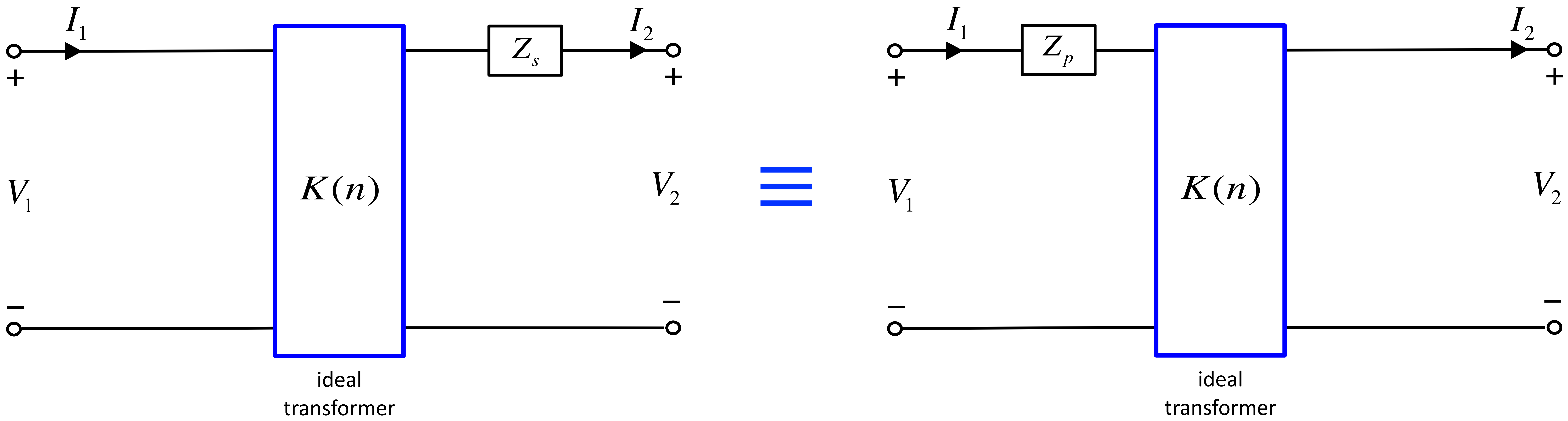
Equivalent impedances

What is equivalence ?

- Same transmission matrices
- Same driving-point impedance

This is a simple consequence of Kirchhoff's and Ohm's laws

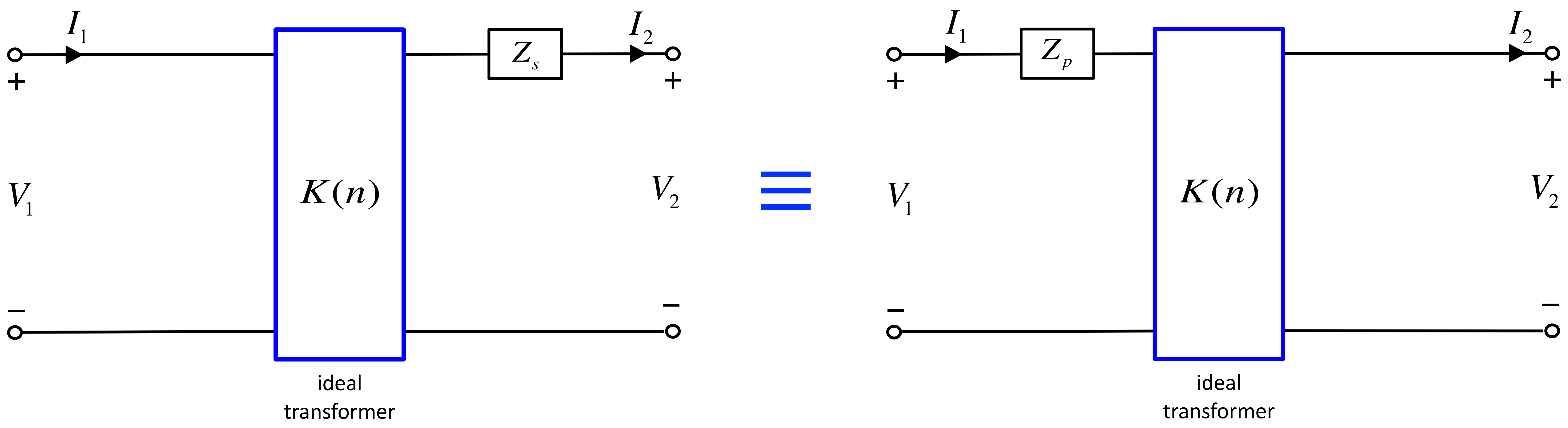
Transmission matrix



External models (transmission matrices) of 2 circuits are equal

if and only if $Z_p = \dfrac{Z_s}{|K(n)|^2}$

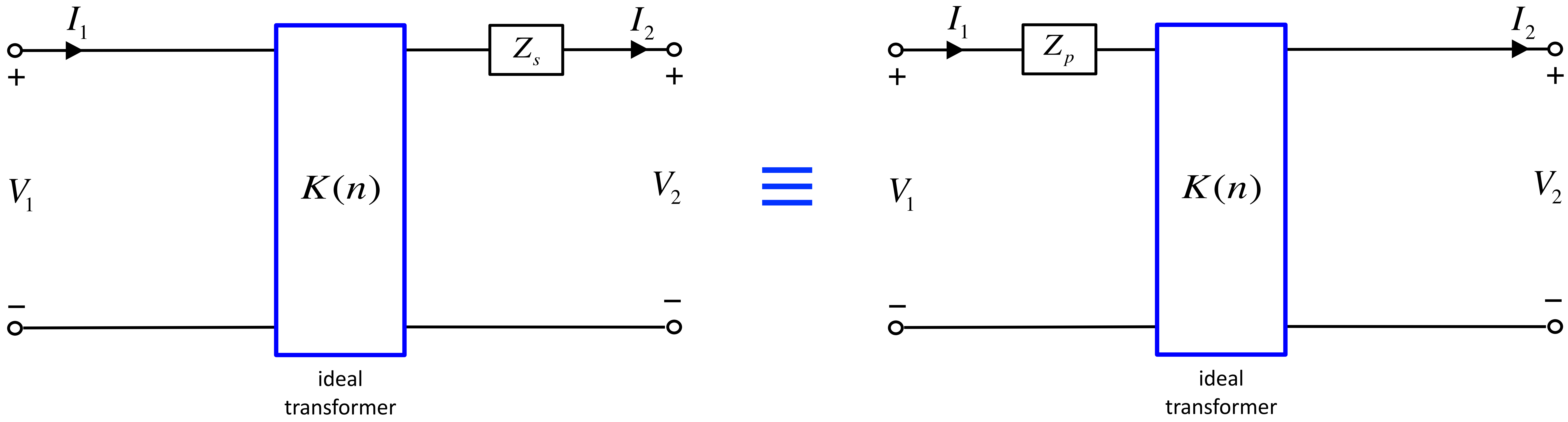
Transmission matrix



$$\begin{bmatrix} V \\ I \end{bmatrix} = \begin{bmatrix} 1 & Z_s \\ 0 & 1 \end{bmatrix} \begin{bmatrix} V_2 \\ I_2 \end{bmatrix}$$

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} K^{-1}(n) & 0 \\ 0 & K^*(n) \end{bmatrix} \begin{bmatrix} V \\ I \end{bmatrix}$$

Transmission matrix



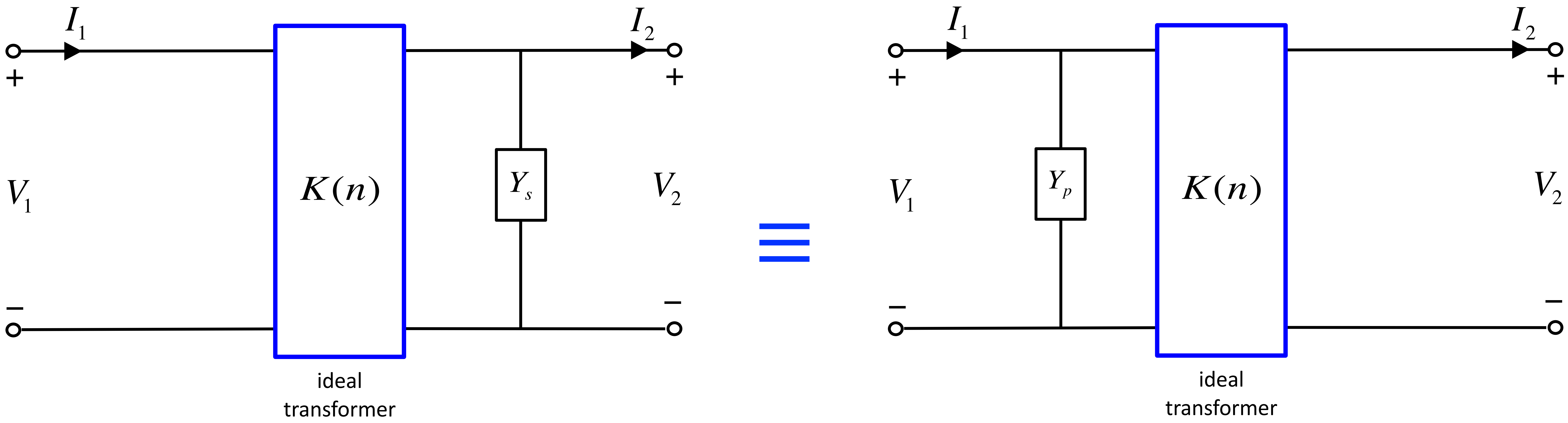
$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} K^{-1}(n) & K^{-1}(n)Z_s \\ 0 & K^*(n) \end{bmatrix} \begin{bmatrix} V_2 \\ I_2 \end{bmatrix}$$

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} K^{-1}(n) & K^*(n)Z_p \\ 0 & K^*(n) \end{bmatrix} \begin{bmatrix} V_2 \\ I_2 \end{bmatrix}$$

External models (transmission matrices) of 2 circuits are equal

if and only if $Z_p = \dfrac{Z_s}{|K(n)|^2}$

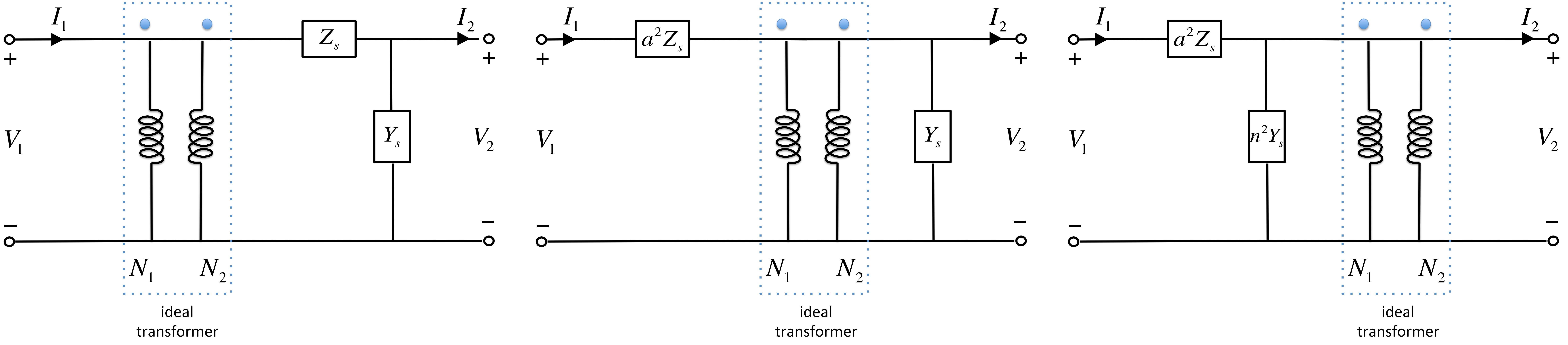
Transmission matrix



External models (transmission matrices) of 2 circuits are equal
if and only if $Y_p = |K(n)|^2 Y_s$

Transmission matrix

Example



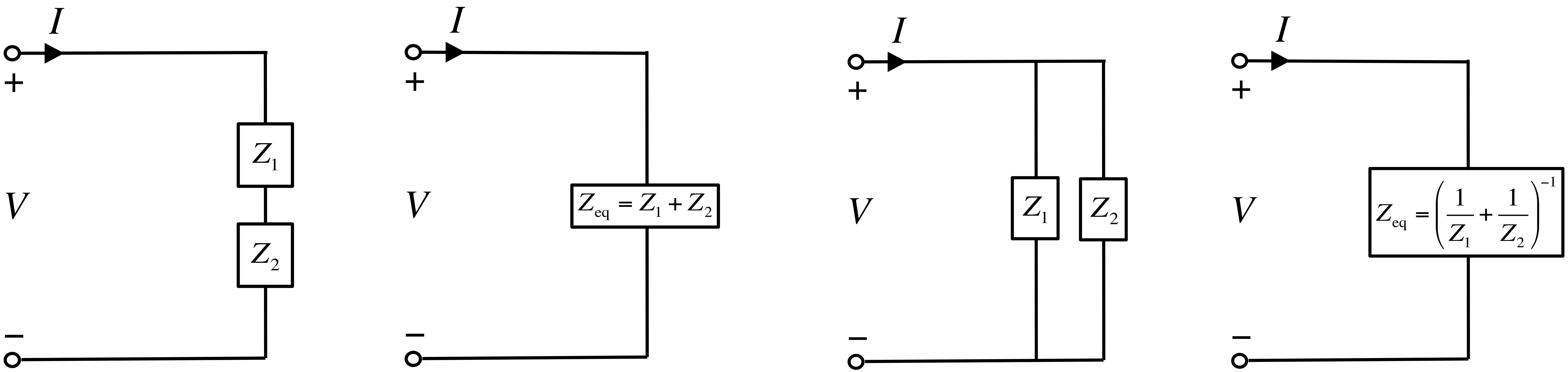
(a) (Z_s, Y_s) in the secondary circuit.

(b) Refer Z_s to the primary.

(c) Refer Y_s to the primary.

