



THE UNIVERSITY
OF QUEENSLAND
AUSTRALIA

CREATE CHANGE

Using electrical simulation models in distribution networks

Building network models is a massive challenge

Why use physics-based “digital twins”?

Computationally feasible today

Inform on what is *ultimately achievable*

Unbiased

Explainable, auditable, validatable,

Legally defensible

More than a century of power engineering knowledge and experience



Why not use physics-based modeling?

No single source of truth today

Building network models from GIS can be very challenging

Validation nontrivial, though manageable

Existing ADMS/DERMS/GIS software platforms have big gaps

... need to invest in new scientific approaches to make network model cleanup and validation cost-effective



Electrical Model Building

Derive network models from source of truth, e.g. GIS

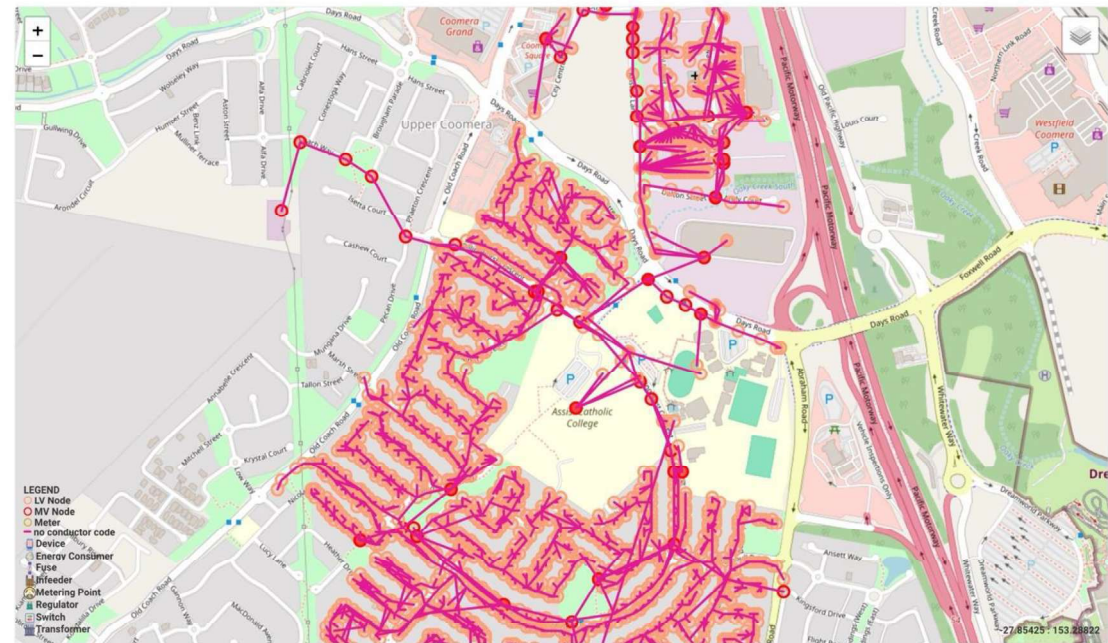
Link up with asset databases, PV registers, standards, etc. using UUIDs

Mapping to a library of Australian construction codes, generate impedances through Carson's equations

Establish neutral grounding points

Representing all electrical components down from the zone substation, MV feeders, distribution transformers, LV feeders

Partition to separate MV/LV



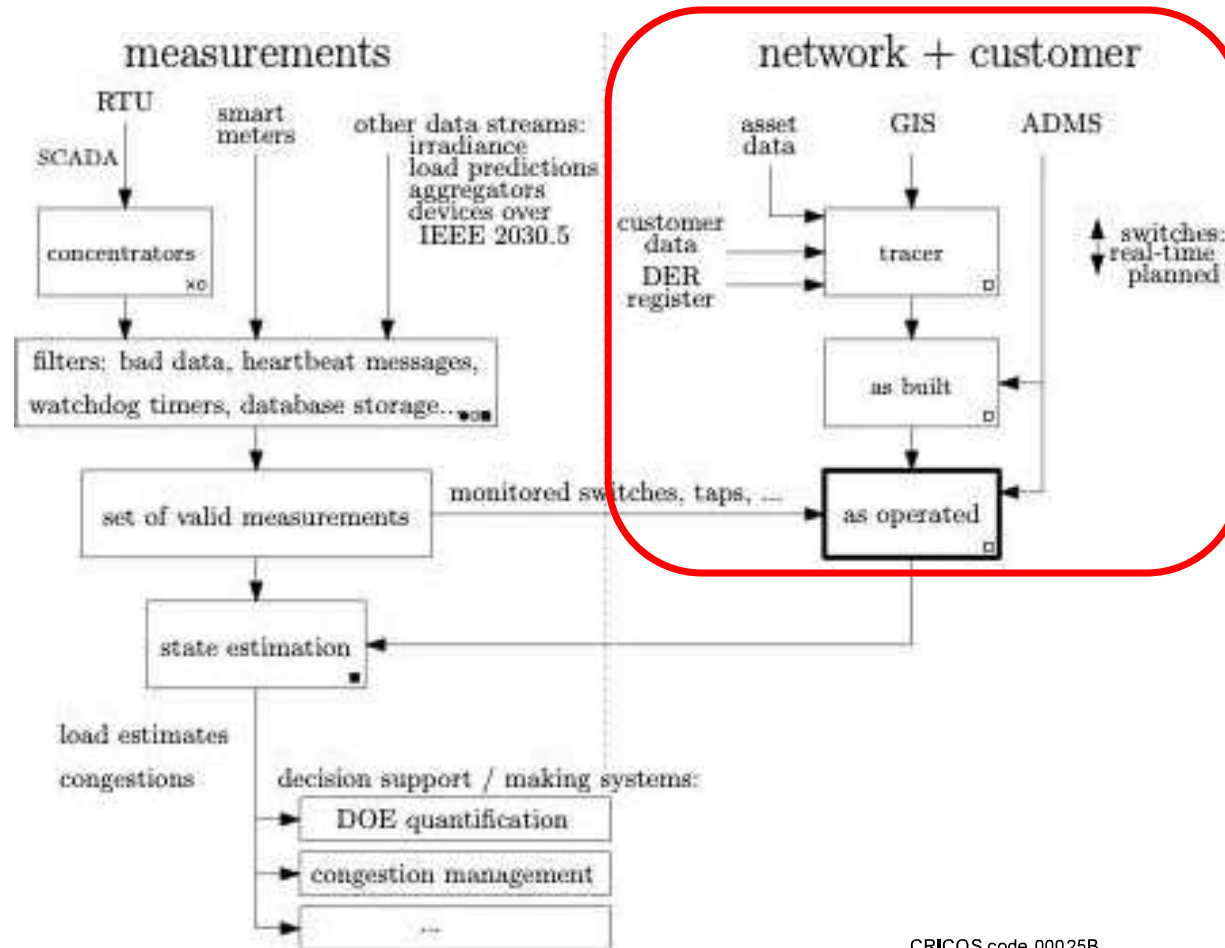
	Issue	Implications and risks
1	Missing phase labels (loads, transformers, etc.)	Inaccurate per-phase power flows, voltage unbalance inexact.
2	Switch states & user-branch connections	See issue 1 + impossible to determine how many consumers are connected to a transformer (aggregate values at feeder head inaccurate).
3*	Meter-to-transformer assignment	See issue 2.
4*	Excessive number of buses	Errors if reductions are performed, increased computational time.
5	Wrong transformer tap	Inaccurate estimates of: end-consumer voltages, hosting capacity, voltage-based curtailment.
6	Missing tap semantics	Taps are usually given integer values, the nominal value is generally not 0, the tap percentage can be unknown, see issue 5.
7*	Unknown vector group usage (ansi vs euro)	Sign error in angle off-set between primary and secondary for Dy transformers.
8*	Unknown winding configuration	Inaccurate voltage values, problematic for harmonic studies.
9*	Mislabeled transformer primary/secondary nominal voltage	See issue 5 + this also implies wrong transformer impedance (as they are typically specified in per unit w.r.t. the transformer power rating and primary voltage).
10*	Wrong transformer rating	Inaccurate classification of congestion; also implies inaccurate transformer impedance (as they are typically specified in per unit w.r.t. the transformer power rating and primary voltage).
11*	Only Kron-reduced impedance matrices available	Assumes neutral voltage rise is marginal under normal conditions, which is likely problematic in sparsely grounded networks. Not compatible with short circuit analysis.
12*	Only sequence impedances available	Equivalent to assuming transposition + multi-grounding of neutral in 4-wire networks.
13*	Meter-phase-alignment for three-phase users	Inaccurate SE and other measurement-based computations.
14*	Missing information on neutral grounding	Inaccurate voltage and current estimates, impact depends on grounding philosophy.
15	Load model (constant power, ZIP) unknown	Analyses may be inaccurate in terms of voltages, unbalance levels, neutral current.
16	Missing load (locations)	SE may increase load at the known locations, leading to inaccurate congestion identification.
17	Measurements rms vs fundamental-only	When using a fundamental-frequency-only (O)PF or SE, contributions of the higher frequencies to the RMS values may lead to inaccuracy.
18*	Regulators modelled as transformers	Impedance values differ between transformers and regulators, inaccurate voltages/currents.
19	Missing capacitor banks (specifications)	Reactive power flows / power factor for loads/generators look statistically unlikely.
20	Approximate cable/line impedance models	Inaccurate estimation of currents (particularly neutral current), and voltage drops.
21*	Unknown (PV) inverter settings	Constant power factor and volt-var/watt lead to very different patterns of overvoltage.
22*	Unknown home battery dispatch strategies	Complementarity between PV, batteries & load overestimated, inaccurate voltages/currents.

“Data quality challenges in existing distribution network datasets”, Geth F., Vanin M. & Van Hertem, D., CIRED, Rome, Italy, June 2023.
<https://arxiv.org/abs/2308.00487>

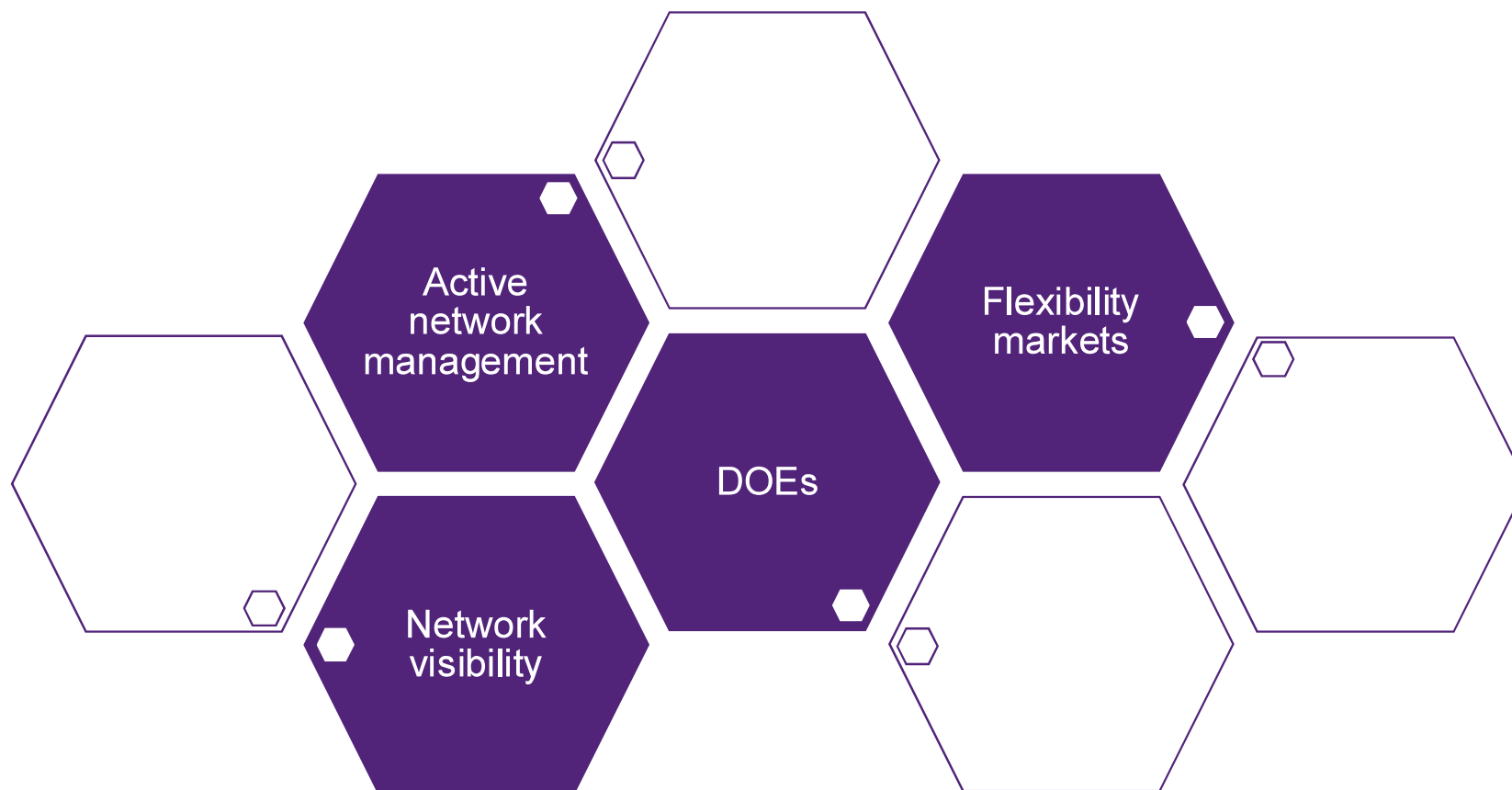
Recommendations

- well-defined semantics for the data models
- consistency checking of data sets, including tagging whether network data has been Kron-reduced or not
- user-friendly data debugging solutions

Visibility to enable DOE



Current developments in distribution

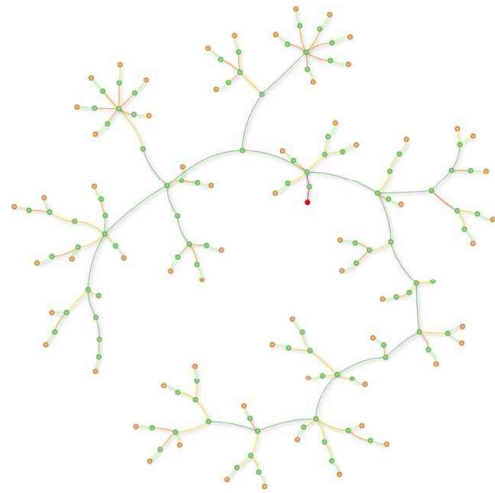


Enablers

- Open standards & interoperability
 - For communication (CSIP-Aus)
 - For modeling (CIM)
- Open source tools & collaboration
 - Validated, auditable power engineering decision support software