Driving-point impedance

Thevenin equivalent



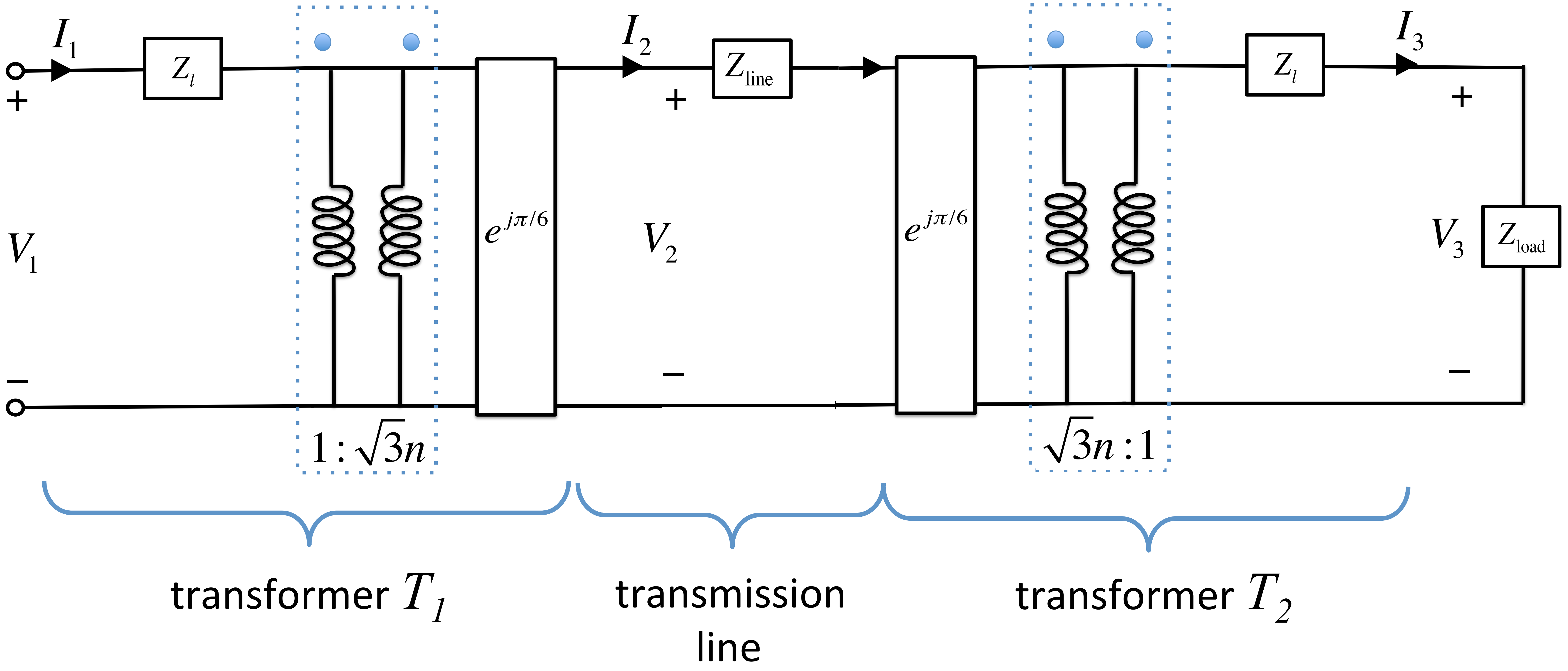
(a) Impedances in series

(b) Impedances in parallel

Thevenin equivalent is a short cut in analyzing circuits with impedances only

Driving-point impedance

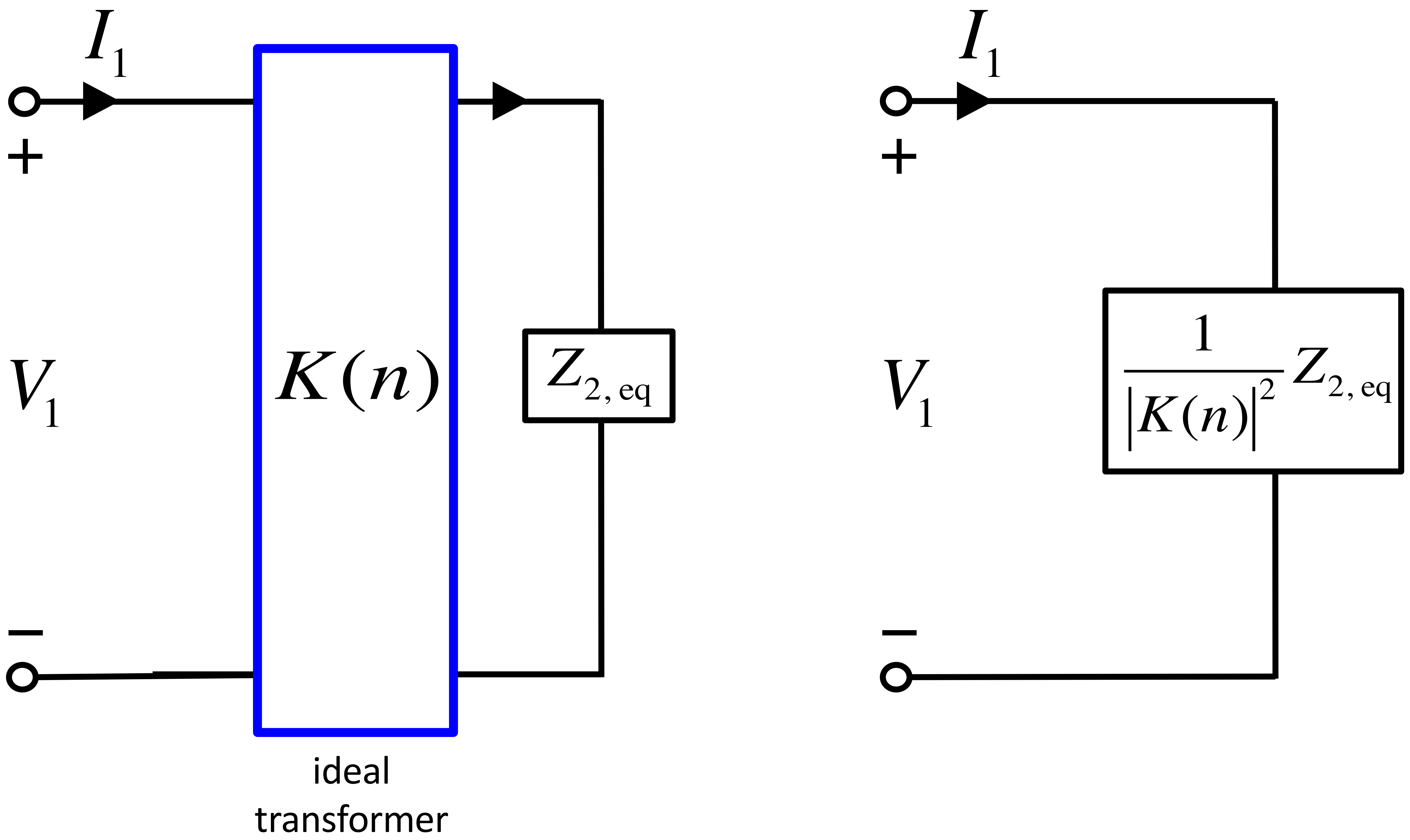
Thevenin equivalent



What if circuits contain both impedance and transformers ?

Driving-point impedance

Referring impedance from secondary to primary

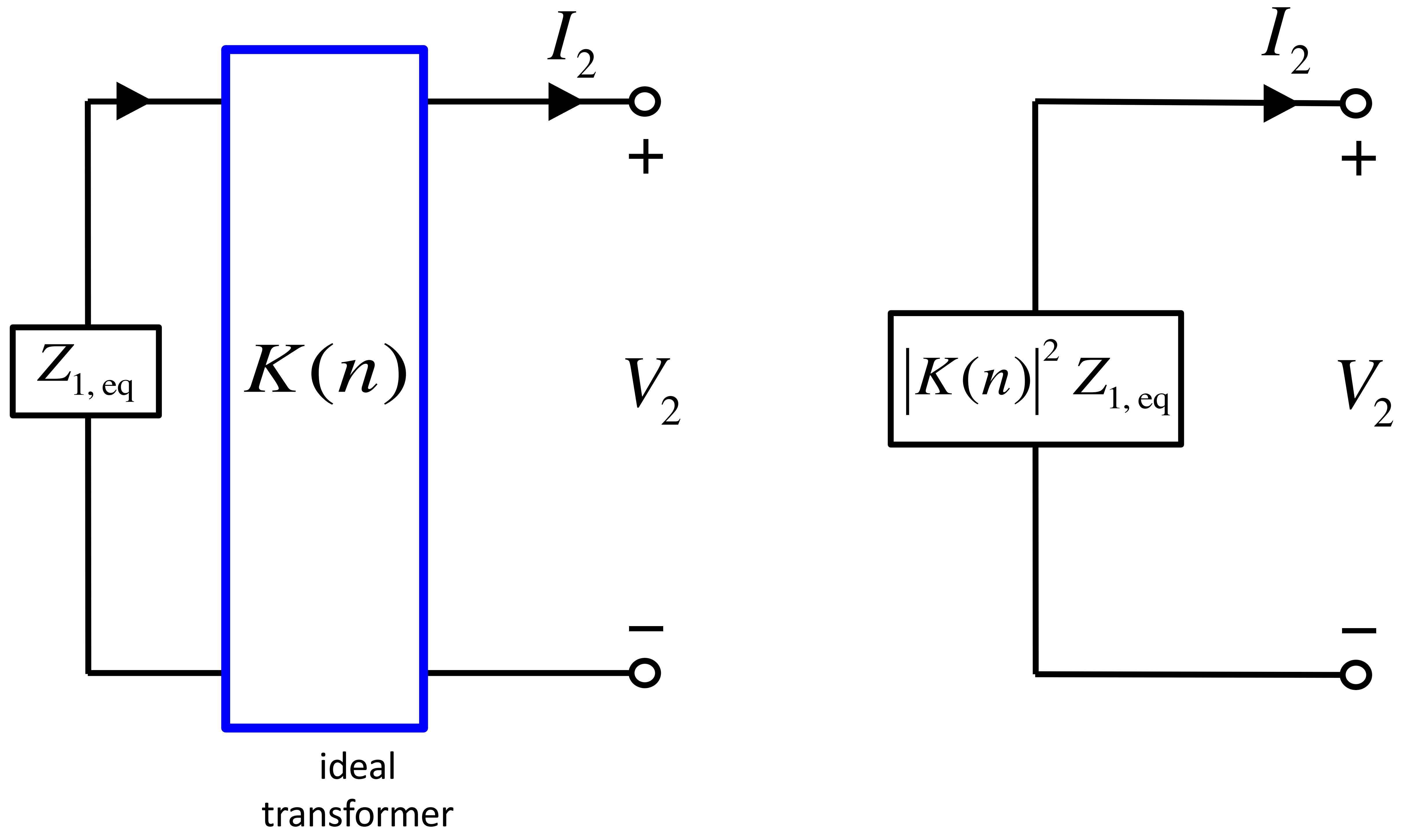


Both circuits have same driving-point impedance V_1/I_1 on primary side

- Can verify using Kirchhoff's and Ohm's laws

Driving-point impedance

Referring impedance from primary to secondary

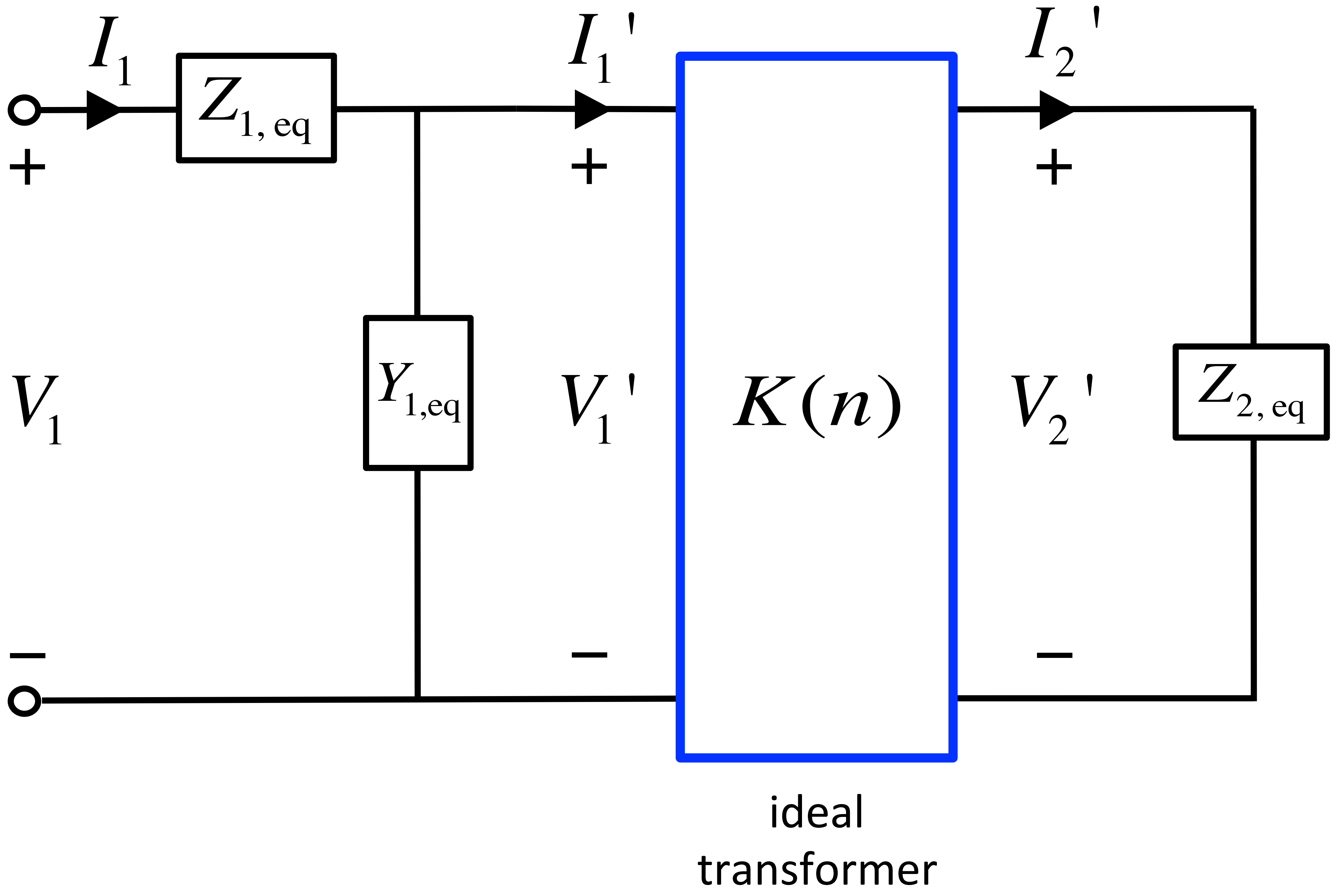


Both circuits have same driving-point impedance V_2/I_2 on secondary side

- Can verify using Kirchhoff's and Ohm's laws

Driving-point impedance

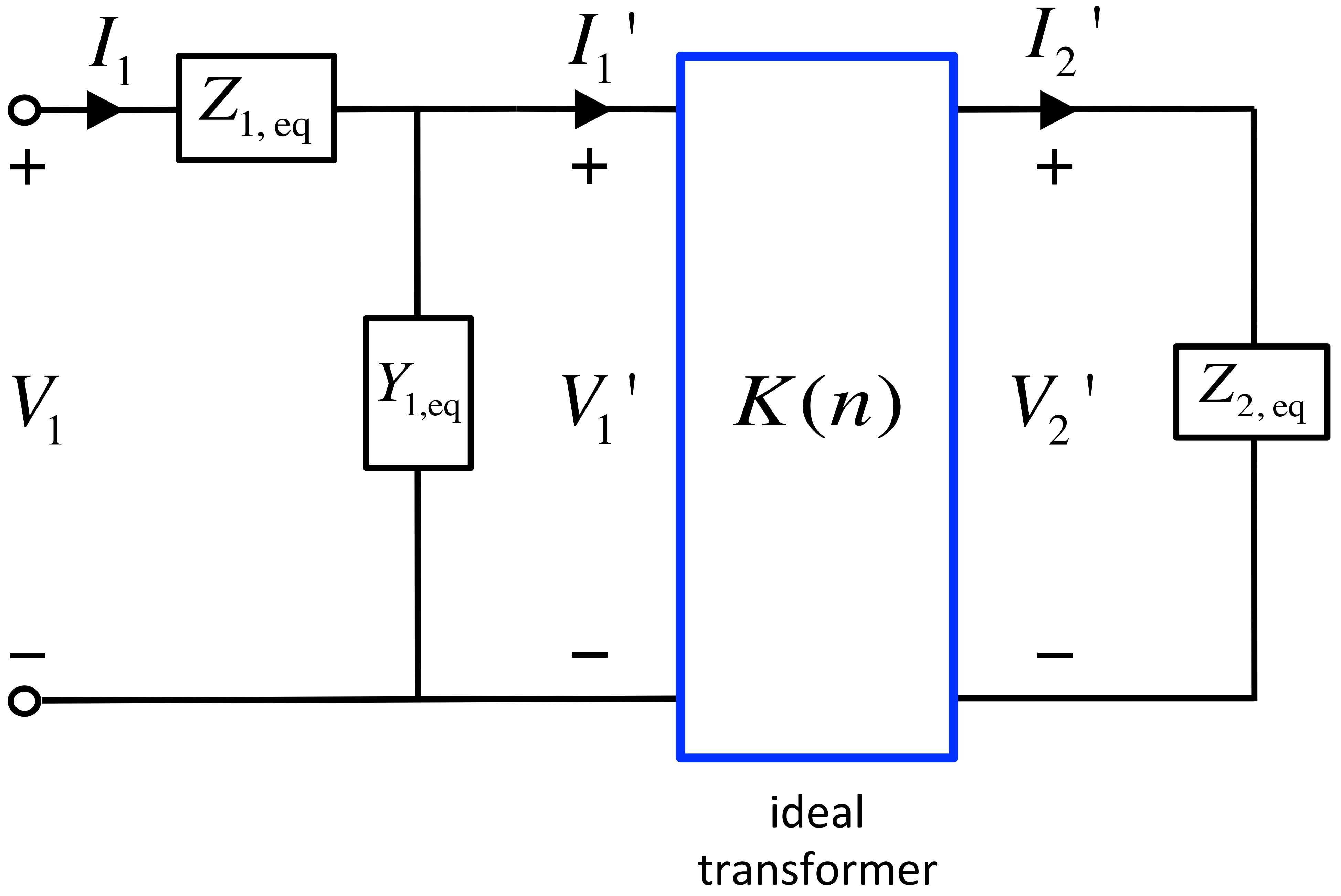
Example

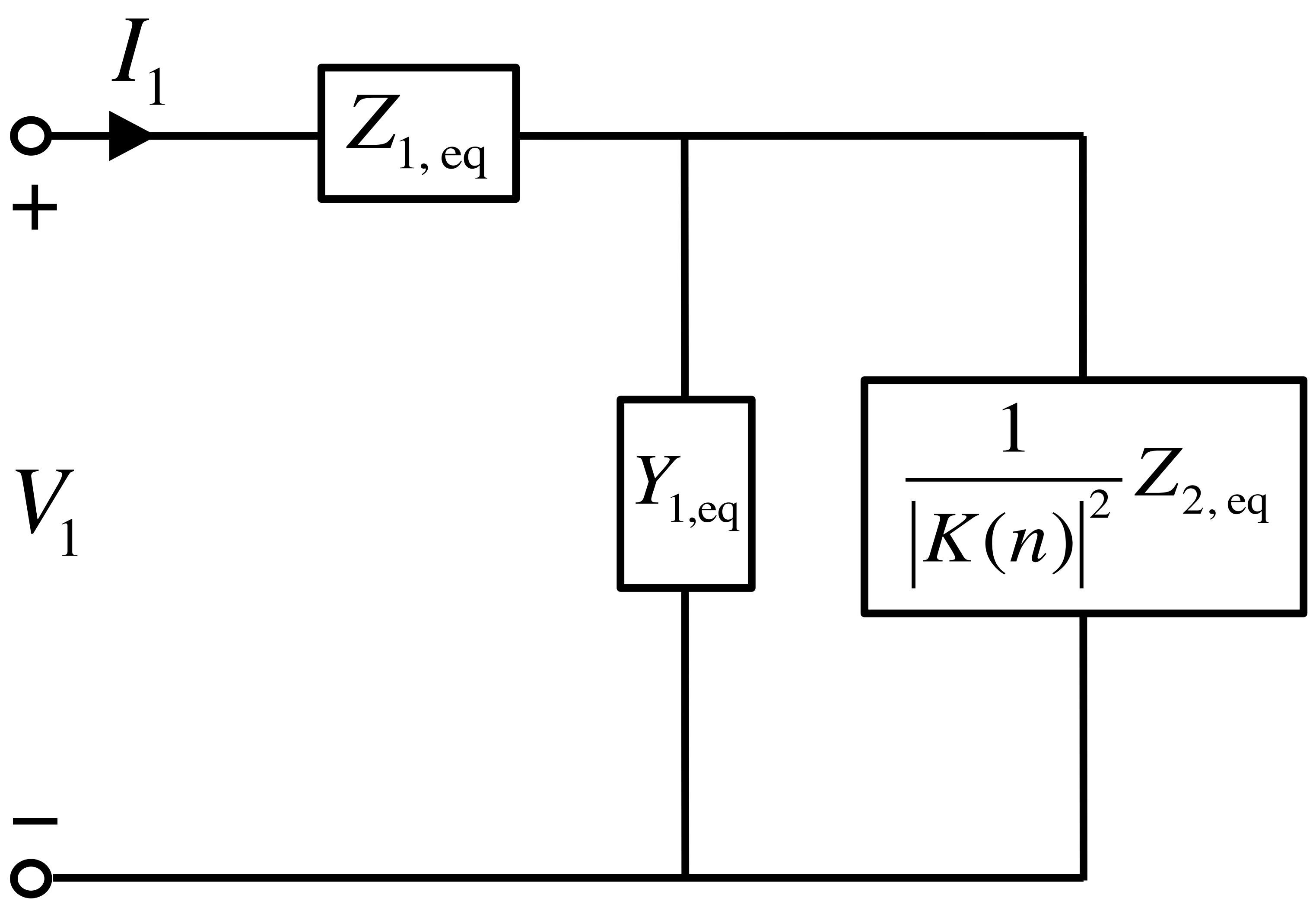


To find V_1/I_1, can analyze using Kirchhoff's and Ohm's laws

Driving-point impedance

Example

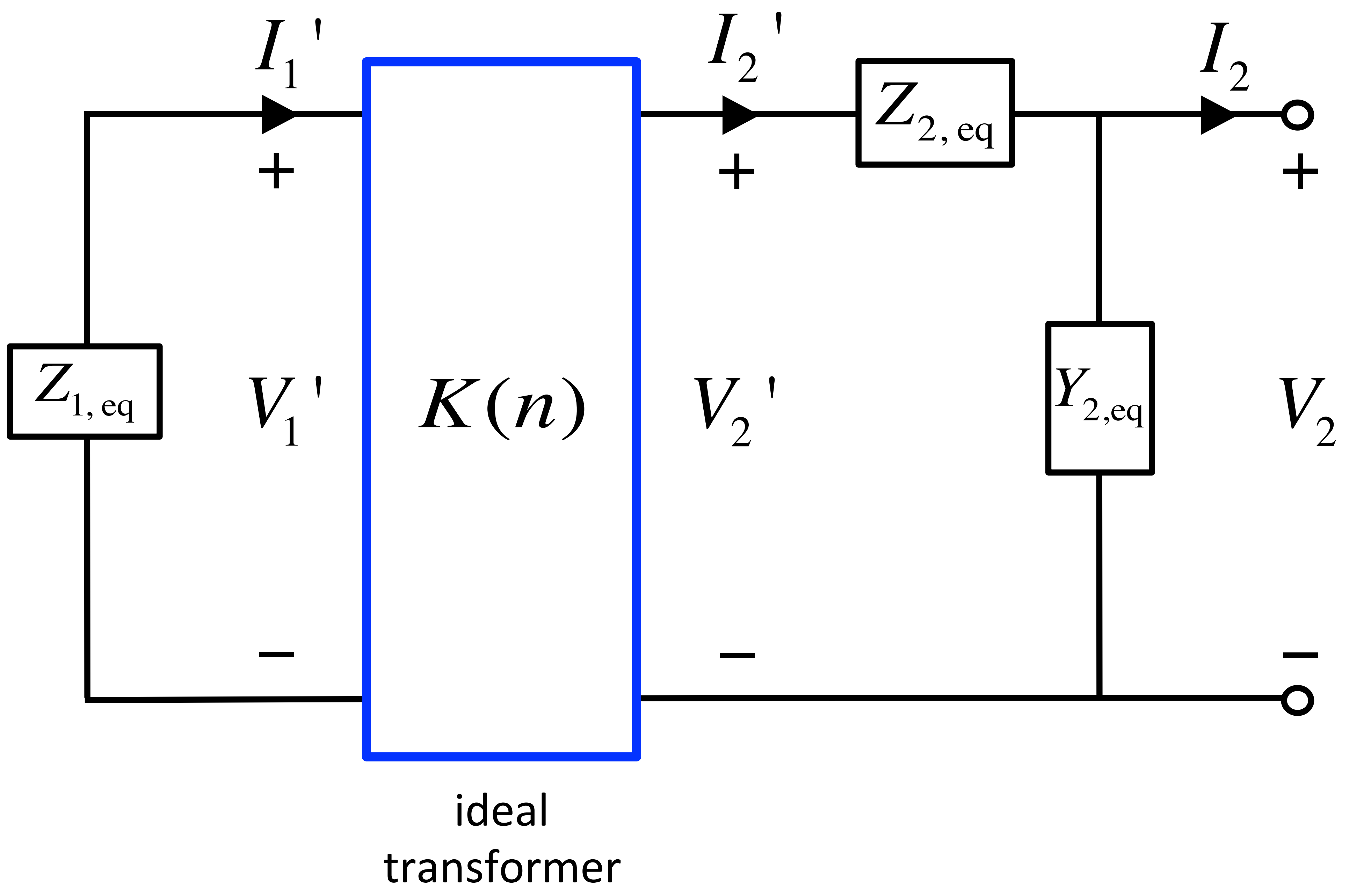




$$\frac{V_1}{I_1} = Z_{1,\text{eq}} + \left(Y_{1,\text{eq}} + \frac{1}{Z_{2,\text{eq}} / |K(n)|^2} \right)^{-1}$$

Driving-point impedance

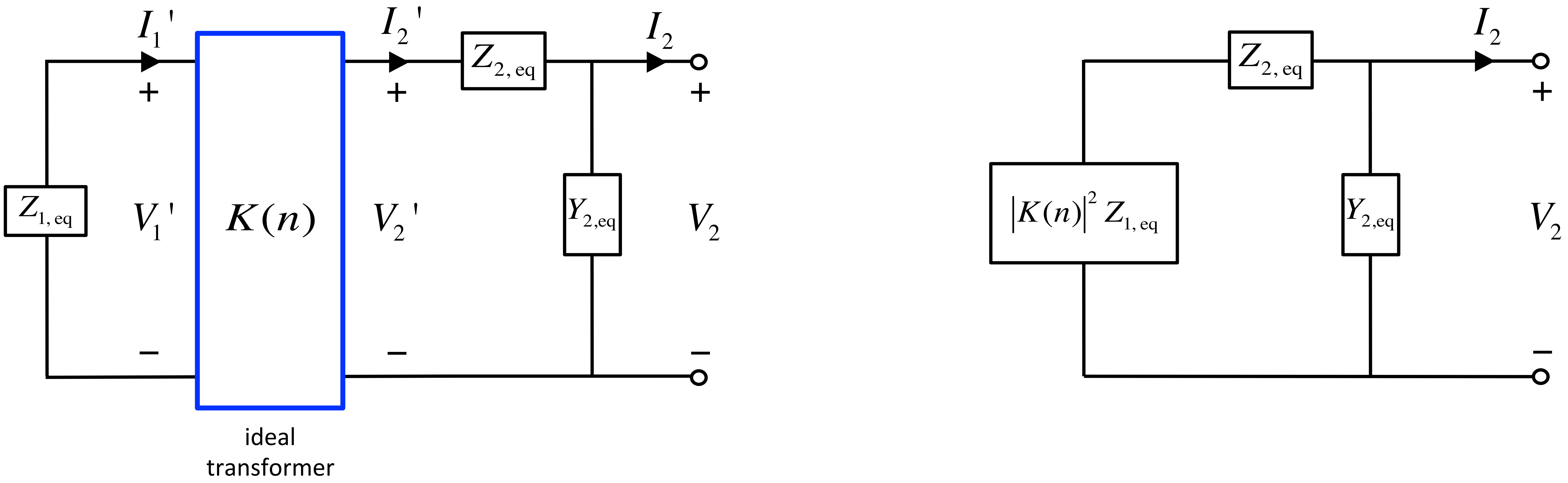
Example



To find V_2/I_2, can analyze using Kirchhoff's and Ohm's laws

Driving-point impedance

Example



$$\frac{V_2}{I_2} = \left(Y_{2,\text{eq}} + \frac{1}{Z_{2,\text{eq}} + |K(n)|^2 \cdot Z_{1,\text{eq}}} \right)^{-1}$$

Driving-point impedance

Reference from one circuit to the other is not always applicable

- Example: circuits containing parallel paths (see example later)
- Generally applicable in a radial network without parallel paths
- Can always analyze original circuit using Kirchhoff's and Ohm's laws

Outline

1. Single-phase transformer
2. Balanced three-phase transformers
3. Equivalent impedance
4. Per-phase analysis
    - Example
    - Normal system
5. Per-unit normalization

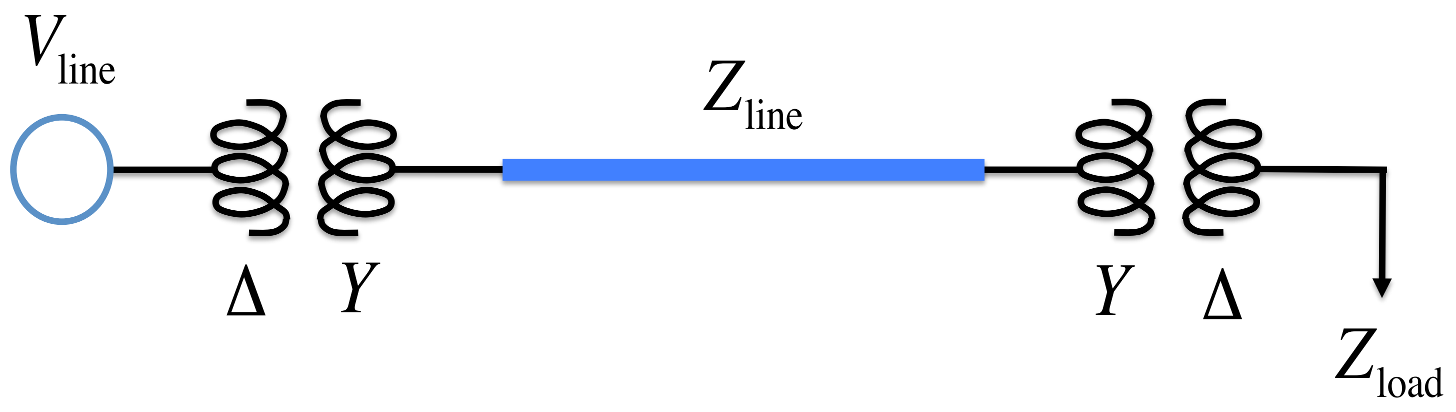
Per-phase analysis

Procedure

1. Convert all sources and loads in Δ configurations into their Y equivalents
2. Convert all ideal transformers in Δ configurations into their Y equivalents
3. Obtain phase a equivalent circuit by connecting all neutrals
4. Solve for desired phase-a variables
   - Use Thevenin equivalent of series impedances and shunt admittances in networks containing transformers whenever applicable, e.g., for a radial network
5. Obtain variables for phases b and c by subtracting 120° and 240° from phase a variables (positive sequence sources)
   - If variables in the internal of Δ configurations are desired, derive them from original circuits

Per-phase analysis

Example

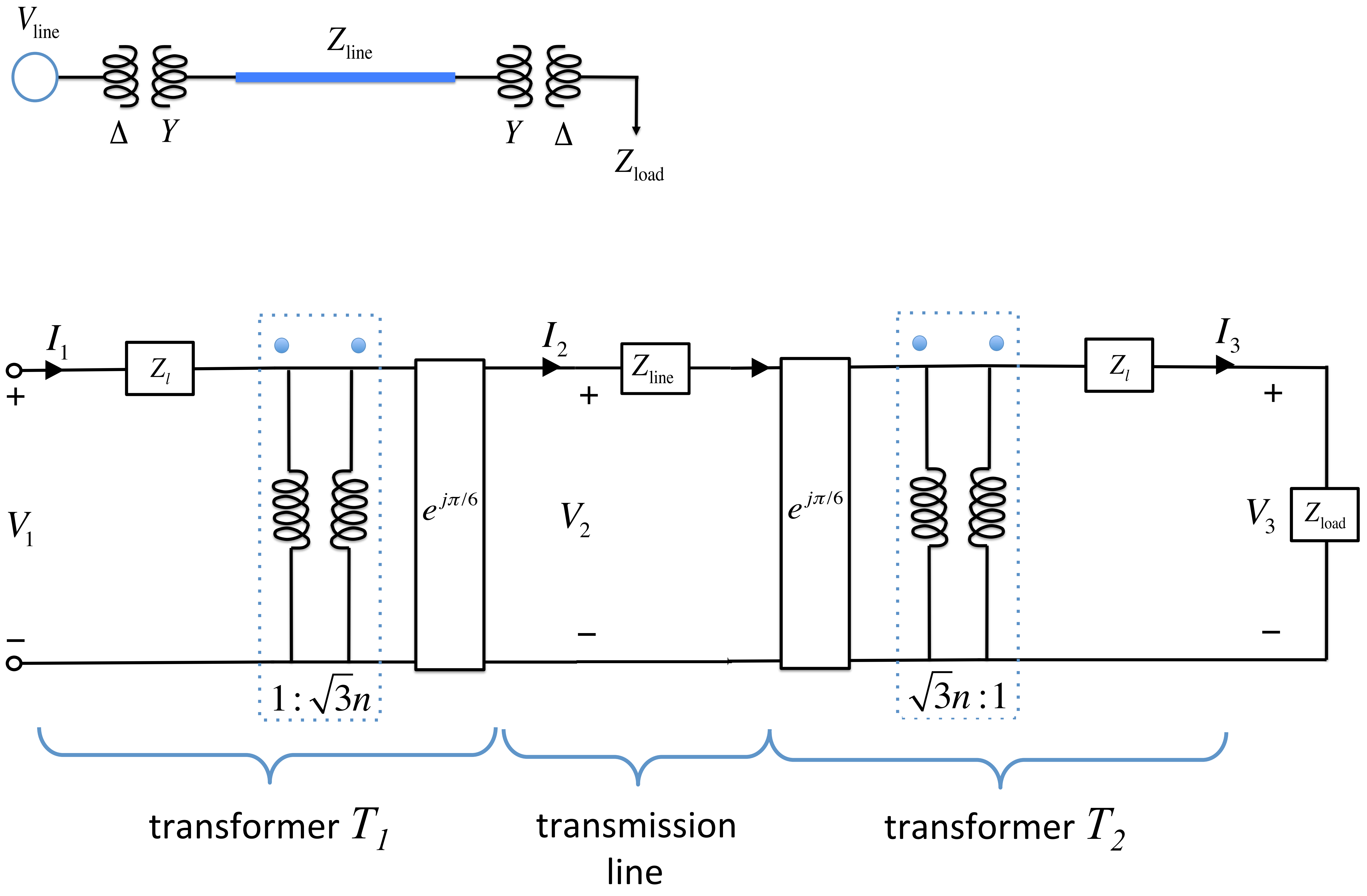


Balanced 3ϕ system

- Generator with line voltage V_{line}
- Step-up ΔY transformer
- Transmission line with series impedance Z_{line}
- Step-down ΔY transformer (primary on right)
- Load with impedance Z_{load}
- Single-phase transformer with voltage gain n and series impedance $3Z_l$ on primary side