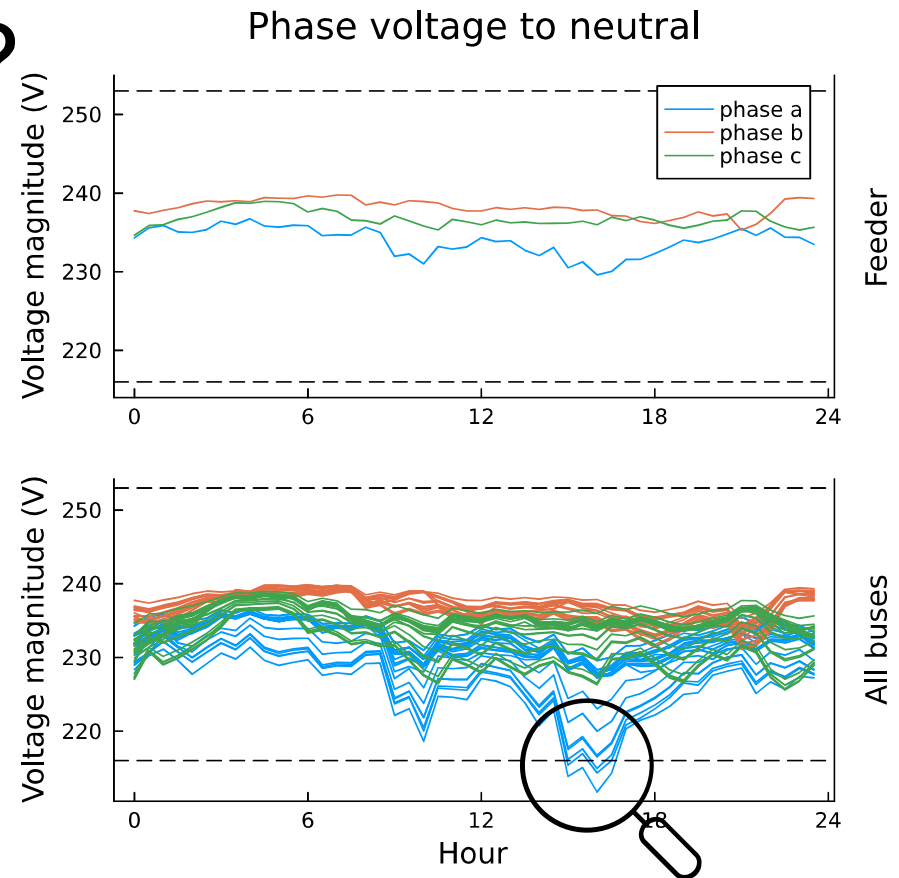
What is phase unbalance?

A distribution network with unbalanced loads



Low voltage feeder taxonomy
Network N

- Houses are connected to different phase
- Consumption is varied throughout the network
- **Unbalance prevents efficient utilization of network infrastructure**



Phase a voltage violates the limits, while other phases stay within the limits

Balanced and unbalanced phasors

Waveform

$$v = |v| \cos(\omega t + \angle v)$$



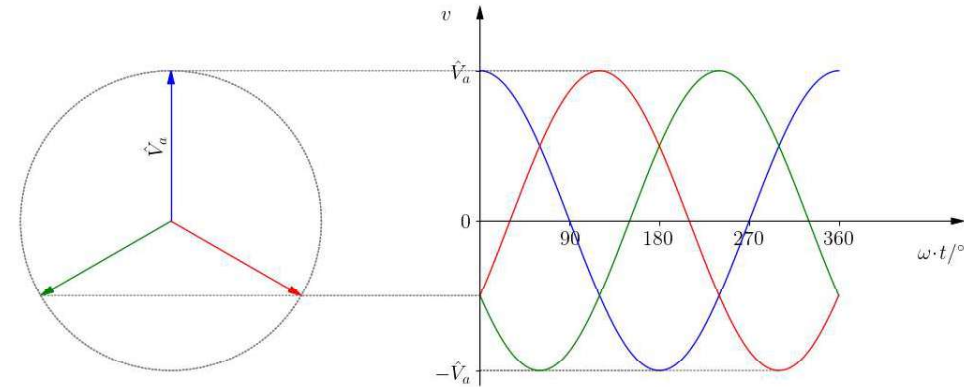
Complex cartesian

$$\begin{aligned} v &= v_{re} + im\ v_{im} \\ v_{re} &= |v| \cos(\angle v) \\ v_{im} &= |v| \sin(\angle v) \end{aligned}$$



Phasor polar

$$v = |v| e^{j\angle v}$$



3 scalars into

$$\begin{aligned} v_a &= |v_a| \angle v_a \\ v_b &= |v_b| \angle v_b \\ v_c &= |v_c| \angle v_c \end{aligned}$$



1 vector

$$\mathbf{v} = \begin{bmatrix} |v_a| \angle v_a \\ |v_b| \angle v_b \\ |v_c| \angle v_c \end{bmatrix} = |\mathbf{v}| \angle \mathbf{v}$$

Balanced and unbalanced phasors

Synchronous generators set phase angles differences

Balanced:

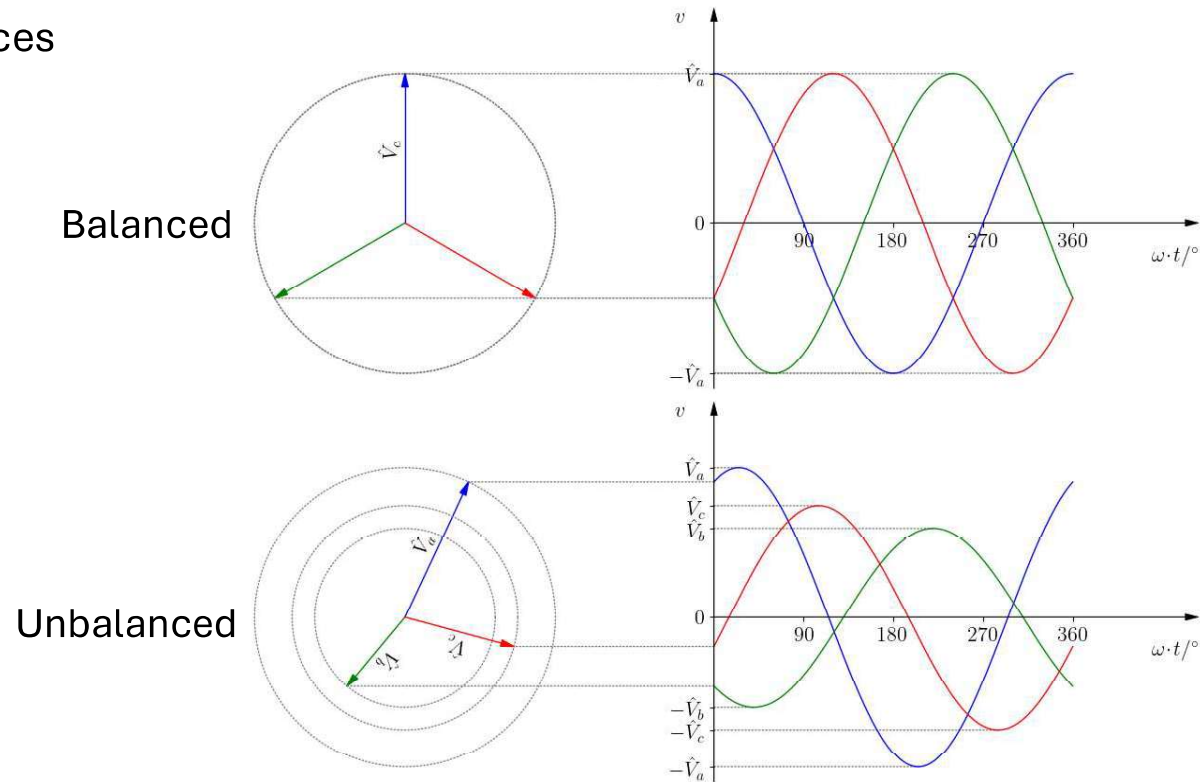
- 120° angle difference between the phases
- same magnitude
- close to 1 pu

Unbalanced:

- phase angle difference between the phases different from 120°
- different magnitudes

Unbalance implies ineffective use of the network's transfer capacity

- avoidable network losses
- worse voltage drop/increase



Balanced and unbalanced phasors

Symmetrical components

Zero sequence \leftarrow

Positive sequence \leftarrow

Negative sequence \leftarrow

$$\begin{bmatrix} V0 \\ V1 \\ V2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} Va \\ Vb \\ Vc \end{bmatrix}, \alpha = e^{\frac{2}{3}\pi i}$$

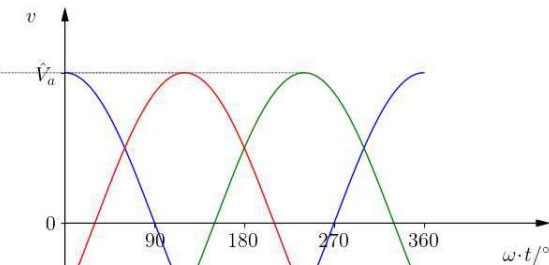
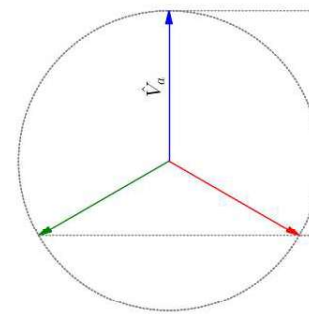
$$\begin{bmatrix} V0 \\ V1 \\ V2 \end{bmatrix} = \begin{bmatrix} 0 + 0im \\ 1 + 0im \\ 0 + 0im \end{bmatrix}$$

$$\begin{bmatrix} V0 \\ V1 \\ V2 \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}$$

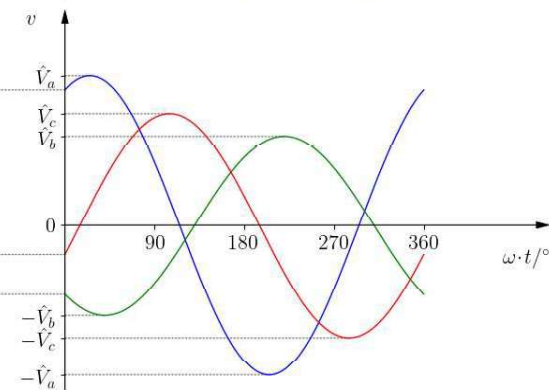
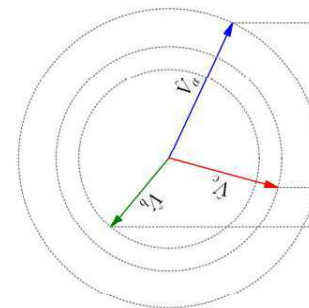
$$\begin{bmatrix} V0 \\ V1 \\ V2 \end{bmatrix} = \begin{bmatrix} 0.0842 + 0.2538im \\ 0.7315 + 0.0078im \\ 0.0906 + 0.1611im \end{bmatrix}$$

$$\begin{bmatrix} V0 \\ V1 \\ V2 \end{bmatrix} = \begin{bmatrix} 0.2674 \\ 0.7316 \\ 0.1848 \end{bmatrix}$$

Balanced



Unbalanced



Balanced and unbalanced phasors

Symmetrical components

Zero sequence \leftarrow

Positive sequence \leftarrow

Negative sequence \leftarrow

$$\begin{bmatrix} V0 \\ V1 \\ V2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} Va \\ Vb \\ Vc \end{bmatrix}, \alpha = e^{\frac{2}{3}\pi i}$$

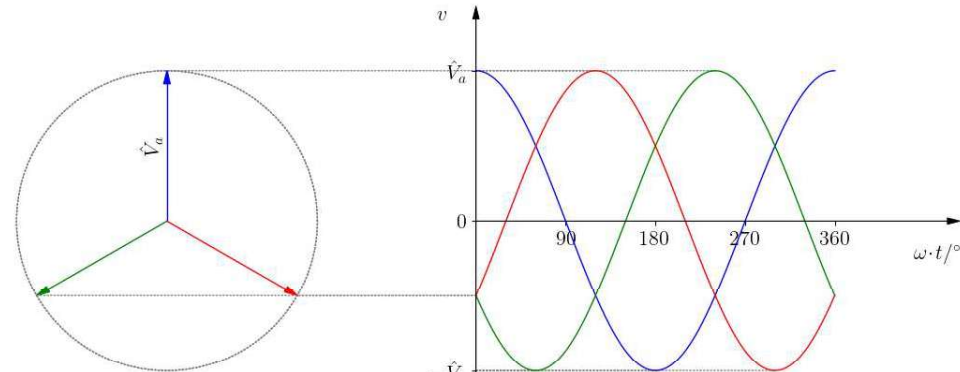
$$\begin{bmatrix} V0 \\ V1 \\ V2 \end{bmatrix} = \begin{bmatrix} 0 + 0im \\ 1 + 0im \\ 0 + 0im \end{bmatrix}$$

$$\begin{bmatrix} V0 \\ V1 \\ V2 \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}$$

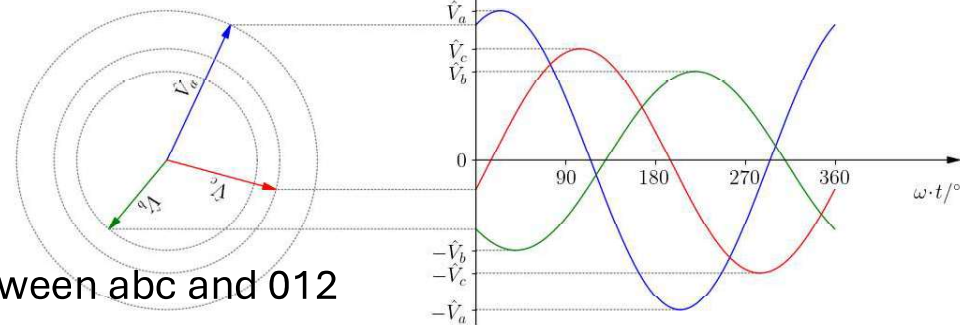
$$\begin{bmatrix} V0 \\ V1 \\ V2 \end{bmatrix} = \begin{bmatrix} 0.0842 + 0.2538im \\ 0.7315 + 0.0078im \\ 0.0906 + 0.1611im \end{bmatrix}$$

$$\begin{bmatrix} V0 \\ V1 \\ V2 \end{bmatrix} = \begin{bmatrix} 0.2674 \\ 0.7316 \\ 0.1848 \end{bmatrix}$$

Balanced



Unbalanced



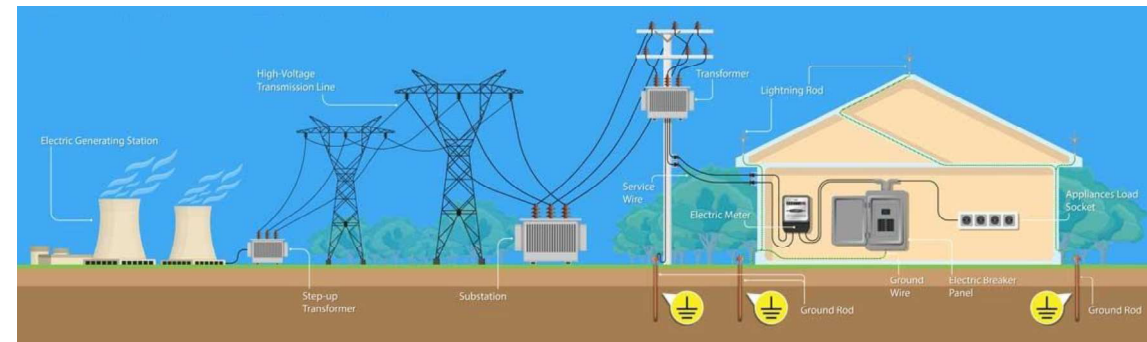
Note:

- For volt/current phasors, there is a one-to-one relationship between abc and 012 coordinates

Neutral conductor grounding

Bonding the neutral conductor voltage to the potential of the earth.

- Never close to perfect, or
- Very expensive to bring it close to zero impedance

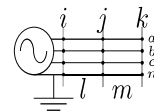


Neutral conductor grounding

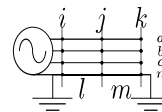
Network neutral grounding configuration variants

Bonding the neutral conductor voltage to the potential of the earth.