Per-phase analysis

Example



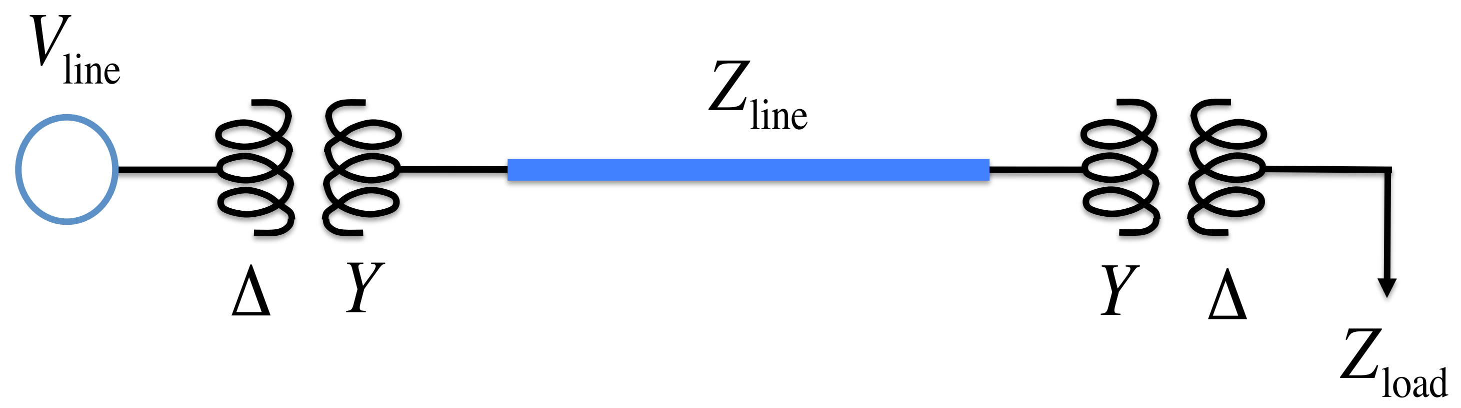
Balanced 3ϕ system

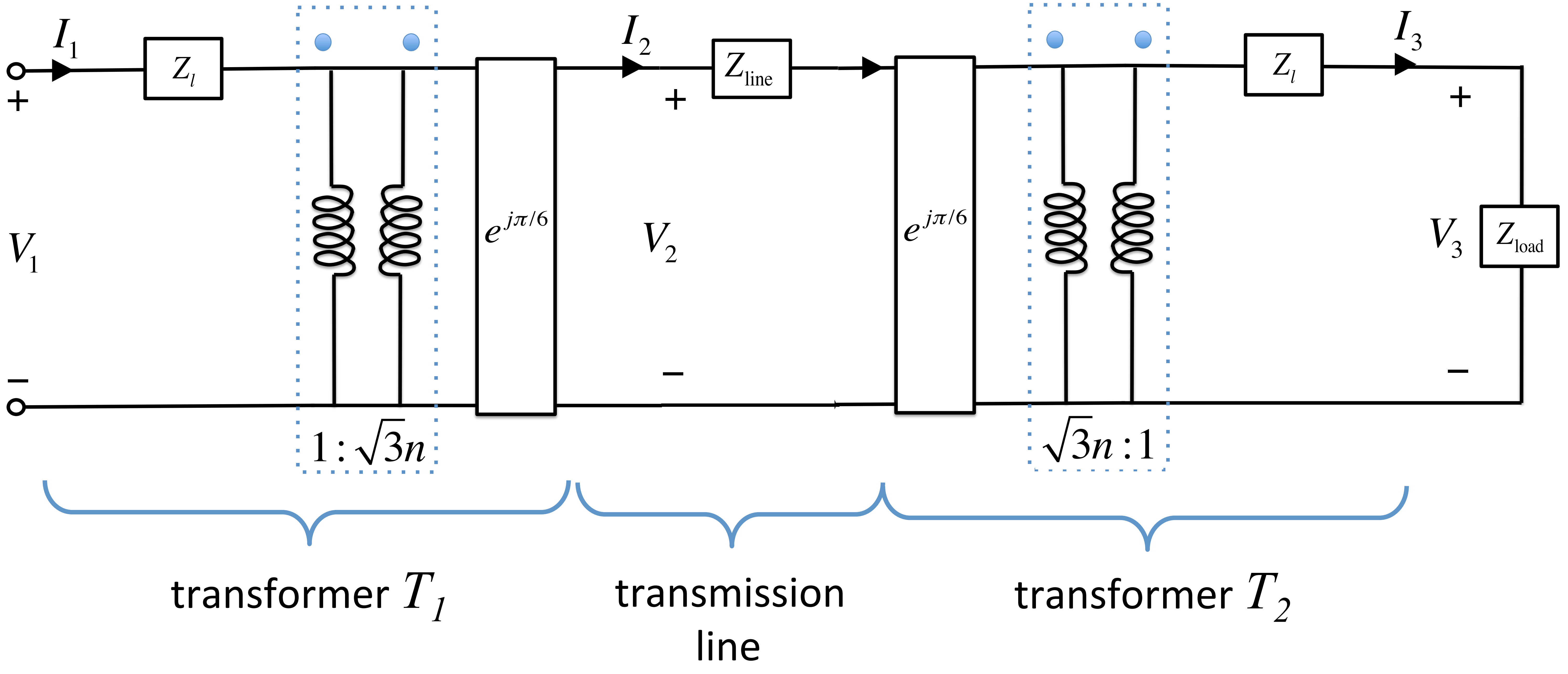
- Generator with line voltage V_{line}
- Step-up ΔY transformer
- Transmission line with series impedance Z_{line}
- Step-down ΔY transformer (primary on right)
- Load with impedance Z_{load}
- Single-phase transformer with turns ratio n and series impedance $3Z_l$ on primary side

$$V_1 = \frac{V_{\text{line}}}{\sqrt{3}\, e^{i\pi/6}} \qquad Z^Y = Z_l$$

Per-phase analysis

Example



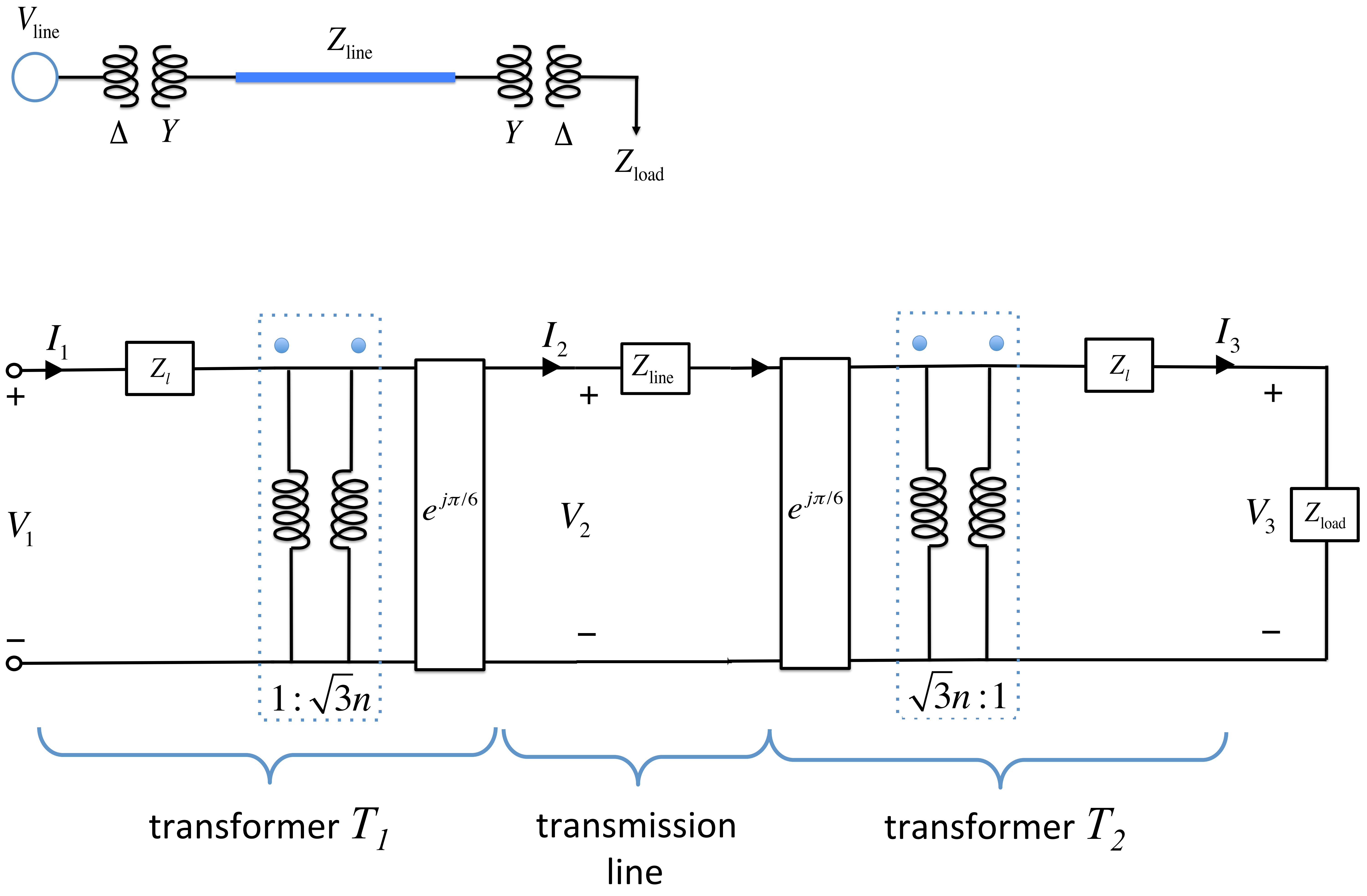


Calculate

- Generator current I_1
- Transmission line current I_2
- Load current I_3
- Load voltage V_3
- Power delivered to load: $V_3 I_3^*$

$$V_1 = \frac{V_{\text{line}}}{\sqrt{3}\, e^{i\pi/6}} \qquad Z^Y = Z_l$$

Per-phase analysis
Example



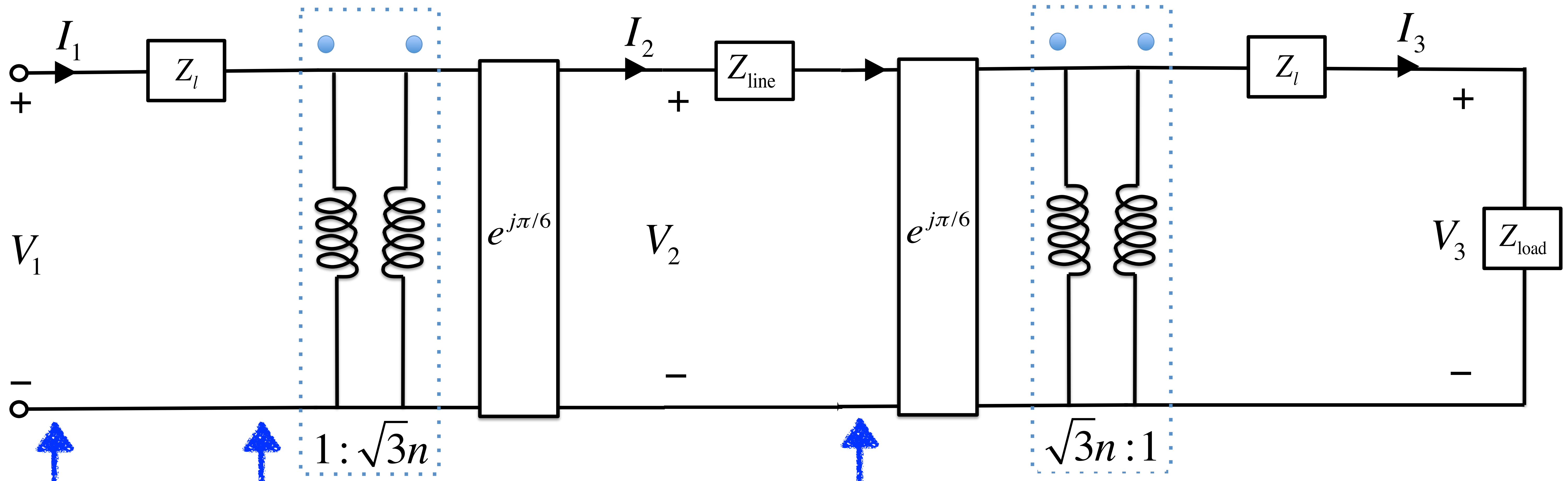
Solution strategy

- Refer all impedances to primary side of step-up transformer
- Derive driving-point impedance V_1/I_1
- Derive generator current I_1
- Propagate calculation towards load

$$V_1 = \frac{V_{\text{line}}}{\sqrt{3}\, e^{i\pi/6}} \qquad Z^Y = Z_l$$

Per-phase analysis

Example



$$|K(n)|^2 (Z_{\text{load}} + Z_l)$$

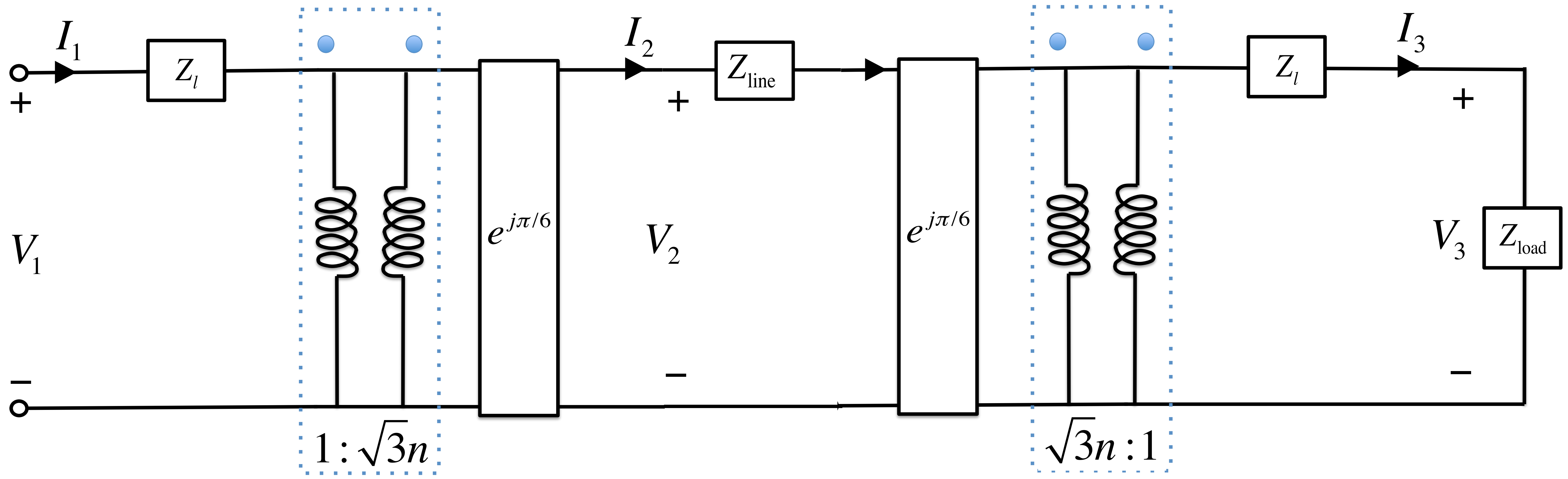
$$\frac{1}{|K(n)|^2} \cdot \left(Z_{\text{line}} + |K(n)|^2 (Z_{\text{load}} + Z_l) \right)$$

$$\frac{V_1}{I_1} = 2Z_l + \frac{Z_{\text{line}}}{|K(n)|^2} + Z_{\text{load}}$$

transformer gains on Z_{load} is canceled

Per-phase analysis

Example



$$I_1 = \frac{V_{\text{line}} \Big/ \left(\sqrt{3} e^{i\pi/6}\right)}{2 Z_l + \frac{Z_{\text{line}}}{|K(n)|^2} + Z_{\text{load}}}$$

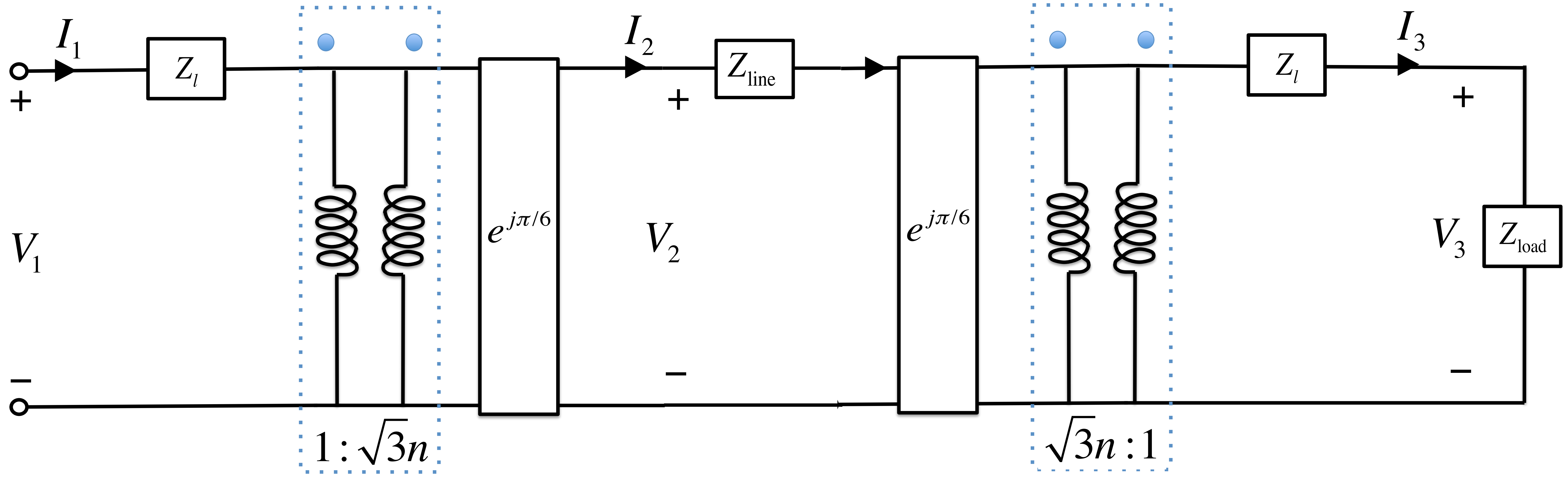
$$I_3 = \bar{K}(n)\, I_2 = I_1$$

$$V_3 = Z_{\text{load}}\, I_3 = Z_{\text{load}}\, I_1$$

$$I_2 = \frac{I_1}{\bar{K}(n)}$$

Per-phase analysis

Example



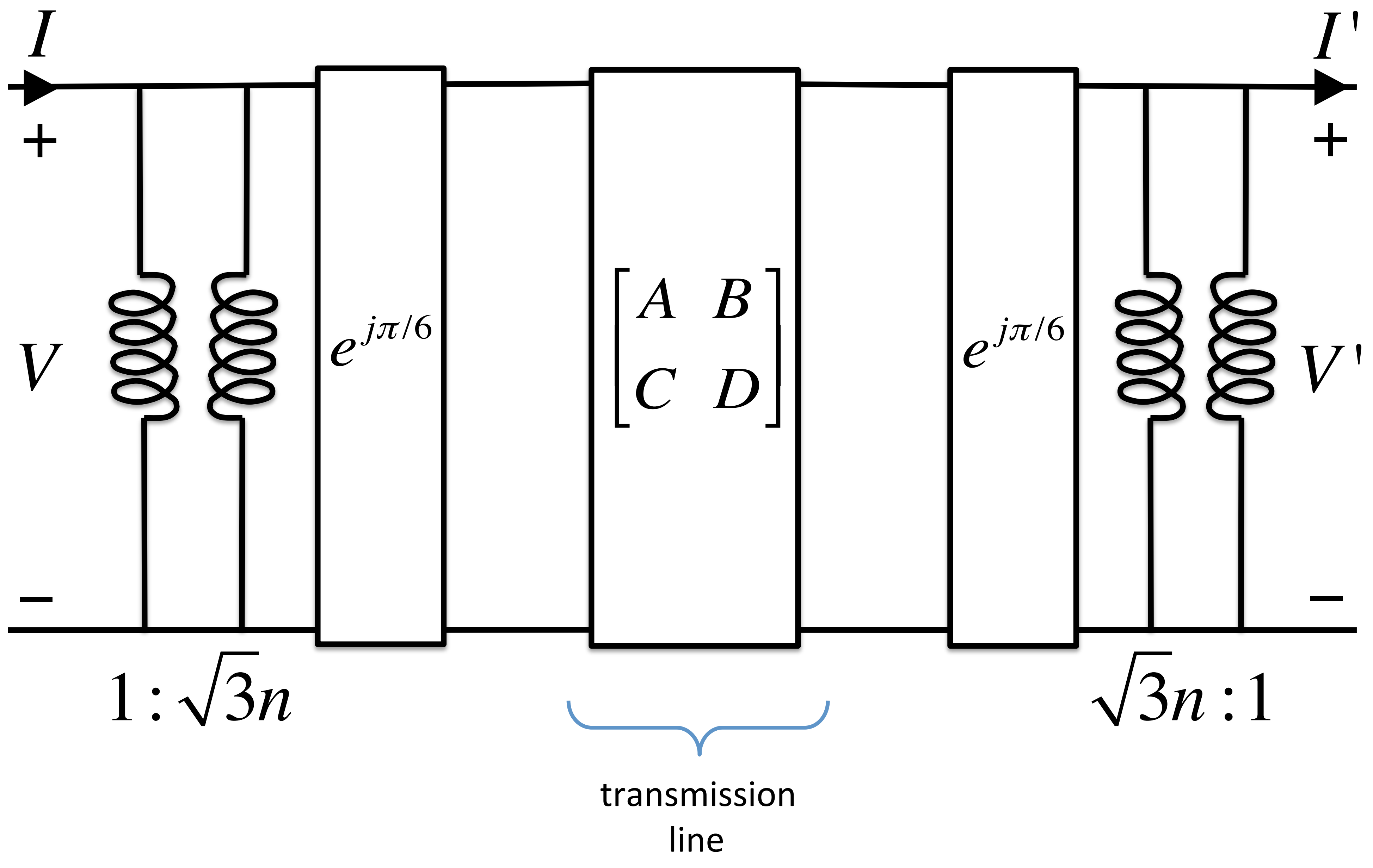
$$I_1 = \frac{V_{\text{line}} \Big/ \left(\sqrt{3}e^{i\pi/6}\right)}{2Z_l + \frac{Z_{\text{line}}}{|K(n)|^2} + Z_{\text{load}}}$$

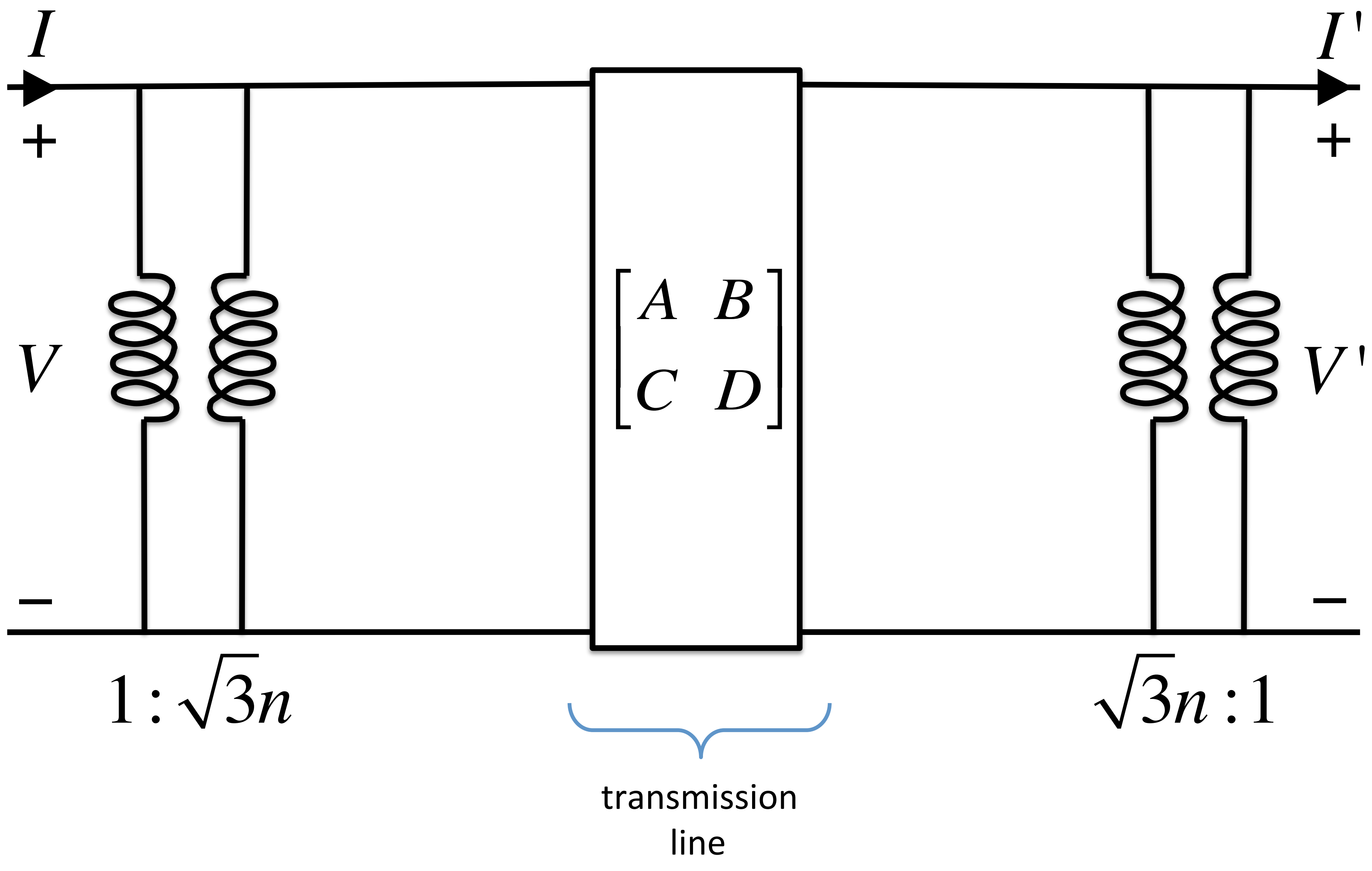
$$I_3 = I_1$$

$$V_3 = Z_{\text{load}} I_1$$

- External behavior does not depend on connection-induced phase shift $e^{i\pi/6}$
- Only internal variables I_{line} does

Simplified model for terminal behavior





Terminal behavior does not depend on $e^{i\pi/6}$

- The simplified model has the same transmission matrix

Normal system

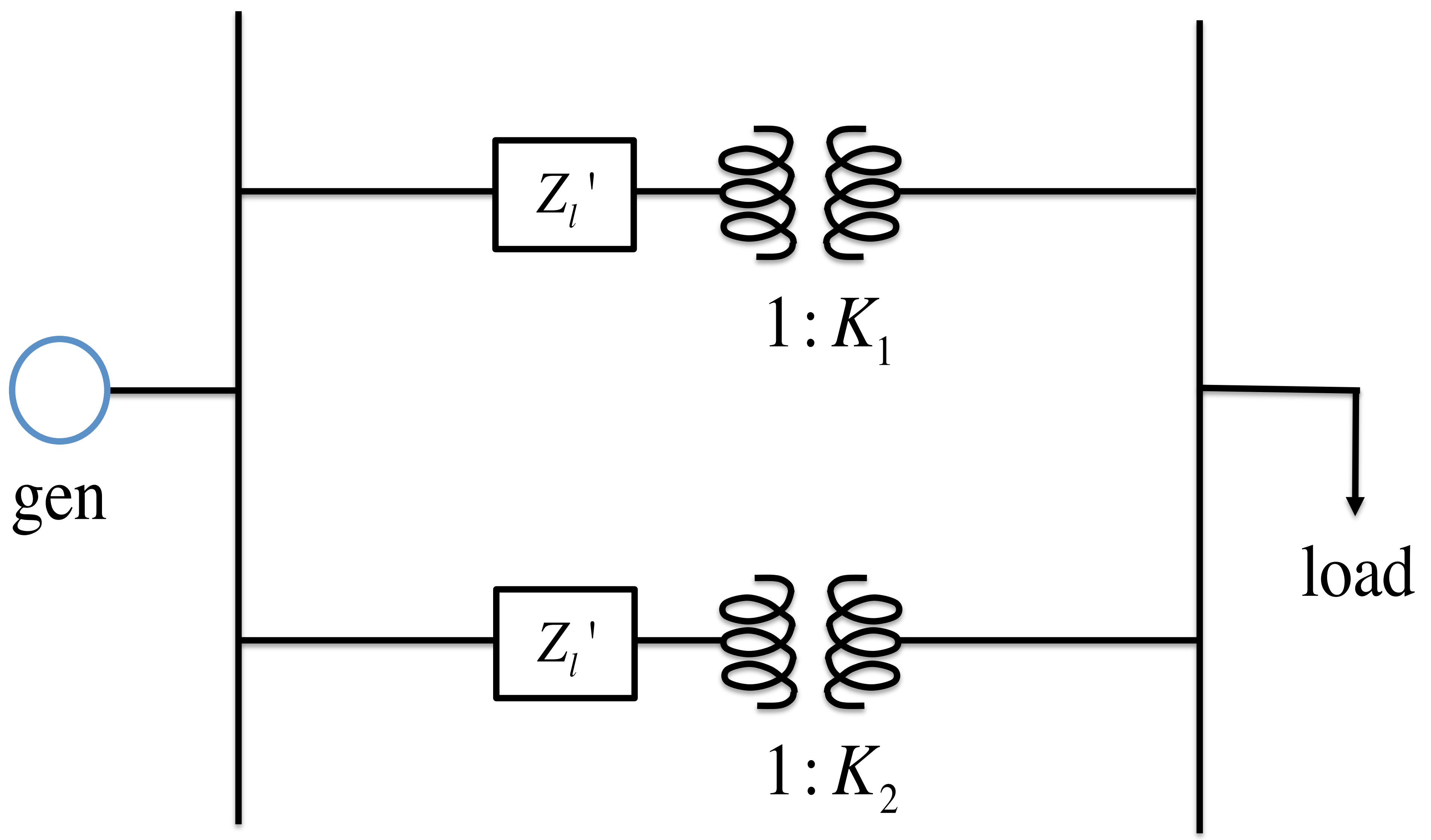
A system is normal if, in its per-phase circuit, the product of complex ideal transformer gains around every loop is 1

Equivalently, on each parallel path,

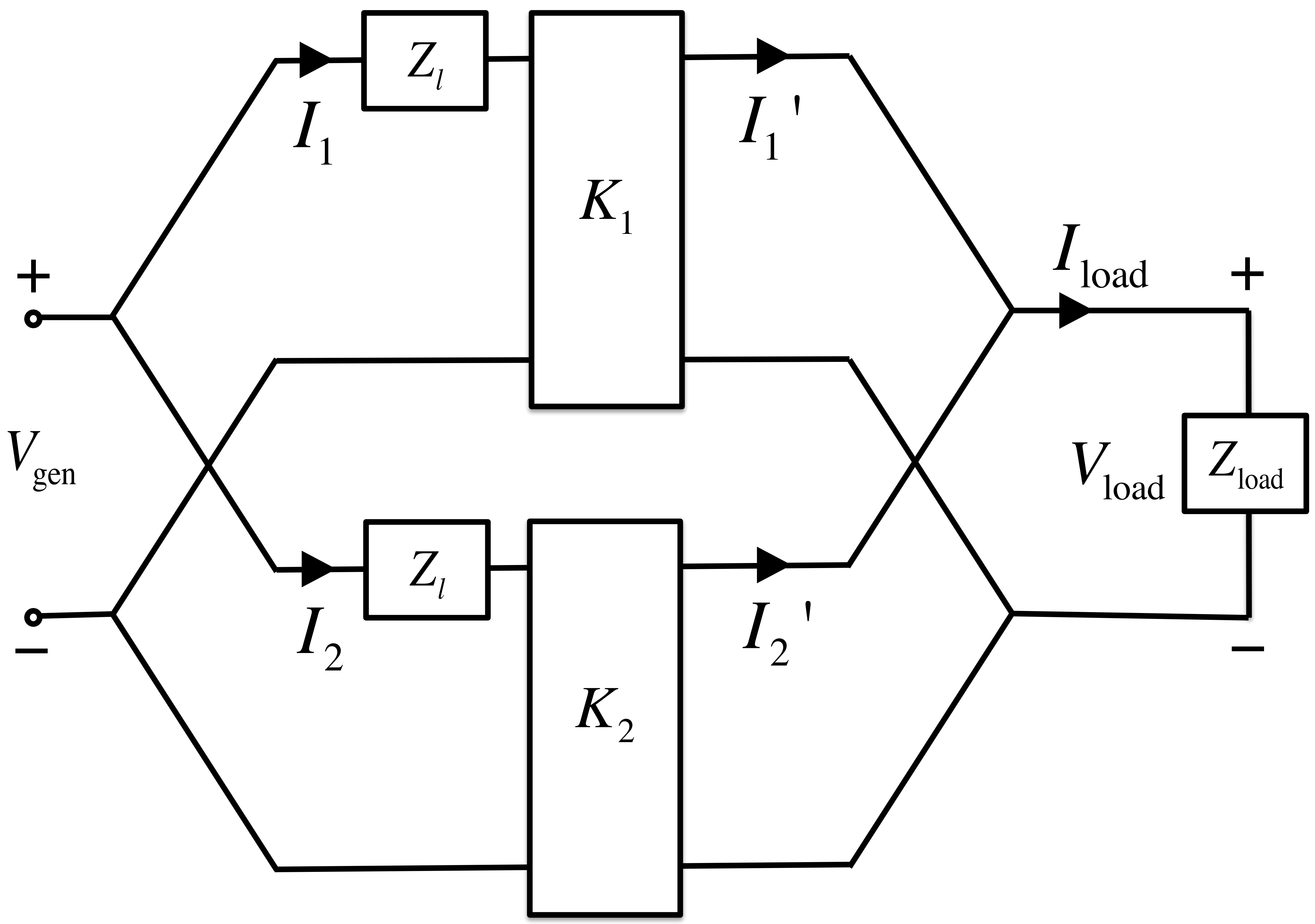
1. Product of ideal transformer gain magnitudes is the same, and
2. Sum of ideal transformer phase shifts is the same

Normal system

Example



Generator & load connected by two 3ϕ transformers in parallel (forming a loop)



Per-phase circuit

Normal system

Example

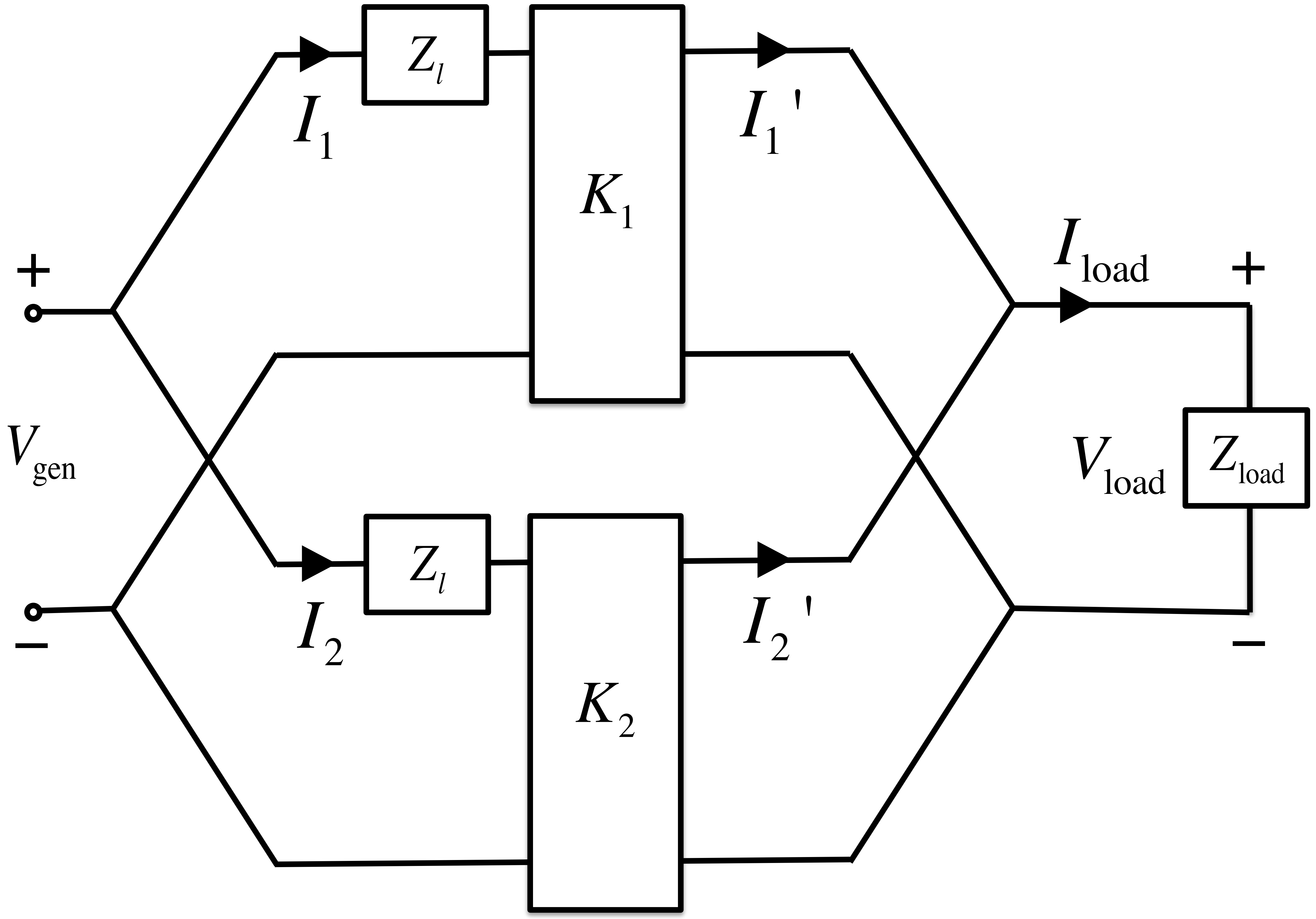
Calculate

- Load current I_{load}
- Line currents I_1', I_2'