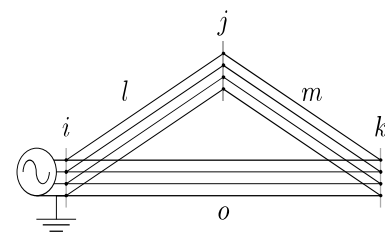
- Never close to perfect, or
- Very expensive to bring it close to perfect.
- **Grounding points in the network**
- **Single, multiple**



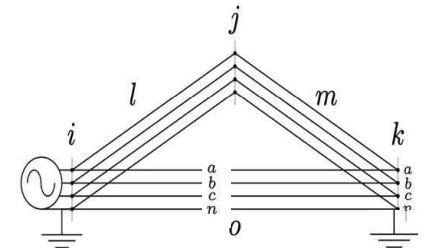
single-grounded radial



multi-grounded radial



single-grounded meshed.



multi-grounded mesh

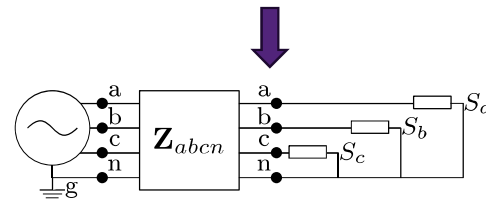
- LV Multi-grounded -> Australia, UK, US
- LV Single grounded -> Germany, Belgium

Neutral conductor grounding

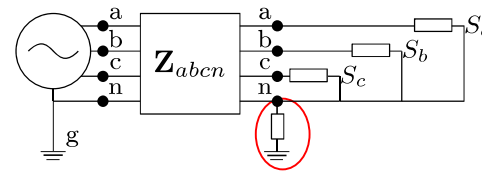
Bonding the neutral conductor voltage to the potential of the earth.

- Never close to perfect, or
- Very expensive to bring it close to perfect.
- Grounding points in the network
 - Single, multiple
- **Neutral conductor grounding**
 - **Floating, Solid, Perfect**

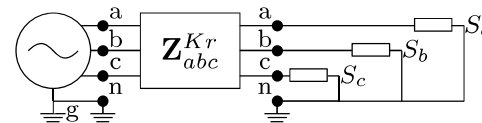
4-wire network



No ground
No grounding of neutral at load bus



Solid grounding
Grounding of neutral at load bus

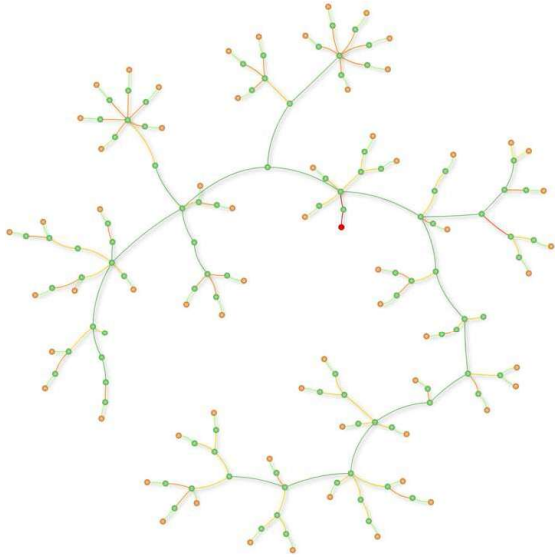


Perfect grounding
Grounding of neutral at load bus

Neutral conductor grounding

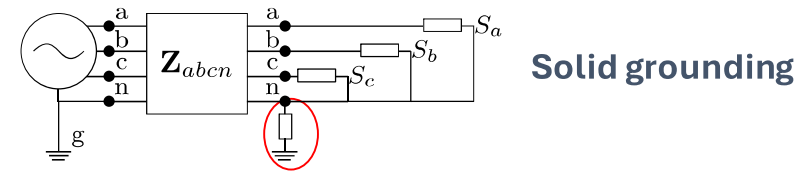
Assume all LV nodes have solid grounding.

This is still an **optimistic** model.



The smaller the network, the more difference in neutral grounding

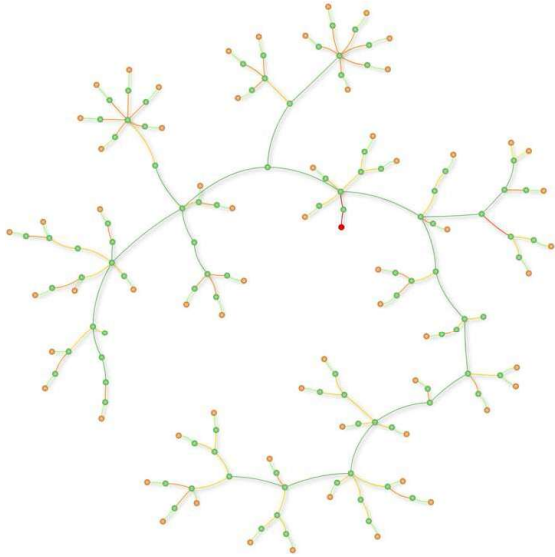
Neutral to ground impedance



Neutral conductor grounding

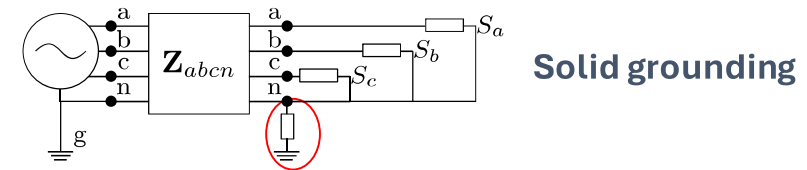
Assume all LV nodes have solid grounding.

This is still an **optimistic** model.

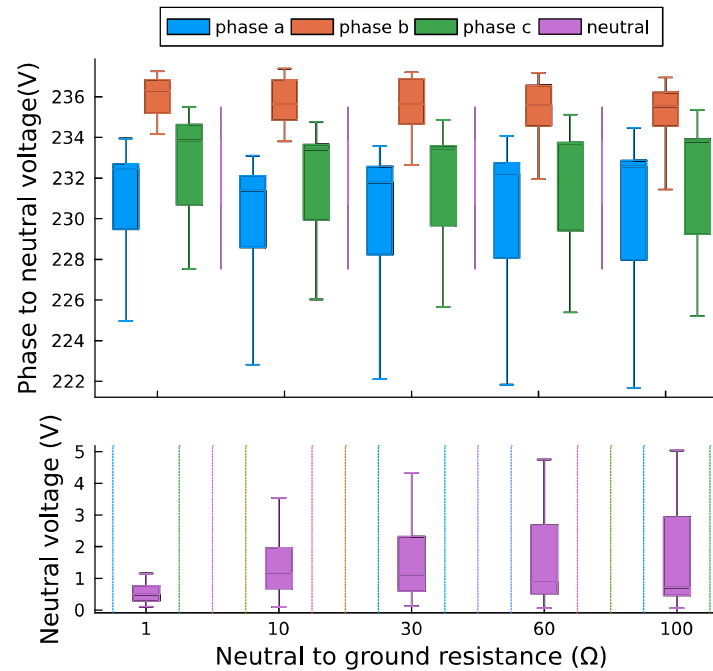


The smaller the network, the more difference in neutral grounding

Neutral to ground impedance



Impact of neutral to ground resistance



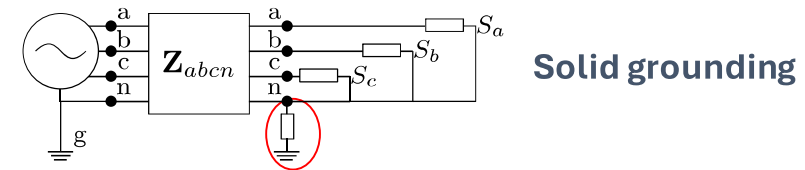
Neutral conductor grounding

Assume all LV nodes have solid grounding.

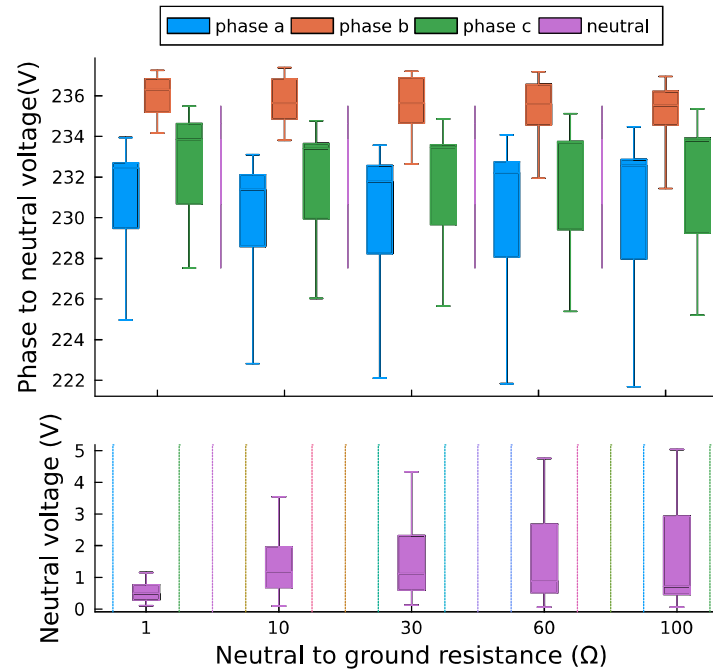
This is still an **optimistic** model.