in terms of $V_{\text{gen}}, Z_l, Z_{\text{load}}$

Implications when

- $K_2 = K_1$ (normal system)
- $K_2 = K_1 \, e^{i\theta}$
- $K_2 = k \cdot K_1$



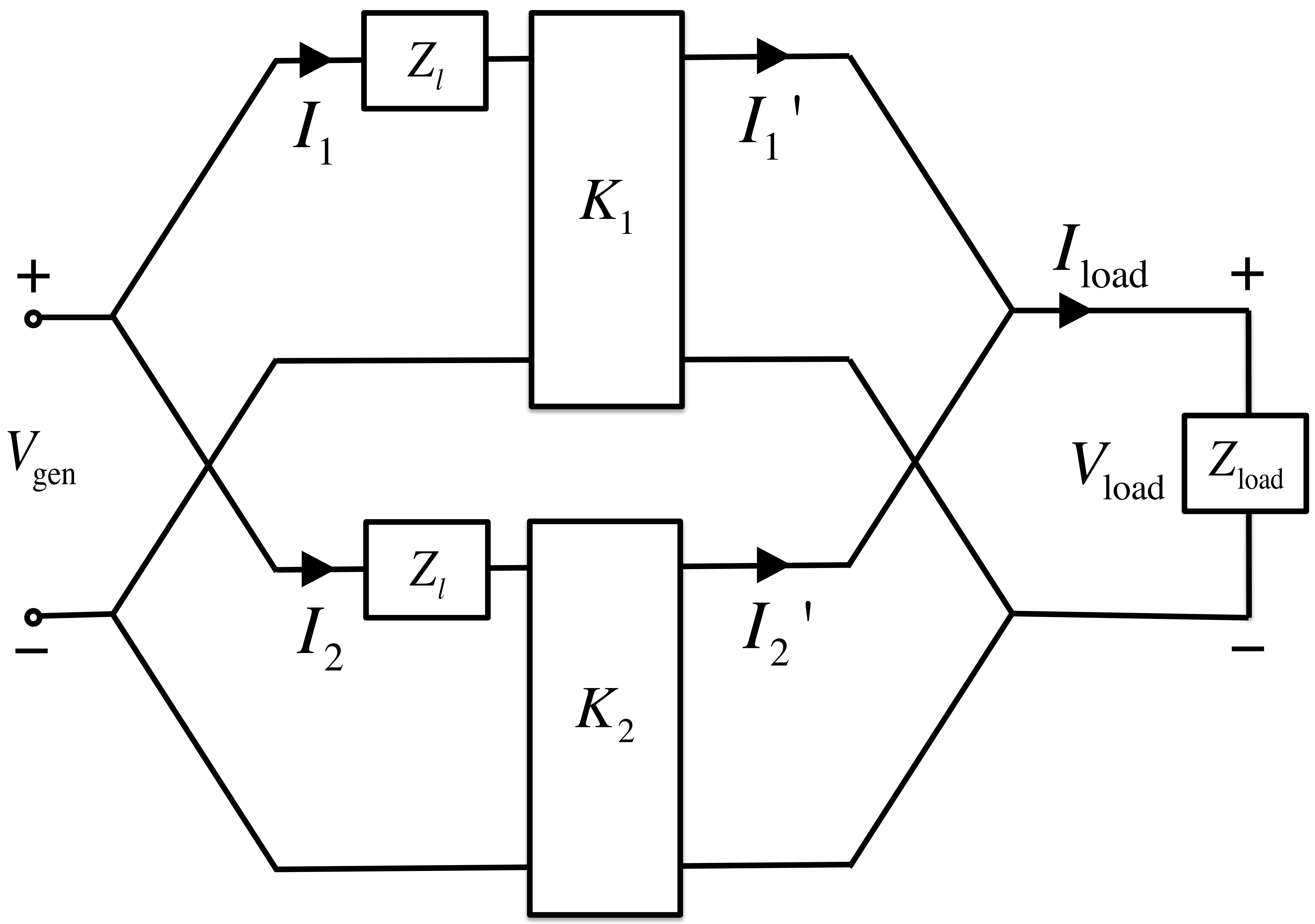
Per-phase circuit

Normal system

Example

$K_2 = K_1$ (normal system):

- $I_1' = I_2'$
- $\dfrac{I_{\text{load}}}{I_1'} = \dfrac{I_{\text{load}}}{I_2'} = 2$



Per-phase circuit

Normal system

Example

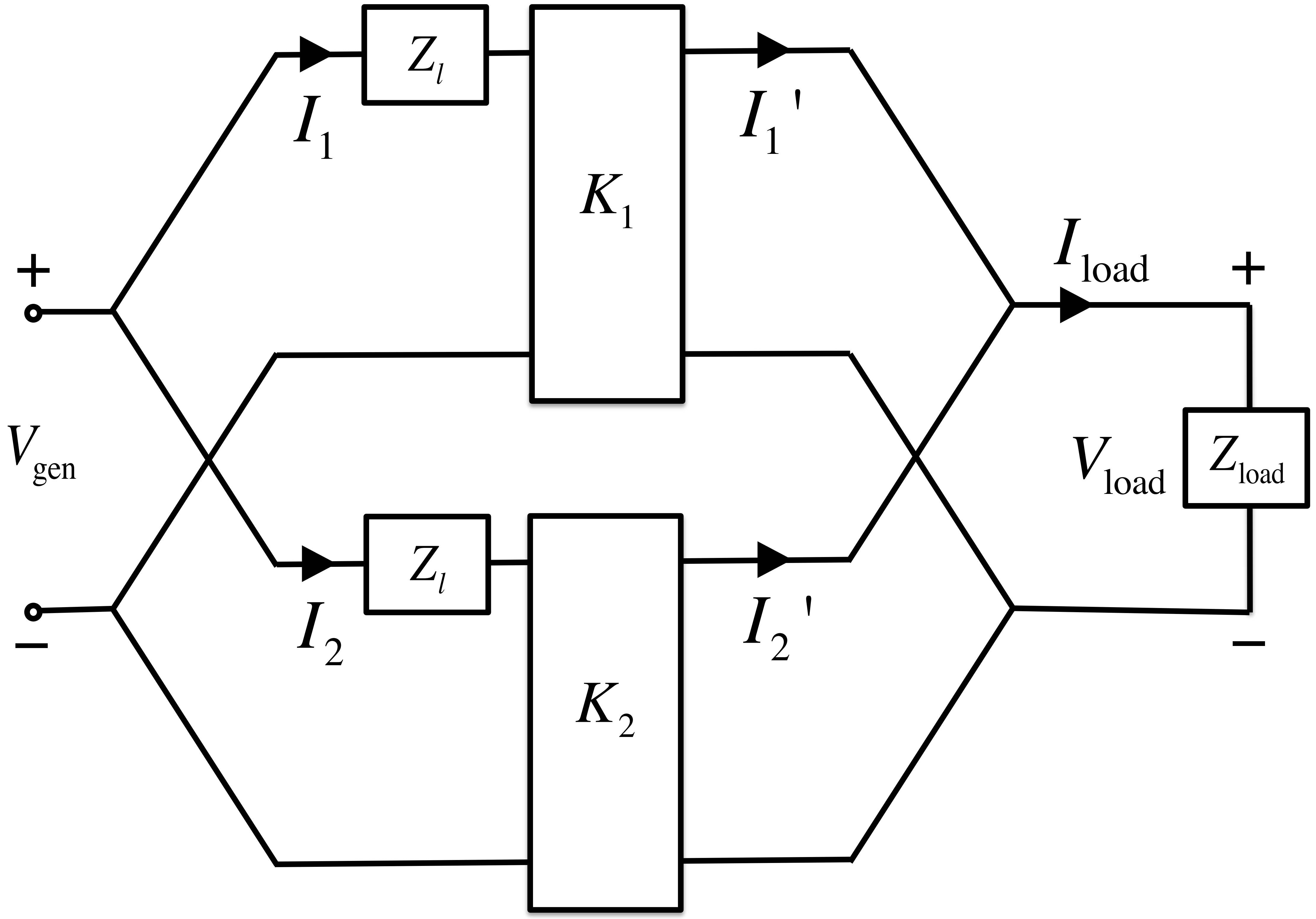
$K_2 = K_1\, e^{i\theta}$:

- $I_1' \neq I_2'$
- $\dfrac{|I_{\text{load}}|}{|I_1'|} = \dfrac{|1+e^{i\theta}|}{|\alpha_1|}, \quad \dfrac{|I_{\text{load}}|}{|I_2'|} = \dfrac{|1+e^{i\theta}|}{|\alpha_2|}$

Example: $K_2 = K_1\, e^{i\pi/6}$:

- $\dfrac{|I_{\text{load}}|}{|I_1'|} = 20.6\,\%\,, \quad \dfrac{|I_{\text{load}}|}{|I_2'|} = 17.1\,\%$

Most current loops between transformers without entering load



Per-phase circuit

Normal system

Example

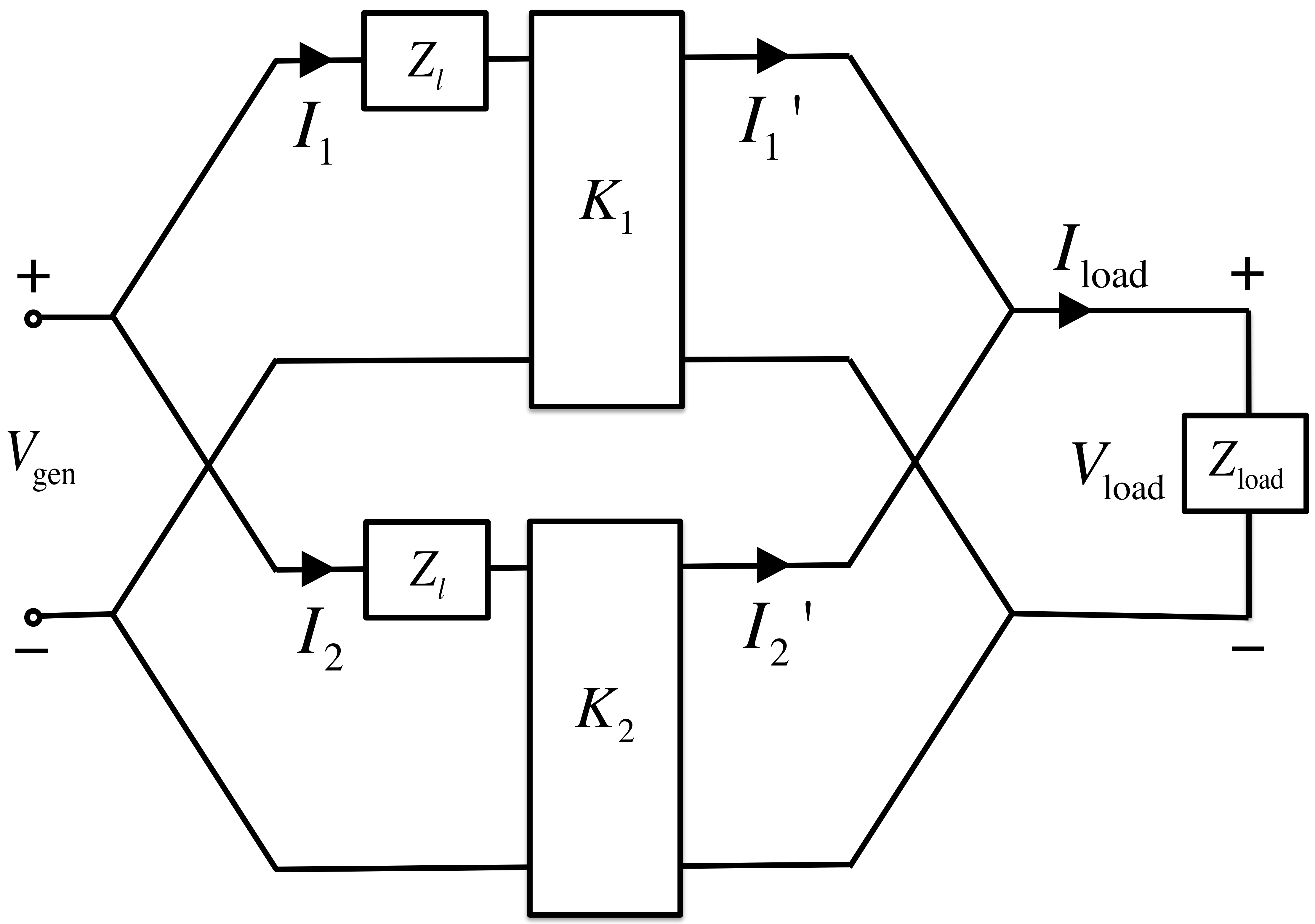
$K_2 = K_1 e^{i\theta}$:

- $I_1' \neq I_2'$
- $\dfrac{\left|I_{\text{load}}\right|}{|I_1'|} = \dfrac{\left|1 + e^{i\theta}\right|}{|\alpha_1|}, \quad \dfrac{\left|I_{\text{load}}\right|}{|I_2'|} = \dfrac{\left|1 + e^{i\theta}\right|}{|\alpha_2|}$

Example: $K_2 = K_1 e^{i\pi/6}$:

- $S_{\text{gen}} = 183 \angle 71°, \quad S_{\text{load}} = 60 \angle 0°$ MVA

Most current loops between transformers without entering load



Per-phase circuit

Normal system

Example

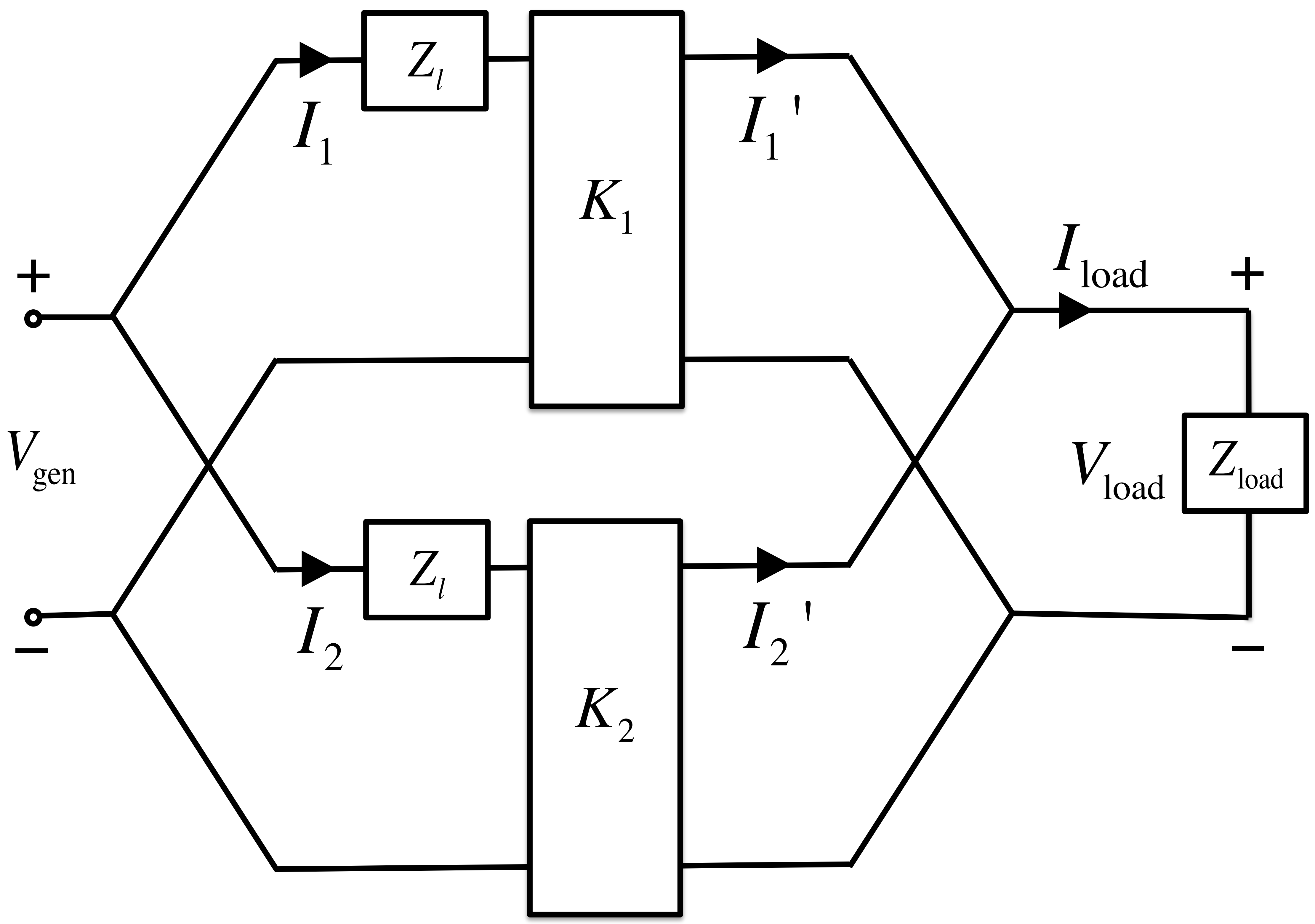
$K_2 = k \cdot K_1$:

- $I_1' \neq I_2'$
- $\dfrac{|I_{\text{load}}|}{|I_1'|} = \dfrac{1 + k^{-1}}{|\alpha_1|}, \quad \dfrac{|I_{\text{load}}|}{|I_2'|} = \dfrac{1 + k}{|\alpha_2|}$

Example: $K_2 = 2K_1$:

- $\dfrac{|I_{\text{load}}|}{|I_1'|} = 29.4\,\%\,, \quad \dfrac{|I_{\text{load}}|}{|I_2'|} = 29.9\,\%$

Most current loops between transformers without entering load



Per-phase circuit

Outline

1. Single-phase transformer
2. Balanced three-phase transformers
3. Equivalent impedance
4. Per-phase analysis
5. Per-unit normalization
    - Kirchhoff's and Ohm's laws
    - Across ideal transformer
    - Three-phase quantities
    - Per-unit per-phase analysis

Per-unit normalization

- Quantities of interest: voltages V, currents I, power S, impedances Z
- $\text{quantity in p.u.} = \dfrac{\text{actual quantity}}{\text{base value of quantity}}$
- Base values
  - Real positive values
  - Same units as actual quantities
- Choose base values to satisfy same physical laws
  - Kirchhoff's and Ohm's laws
  - Across ideal transformer
  - Relationship between 3ϕ and 1ϕ quantities

Per-unit normalization

General procedure

1. Choose voltage base value V_{1B} for (say) area 1
2. Choose power base value S_B for entire network
3. Calculate all other base values from physical laws

Example: Choose

1. V_{1B} = nominal voltage magnitude of area 1
2. S_B = rated apparent power of a transformer in area 1

How to calculate the other base values (V_{iB}, I_{iB}, Z_{iB})?

- Consider single-phase or per-phase circuit of balanced 3ϕ system

Kirchhoff's and Ohm's laws

Given base values $\left(V_{1B}, S_B\right)$, within area 1:

$$I_{1B} \ := \ \frac{S_B}{V_{1B}} \ \ A, \qquad Z_{1B} \ := \ \frac{V_{1B}^2}{S_B} \ \ \Omega$$

Then: physical laws are satisfied by both the base values and p.u. quantities

$$\begin{aligned} V_{1B} &= \ Z_{1B} I_{1B}, \qquad & V_{1\text{pu}} &= \ Z_{1\text{pu}} I_{1\text{pu}} \\ S_B &= \ V_{1B} I_{1B}, \qquad & S_{1\text{pu}} &= \ V_{1\text{pu}} I_{1\text{pu}} \end{aligned}$$

Can perform circuit analysis using pu quantities instead of actual quantities

Kirchhoff's and Ohm's laws

Other quantities

These quantities $\left(V_{1B}, S_B, I_{1B}, Z_{1B}\right)$ serve as base values for other quantities within area 1, with appropriate units

- S_B is base value for real power in W, reactive power in var

$$P_{1\text{pu}} := \frac{P_1}{S_B}, \qquad Q_{1\text{pu}} := \frac{Q_1}{S_B}, \qquad S_{1\text{pu}} = P_{1\text{pu}} + iQ_{1\text{pu}}$$

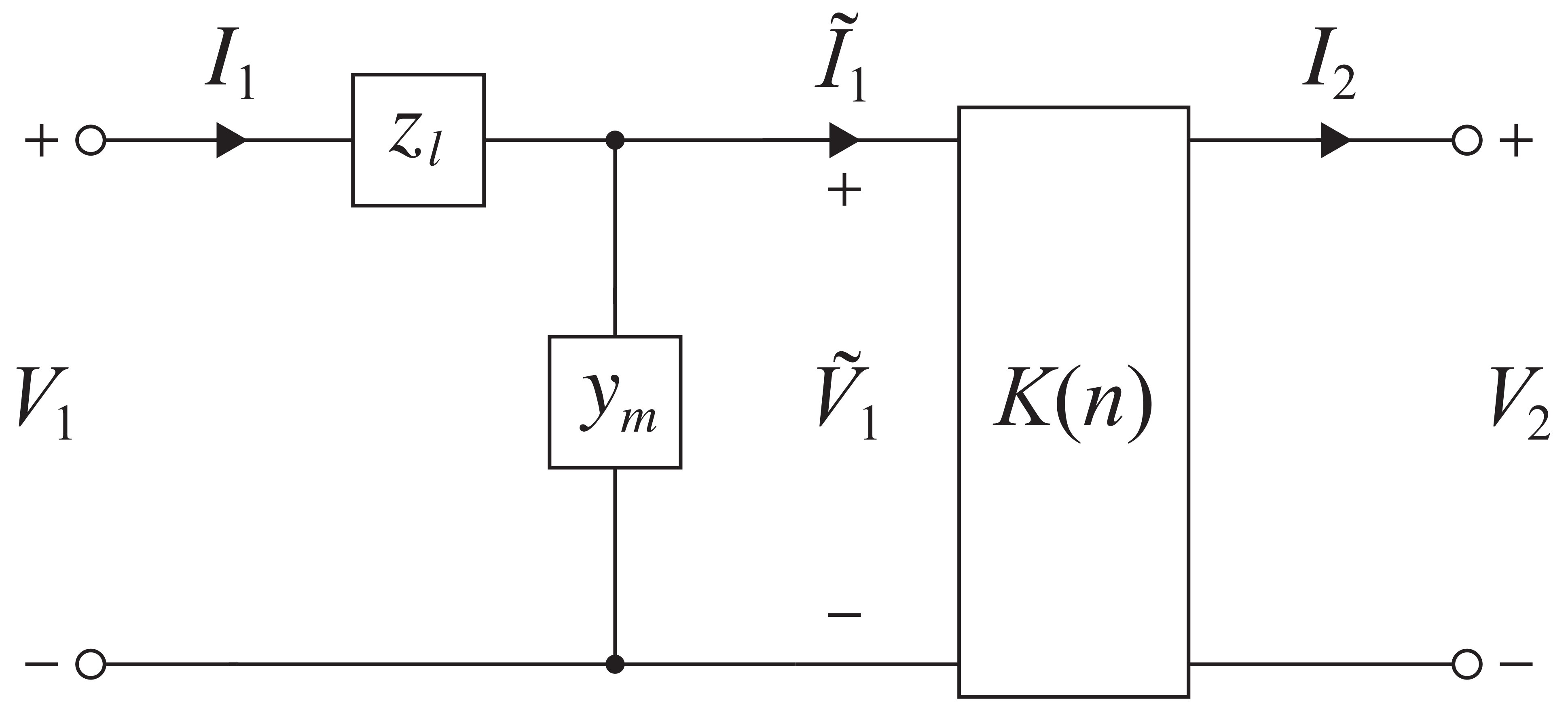
- Z_{1B} is base value for resistances & reactances in Ω

$$R_{1\text{pu}} := \frac{R_1}{Z_{1B}}, \qquad X_{1\text{pu}} := \frac{X_1}{Z_{1B}}, \qquad Z_{1\text{pu}} = R_{1\text{pu}} + iX_{1\text{pu}}$$

- $Y_{1B} := 1/Z_{1B}$ in $\Omega^{-1}$is base value for conductances, susceptances, & admittances

$$G_{1\text{pu}} := \frac{G_1}{Y_{1B}}, \qquad B_{1\text{pu}} := \frac{B_1}{Y_{1B}}, \qquad Y_{1\text{pu}} = G_{1\text{pu}} + iB_{1\text{pu}} = \frac{1}{Z_{1\text{pu}}}$$

Across ideal transformer



Choose $\left(V_{2B}, I_{2B}, Z_{2B}\right)$ according to

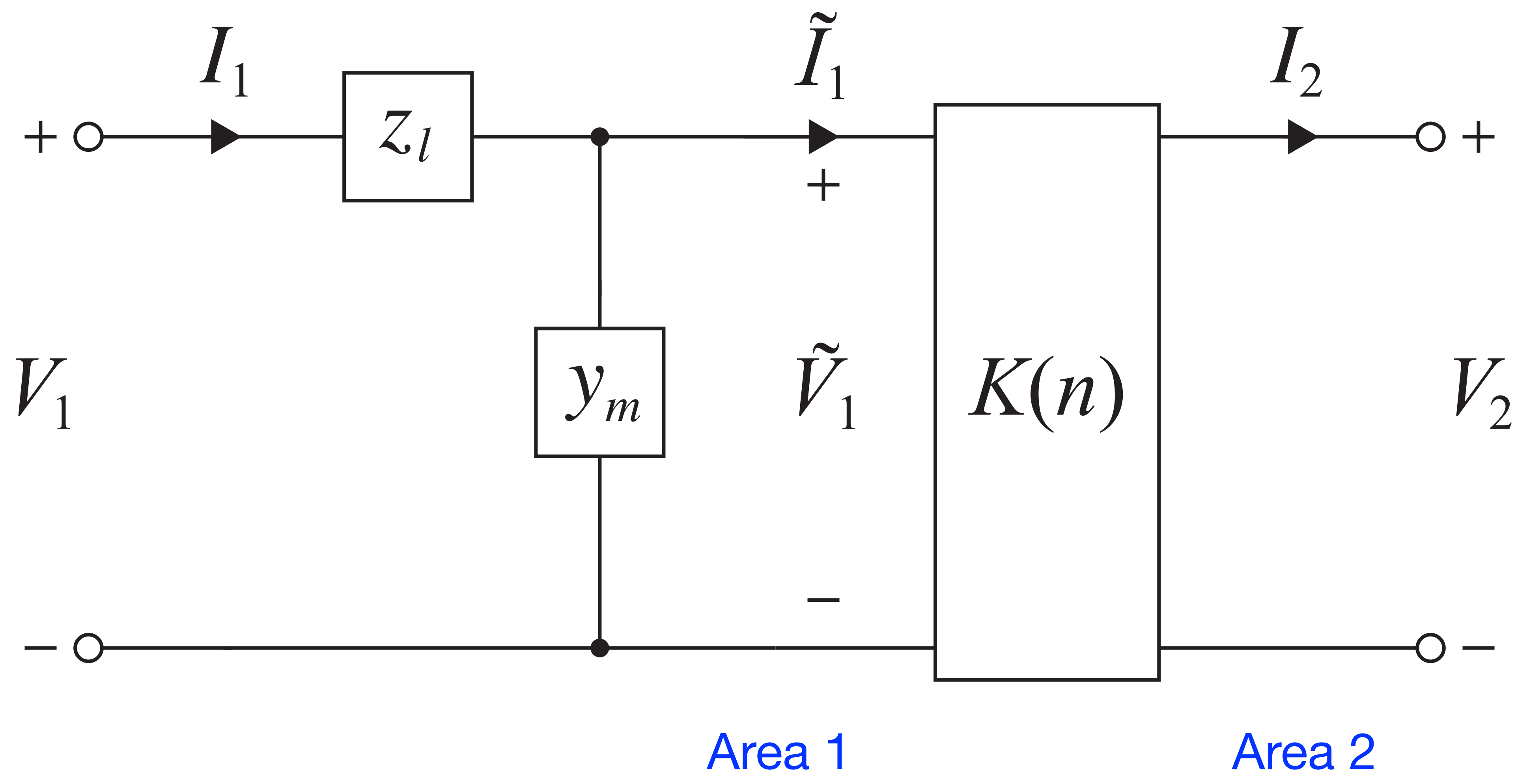
$$V_{2B} := \ |K(n)|\, V_{1B} \quad V$$

$$I_{2B} := \ \frac{I_{1B}}{|K(n)|} \quad A$$

$$Z_{2B} := \ |K(n)|^2 Z_{1B} \ \ \Omega$$

Base values remain real positive
S_B remains base value for power

Across ideal transformer



External behavior

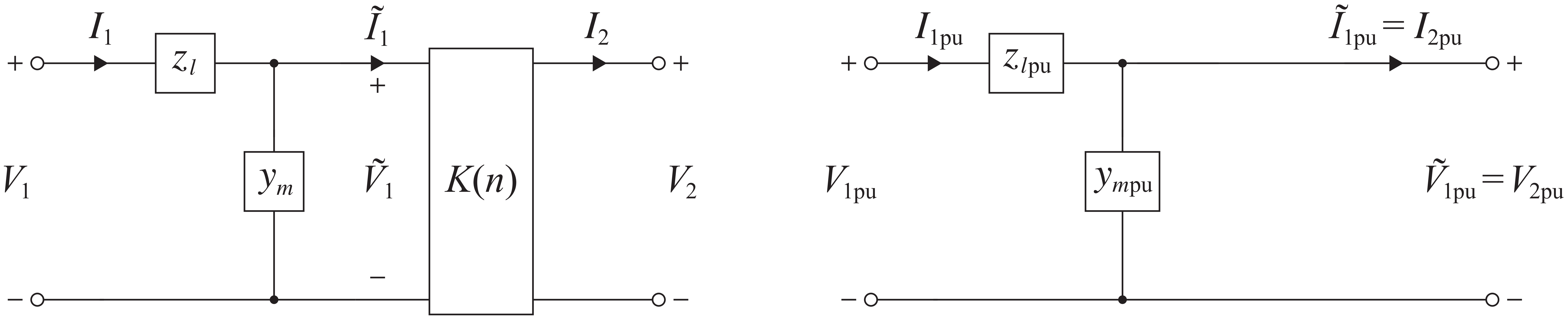
$$\tilde{V}_{1\text{pu}} = \frac{\tilde{V}_1}{V_{1B}} = \frac{V_2}{K(n)} \frac{|K(n)|}{V_{2B}} = V_{2\text{pu}}\, e^{-j\angle K(n)}$$

$$\tilde{I}_{1\text{pu}} = \frac{\tilde{I}_1}{\tilde{I}_{1B}} = \frac{K^*(n) I_2}{|K(n)| I_{2B}} = I_{2\text{pu}}\, e^{-j\angle K(n)}$$

If $\angle K(n) = 0$ then

$$\tilde{V}_{1\text{pu}} = V_{2\text{pu}}, \quad \tilde{I}_{1\text{pu}} = I_{2\text{pu}}$$

Across ideal transformer



External behavior

$$\tilde{V}_{1\text{pu}} = \frac{\tilde{V}_1}{V_{1B}} = \frac{V_2}{K(n)} \frac{|K(n)|}{V_{2B}} = V_{2\text{pu}}\, e^{-j\angle K(n)}$$

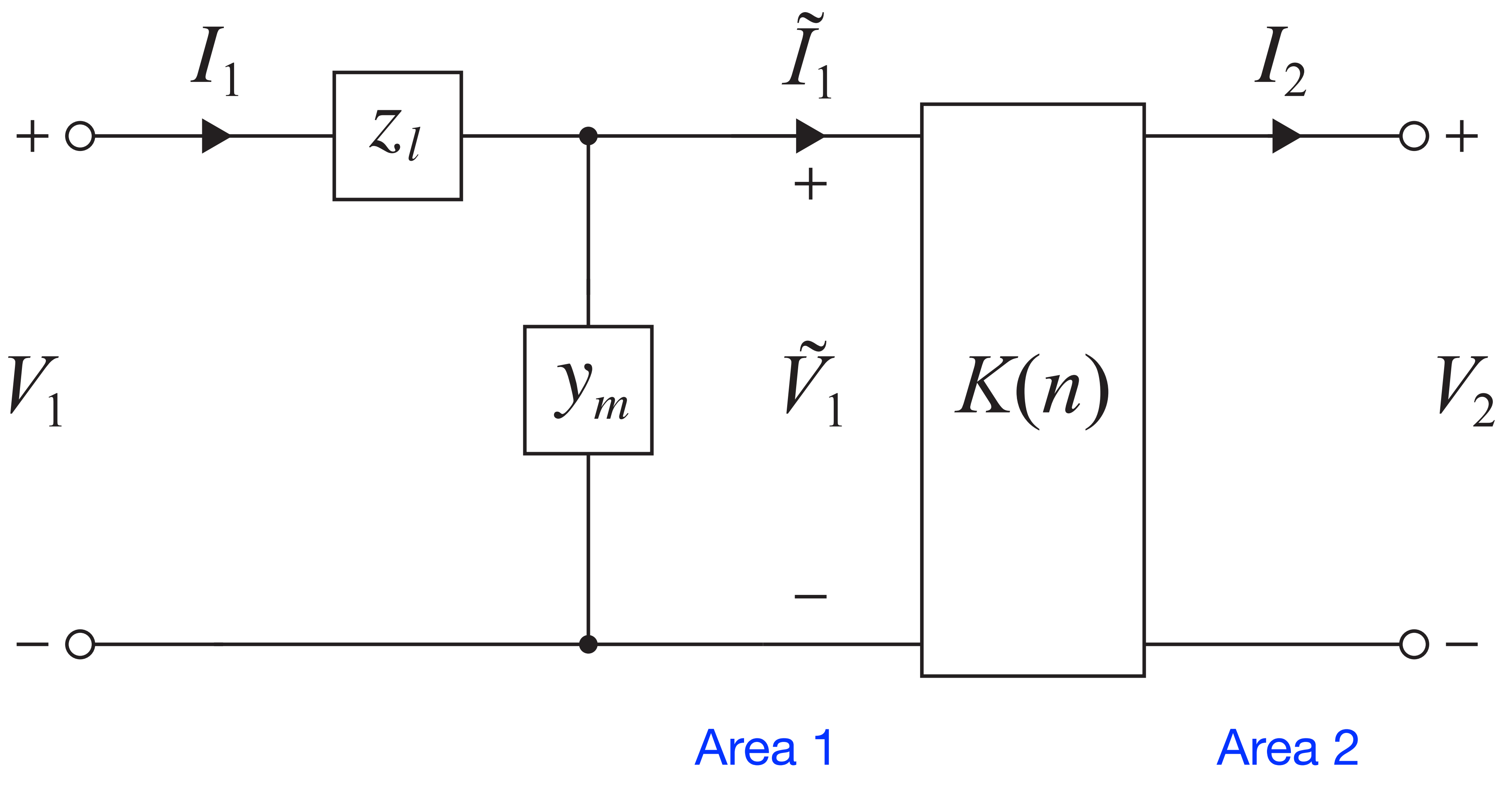
$$\tilde{I}_{1\text{pu}} = \frac{\tilde{I}_1}{\tilde{I}_{1B}} = \frac{K^*(n) I_2}{|K(n)|\, I_{2B}} = I_{2\text{pu}}\, e^{-j\angle K(n)}$$