- A non-zero neutral conductor voltage decreases the power you can transfer before you hit the limits
 - significant under-estimation of voltage magnitude problems
 - over or under-estimation of voltage unbalance

Neutral to ground impedance



Impact of neutral to ground resistance



Network components

Buses

Power delivery elements

- Transformers
- Cables and overhead lines
- Switches and breakers

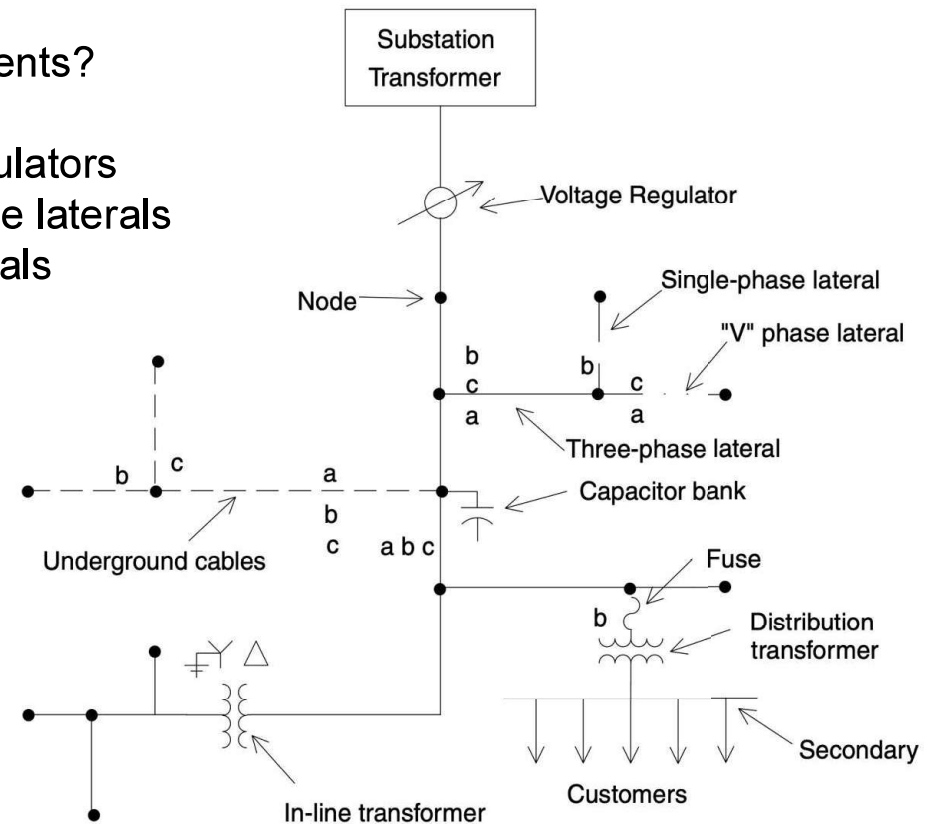
Power conversion elements

- Generators (distributed)
- Loads
- Shunts (capacitor banks)
- Storage
- EV

Inverters

Other components?

- Fuses
- Voltage regulators
- Single-phase laterals
- SWER laterals



Bus / terminals / branches



buses have nodes for each of the conductors

- bus i , node a, b, c, n, g

ground = 0 V, everything is defined relative to that

i

- a
- b phases
- c
- n neutral
- g ground

Bus / terminals / branches



buses have nodes for each of the conductors

- bus i , node a, b, c, n, g

ground = 0 V, everything is defined relative to that

ground is generally implicit

i

- a
- b phases
- c
- n neutral
- g ground

i

- a
- b phases
- c
- n neutral
- g ground

Bus / terminals / branches



not all buses are three-phase *with* neutral conductor

without neutral, loads/generators need to be connected in 'delta',

e.g. between a and b.

i

- a
- b phases
- c
- n neutral
- g ground

i

- a
- b phases
- c
- n neutral
- g ground

i

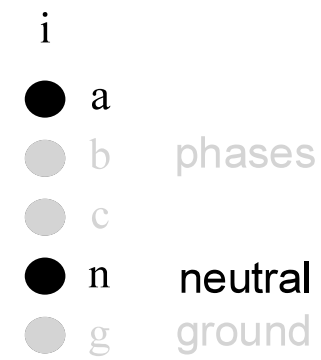
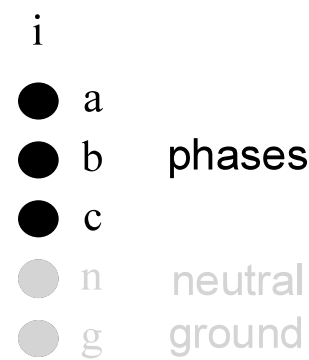
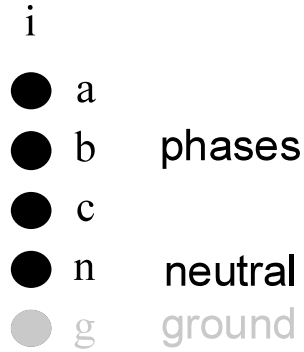
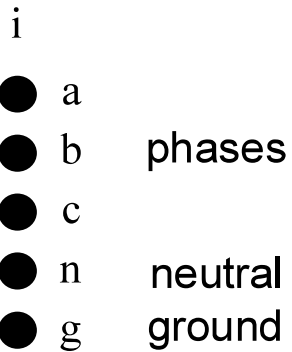
- a
- b phases
- c
- n neutral
- g ground

Bus / terminals / branches



branches can be single-phase, two-phase as well

e.g. single-phase load between phase b and neutral ('wye'-connected)