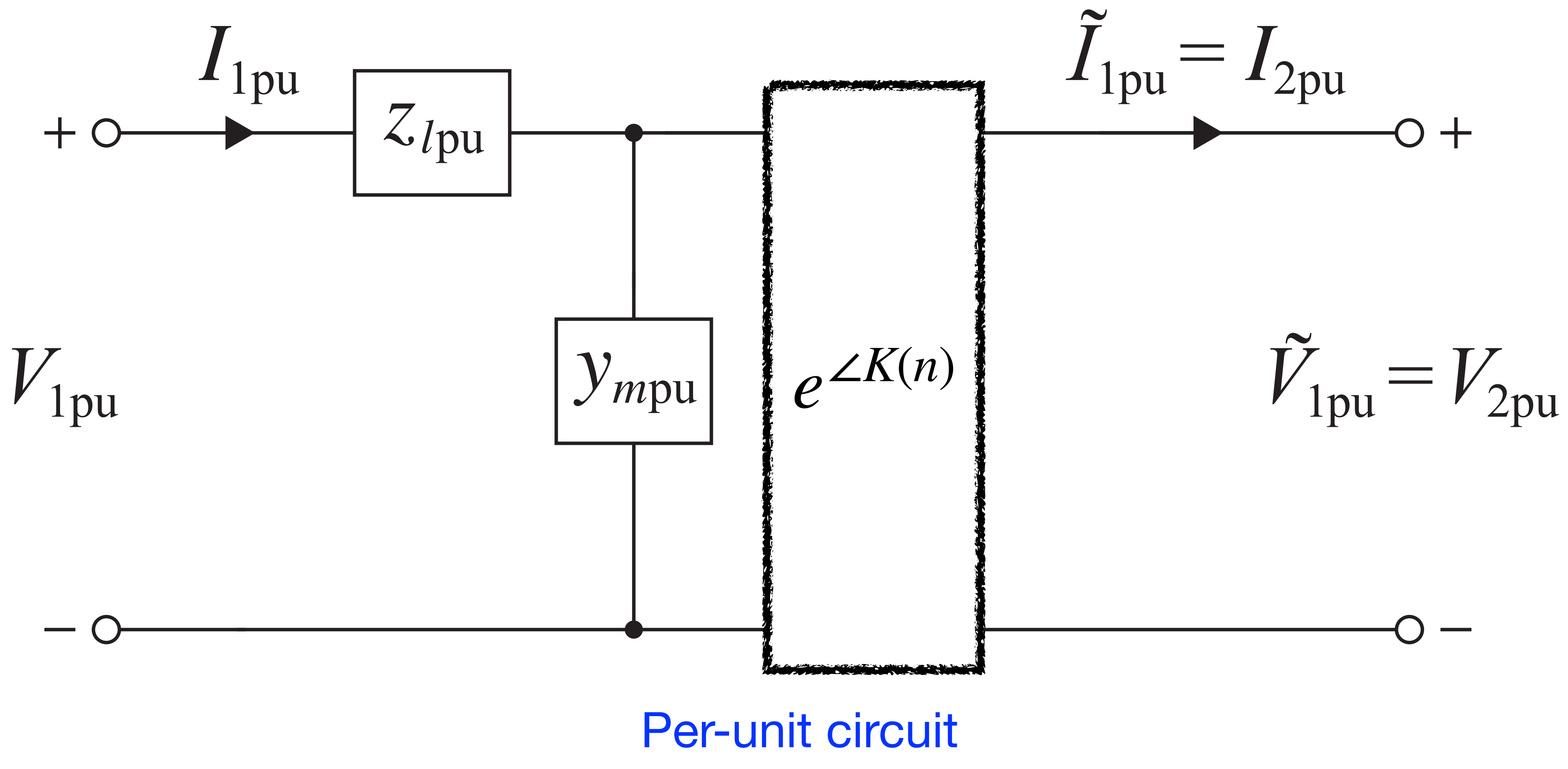
If $\angle K(n) = 0$ then

$$\tilde{V}_{1\text{pu}} = V_{2\text{pu}}, \quad \tilde{I}_{1\text{pu}} = I_{2\text{pu}}$$

Ideal transformer has disappeared !

Across ideal transformer





External behavior

$$\tilde{V}_{1\mathrm{pu}} = \frac{\tilde{V}_1}{V_{1B}} = \frac{V_2}{K(n)} \frac{|K(n)|}{V_{2B}} = V_{2\mathrm{pu}}\, e^{-j\angle K(n)}$$

$$\tilde{I}_{1\mathrm{pu}} = \frac{\tilde{I}_1}{\tilde{I}_{1B}} = \frac{K^*(n) I_2}{|K(n)|\, I_{2B}} = I_{2\mathrm{pu}}\, e^{-j\angle K(n)}$$

Otherwise

- pu circuit contains an off-nominal phase-shifting transformer

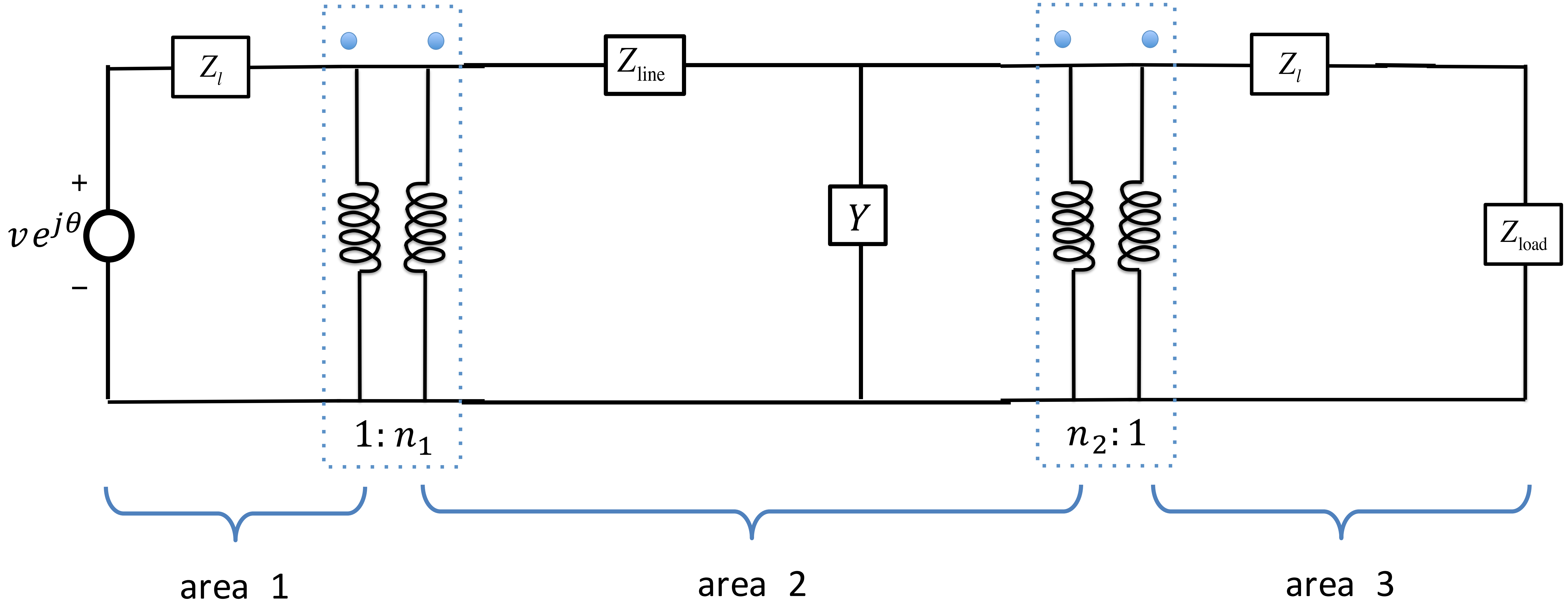
Across ideal transformer

Example

Given nameplate rating of generator

- Voltage v V
- Apparent power s VA

Calculate base values



Voltage base $V_{1B} := v$, power base $S_B := s$

- Area 1: $I_{1B} := s/v, \;\; Z_{1B} := v^2/s$
- Area 2: $V_{2B} := n_1 v, \;\; I_{2B} := s/(n_1 v), \;\; Z_{2B} := (n_1 v)^2/s, \;\; Y_{2B} := s/(v_1 v)^2$
- Area 3: $V_{3B} := n_1 v/n_2, \;\; I_{3B} := n_2 s/(n_1 v), \;\; Z_{3B} := (n_1 v)^2/(n_2^2 s), \;\; Y_{3B} := (n_2^2 s)/(v_1 v)^2$

3ϕ quantities

Given 1ϕ devices (generators, lines, loads) with

- with 1ϕ quantities $\left(S^{1\phi}, V^{1\phi}, I^{1\phi}, Z^{1\phi}\right)$
- and their base values

Construct balanced 3ϕ devices from these 1ϕ devices

- What are 3ϕ quantities of interest?
- What are base values so that 3ϕ quantities equal to 1ϕ quantities in p.u.?

Base values should satisfy the same 3ϕ relationships as actual quantities
Values depend on the configuration, Y or Δ

3ϕ quantities
Y configuration

In terms of

$\left(S^{1\phi}, V^{1\phi}, I^{1\phi}, Z^{1\phi}\right)$

and their base values

- 3ϕ power (total power to/from 3 1ϕ devices):

$$S^{3\phi} = 3S^{1\phi},$$

- Line-to-line voltage

$$V^{\text{ll}} = \sqrt{3}e^{i\pi/6}\,V^{\text{ln}},$$

- Line current

$$I^{3\phi} = I_{an} = I^{1\phi},$$

- Line-to-neutral voltage

$$V^{\text{ln}} = V^{1\phi},$$

- Impedance

$$Z^{3\phi} = Z^{1\phi},$$

3ϕ quantities

Y configuration

In terms of

$\left(S^{1\phi}, V^{1\phi}, I^{1\phi}, Z^{1\phi}\right)$

and their base values

- 3ϕ power (total power to/from 3 1ϕ devices):

$$S^{3\phi} = 3S^{1\phi}, \qquad S_B^{3\phi} = 3S_B^{1\phi}$$

- Line-to-line voltage

$$V^{\text{ll}} = \sqrt{3}e^{i\pi/6}\, V^{\text{ln}}, \qquad V_B^{\text{ll}} = \sqrt{3}\, V_B^{\text{ln}}$$

- Line current

$$I^{3\phi} = I_{an} = I^{1\phi}, \qquad I_B^{3\phi} = I_B^{1\phi}$$

- Line-to-neutral voltage

$$V^{\text{ln}} = V^{1\phi}, \qquad V_B^{\text{ln}} = V_B^{1\phi}$$

- Impedance

$$Z^{3\phi} = Z^{1\phi}, \qquad Z_B^{3\phi} = Z_B^{1\phi}$$

Calculation

Base values satisfy the same relationship

3ϕ quantities

Δ configuration

In terms of

$\left(S^{1\phi}, V^{1\phi}, I^{1\phi}, Z^{1\phi}\right)$

and their base values

- 3ϕ power (total power to/from 3 1ϕ devices):

$$S^{3\phi} = 3S^{1\phi},$$

- Line-to-line voltage

$$V^{\mathrm{ll}} = \sqrt{3}e^{i\pi/6}\,V^{\mathrm{ln}},$$

- Line current

$$I^{3\phi} = I_{ab} - I_{ca} = \sqrt{3}\,e^{-i\pi/6}\,I^{1\phi},$$

- Line-to-neutral voltage

$$V^{\mathrm{ln}} = \left(\sqrt{3}\,e^{i\pi/6}\right)^{-1} V^{1\phi},$$

- Impedance

$$Z^{3\phi} = Z^{1\phi}/3,$$

Note:

V^{ln}, $Z^{3\phi}$ are voltage and & impedance in Y equivalent circuit

3ϕ quantities
Δ configuration

In terms of

$$\left(S^{1\phi}, V^{1\phi}, I^{1\phi}, Z^{1\phi}\right)$$

and their base values

Note:

V^{ln}, $Z^{3\phi}$ are voltage and & impedance in Y equivalent circuit

- 3ϕ power (total power to/from 3 1ϕ devices):

$$S^{3\phi} = 3S^{1\phi}, \qquad S_B^{3\phi} = 3S_B^{1\phi}$$

- Line-to-line voltage

$$V^{\text{ll}} = \sqrt{3}e^{i\pi/6}\,V^{\text{ln}}, \qquad V_B^{\text{ll}} = \sqrt{3}\,V_B^{\text{ln}}$$

- Line current

$$I^{3\phi} = I_{ab} - I_{ca} = \sqrt{3}\,e^{-i\pi/6}\,I^{1\phi}, \qquad I_B^{3\phi} = \sqrt{3}\,I_B^{1\phi}$$

- Line-to-neutral voltage

$$V^{\text{ln}} = \left(\sqrt{3}\,e^{i\pi/6}\right)^{-1} V^{1\phi}, \qquad V_B^{\text{ln}} = (\sqrt{3})^{-1} V_B^{1\phi}$$

- Impedance

$$Z^{3\phi} = Z^{1\phi}/3, \qquad Z_B^{3\phi} = Z_B^{1\phi}/3$$

Per-unit quantities

Per-unit quantities satisfy

$$S_{\text{pu}}^{3\phi} = S_{\text{pu}}^{1\phi}, \qquad V_{\text{pu}}^{\text{ll}} = V_{\text{pu}}^{\text{ln}}, \qquad Z_{\text{pu}}^{3\phi} = Z_{\text{pu}}^{1\phi}$$

$$\left|V_{\text{pu}}^{\text{ln}}\right| = \left|V_{\text{pu}}^{1\phi}\right|, \qquad \left|I_{\text{pu}}^{3\phi}\right| = \left|I_{\text{pu}}^{1\phi}\right|$$

- 3ϕ quantities equal 1ϕ quantities in p.u.
- modulo phase shifts in Δ configuration:

$$V_{\text{pu}}^{\text{ln}} := \frac{V^{\text{ln}}}{V_B^{\text{ln}}} = \frac{\left(\sqrt{3}e^{i\pi/6}\right)^{-1} V^{1\phi}}{\left(\sqrt{3}\right)^{-1} V_B^{1\phi}} = e^{-i\pi/6}\, V_{\text{pu}}^{1\phi}$$

Per-unit per-phase analysis

1. For single-phase system, pick power base $S_B^{1\phi}$ for entire system and voltage base $V_{1B}^{1\phi}$ in area 1, e.g., induced by nameplate ratings of transformer
2. For balanced 3ϕ system, pick 3ϕ power base $S_B^{3\phi}$ and line-to-line voltage base V_B^{ll} induced by nameplate ratings of 3ϕ transformer. Then choose power & voltage bases for per-phase equivalent circuit:

$$S_B^{1\phi} := S_B^{3\phi} \Big/ 3, \qquad V_{1B}^{1\phi} := V_{1B}^{\text{ll}} \Big/ \sqrt{3}$$

   $S_{1B}^{1\phi}$ will be power base for entire per-phase circuit.

3. Calculate current and impedance bases in that area:

$$I_{1B} := \frac{S_B^{1\phi}}{V_{1B}^{1\phi}}, \qquad Z_{1B} := \frac{\left(V_{1B}^{1\phi}\right)^2}{S_B^{1\phi}}$$

Per-unit per-phase analysis

4. Calculate base values for voltages, currents, and impedances in areas i connected to area 1 using the magnitude n_i of transformer gains (assume area 1 is primary):

$$V_{iB}^{1\phi} := n_i V_{1B}^{1\phi}, \qquad V_{iB}^{\text{ll}} := n_i V_{1B}^{\text{ll}}, \qquad I_{iB} := \frac{1}{n_i} I_{1B}, \qquad Z_{iB} := n_i^2 Z_{1B}$$

Continue this process to calculate the voltage, current, and impedance base values for all areas

Per-unit per-phase analysis

5. For real, reactive, apparent power in entire system, use $S_B^{1\phi}$ as base value.

   For resistances and reactances, use Z_{iB} as base value in area i.

   For admittances, conductances, and susceptancesq, use $Y_{iB} := 1/Z_{iB}$ as base value in area i

6. Draw impedance diagram of entire system, and solve for desired per-unit quantities

7. Convert back to actual quantities if desired

Summary

1. Single-phase transformer
    - Ideal transformer gain n, equivalent circuit
2. Three-phase transformer
    - $YY, \Delta\Delta, \Delta Y, Y\Delta$: external behavior, YY equivalent
3. Equivalent impedance
    - Short cut for analyzing circuits containing transformers
    - Transmission matrix, driving-point impedance
4. Per-phase analysis
5. Per-unit normalization
    - Physical laws, across transformer, 3ϕ quantities, per-unit per-phase analysis