Bus / terminals / branches



i

- a
- b phases
- c
- n neutral
- g ground

i

- a
- b phases
- c
- n neutral
- g ground

i

- a
- b phases
- c
- n neutral
- g ground

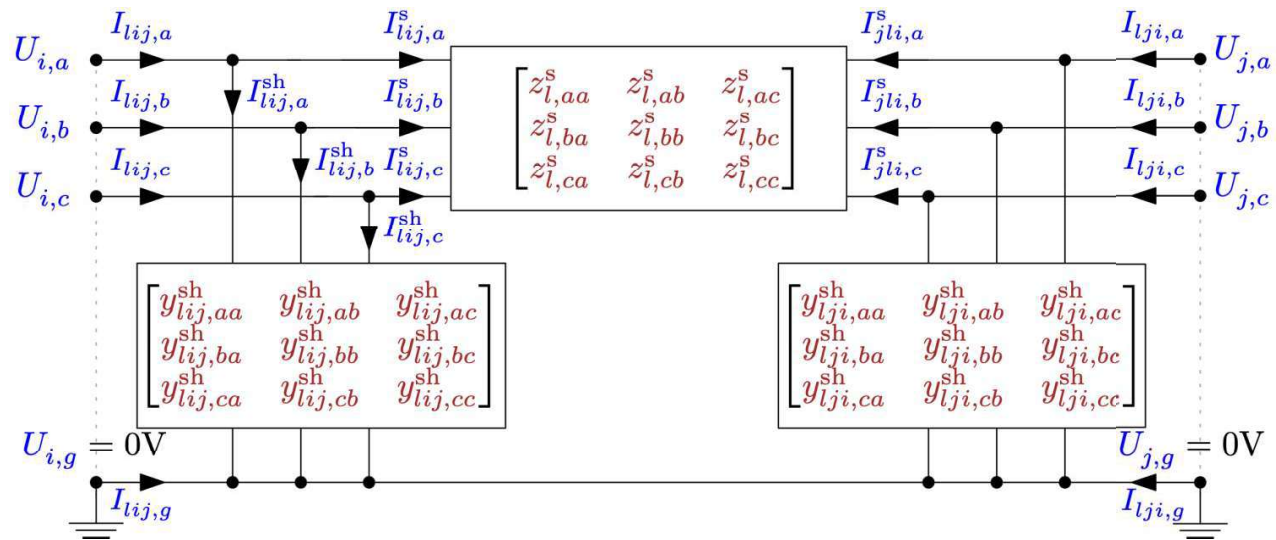
i

- a
- b phases
- c
- n neutral
- g ground

i

- a
- b phases
- c
- n neutral
- g ground

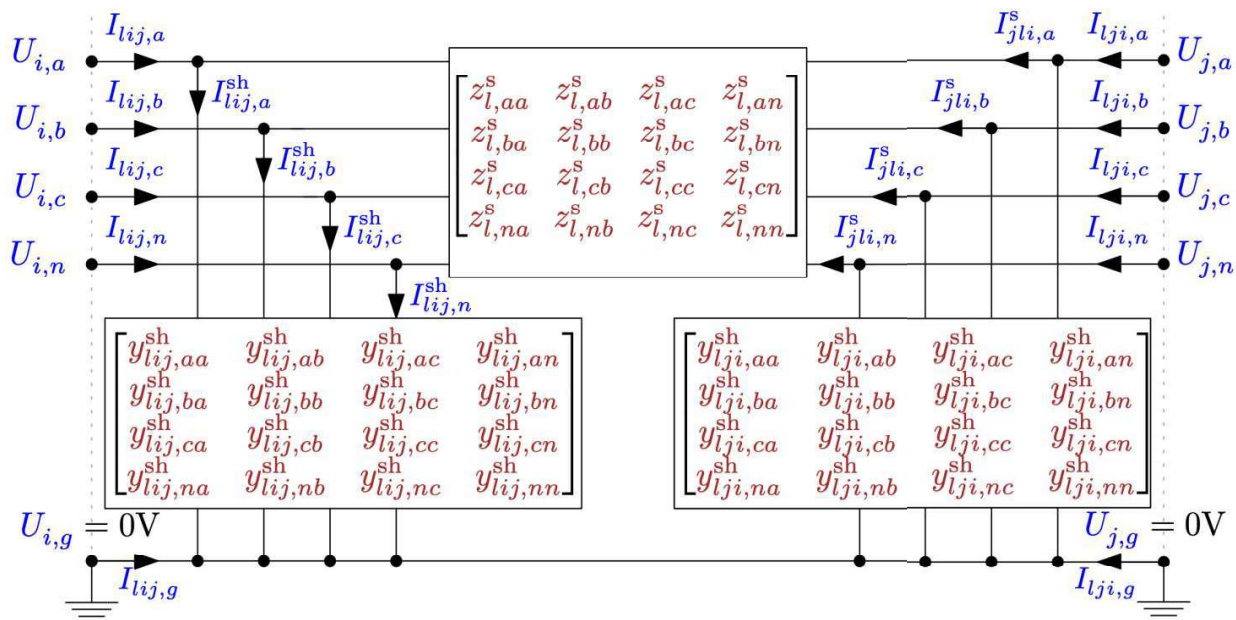
3-wire branch



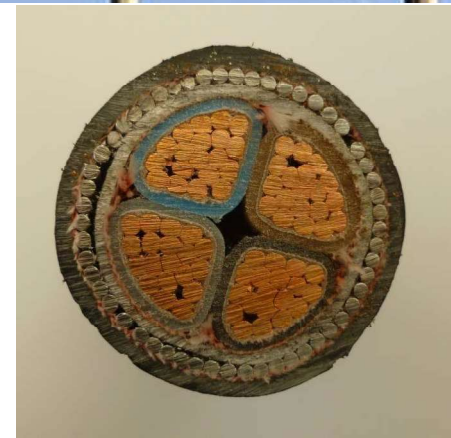
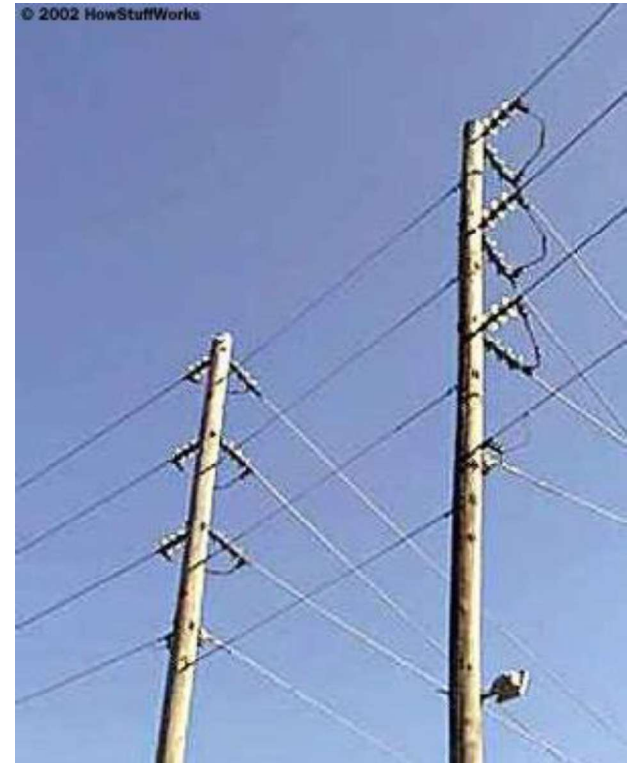
$2 \times 3 \times 9$ real parameters per branch



4-wire branch



2 x 3 x 16 real parameters per branch



CRICOS code 00025B

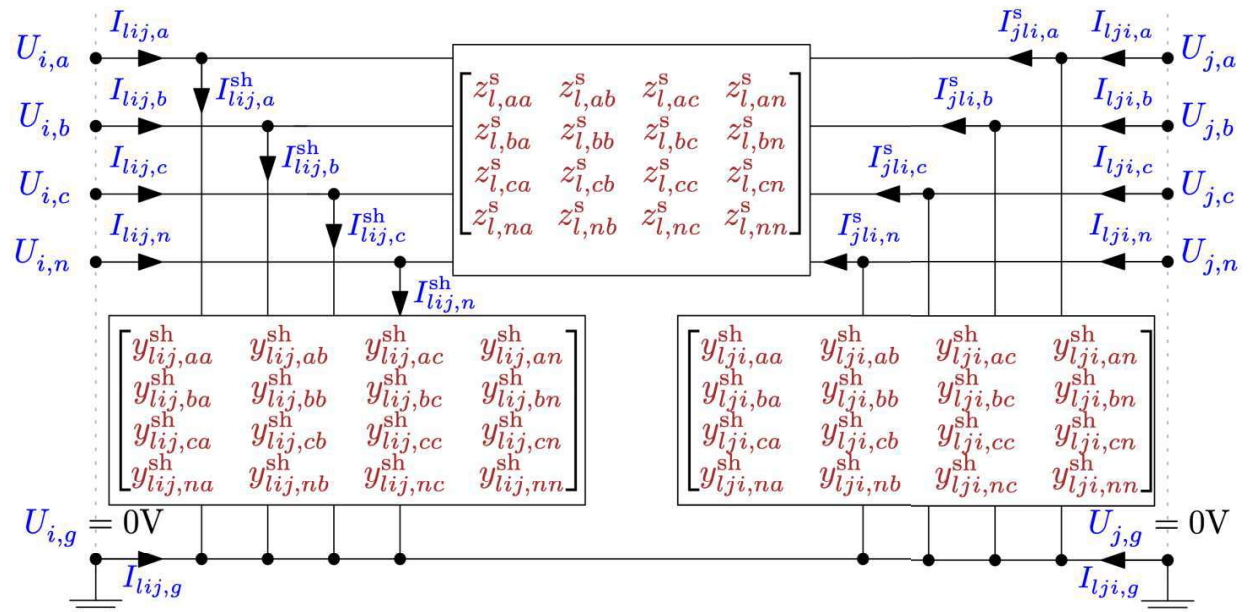
4-wire branch

node voltage $\mathbf{U}_i = \begin{bmatrix} U_{i,a} \\ U_{i,b} \\ U_{i,c} \\ U_{i,n} \end{bmatrix}$

line current $\mathbf{I}_{lij} = \begin{bmatrix} I_{lij,a} \\ I_{lij,b} \\ I_{lij,c} \\ I_{lij,n} \end{bmatrix}$

line power $\mathbf{S}_{lij} = \begin{bmatrix} P_{lij,aa} + jQ_{lij,aa} & P_{lij,ab} + jQ_{lij,ab} & P_{lij,ac} + jQ_{lij,ac} \\ P_{lij,ba} + jQ_{lij,ba} & P_{lij,bb} + jQ_{lij,bb} & P_{lij,bc} + jQ_{lij,bc} \\ P_{lij,ca} + jQ_{lij,ca} & P_{lij,cb} + jQ_{lij,cb} & P_{lij,cc} + jQ_{lij,cc} \end{bmatrix}$

power flow $\mathbf{S}_{lij} = \mathbf{U}_i (\mathbf{I}_{lij})^H = \mathbf{P}_{lij} + j\mathbf{Q}_{lij}$



4-wire branch

$$\mathbf{U}_j = \mathbf{U}_i - \mathbf{z}_l^S \mathbf{I}_{lij}^S.$$

$$\mathbf{I}_{lij} = \mathbf{y}_{lij}^{sh} \mathbf{U}_i + \mathbf{I}_{lij}^S.$$

$$\mathbf{I}_{lji} = \mathbf{y}_{lji}^{sh} \mathbf{U}_j + \mathbf{I}_{lji}^S.$$

$$\mathbf{I}_{lij}^S = -\mathbf{I}_{lji}^S.$$

Bounds

$$\mathbf{U}_i^{\min} = \begin{bmatrix} U_{i,a}^{\min} \\ U_{i,b}^{\min} \\ U_{i,c}^{\min} \end{bmatrix} \leq \begin{bmatrix} |U_{i,a}| \\ |U_{i,b}| \\ |U_{i,c}| \end{bmatrix} \leq \begin{bmatrix} U_{i,a}^{\max} \\ U_{i,b}^{\max} \\ U_{i,c}^{\max} \end{bmatrix} = \mathbf{U}_i^{\max}$$

$$\begin{bmatrix} |I_{lij,a}| \\ |I_{lij,b}| \\ |I_{lij,c}| \end{bmatrix} \leq \begin{bmatrix} I_{lij,a}^{\text{rated}} \\ I_{lij,b}^{\text{rated}} \\ I_{lij,c}^{\text{rated}} \end{bmatrix} = \mathbf{I}_{lij}^{\text{rated}}$$

$$\begin{bmatrix} |S_{lij,aa}| \\ |S_{lij,bb}| \\ |S_{lij,cc}| \end{bmatrix} \leq \begin{bmatrix} S_{lij,a}^{\text{rated}} \\ S_{lij,b}^{\text{rated}} \\ S_{lij,c}^{\text{rated}} \end{bmatrix} = \mathbf{S}_{lij}^{\text{rated}}$$

Kirchhoff's current law

Transmission network

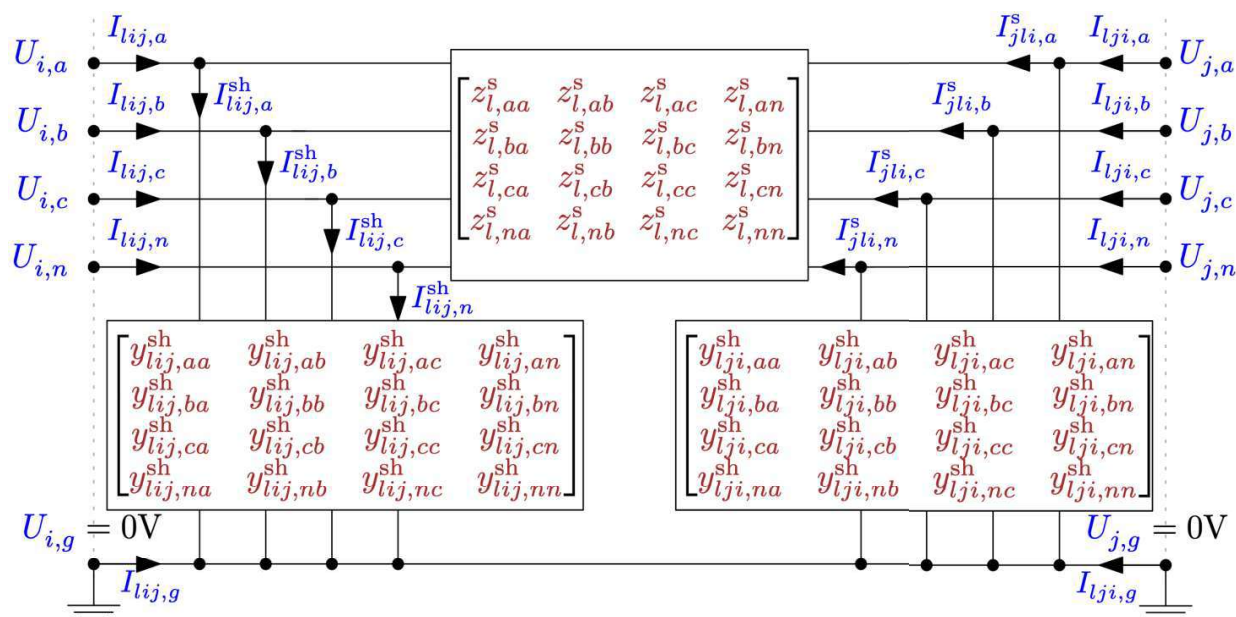
$$U_j = U_i - z_l^S I_{lij}^S$$

complex scalars

Distribution multiconductor network

$$\mathbf{U}_j = \mathbf{U}_i - \mathbf{z}_l^S \mathbf{I}_{lij}^S$$

complex vectors and matrices



Loads

Given a setpoint and load model, we want to derive current and voltage

- E.g. 1kW + j0.5 kvar between phase and neutral, for each phase.

Configuration

- Delta
- Wye

Model

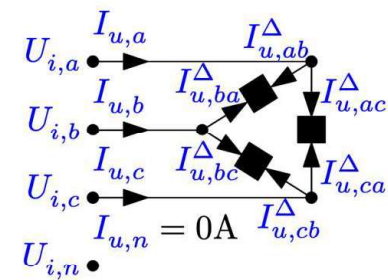
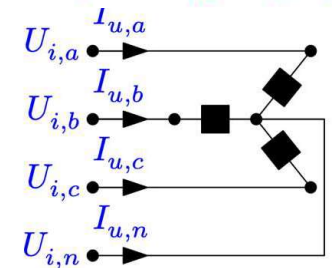
- Constant power
- Constant current
- Constant impedance
- Exponential
- ...

$$\begin{bmatrix} I_{d,a} \\ I_{d,b} \\ I_{d,c} \end{bmatrix} \leftarrow \begin{bmatrix} (S_{d,a}^{\text{ref}} / (U_{i,a} - U_{i,n}))^* \\ (S_{d,b}^{\text{ref}} / (U_{i,b} - U_{i,n}))^* \\ (S_{d,c}^{\text{ref}} / (U_{i,c} - U_{i,n}))^* \end{bmatrix}$$

$$\begin{bmatrix} S_{d,a} \\ S_{d,b} \\ S_{d,c} \end{bmatrix} \leftarrow \begin{bmatrix} S_{d,a}^{\text{ref}} \frac{|U_{i,a} - U_{i,n}|}{U_{d,a}^{\text{ref}}} \\ S_{d,b}^{\text{ref}} \frac{|U_{i,b} - U_{i,n}|}{U_{d,b}^{\text{ref}}} \\ S_{d,c}^{\text{ref}} \frac{|U_{i,c} - U_{i,n}|}{U_{d,c}^{\text{ref}}} \end{bmatrix} \rightarrow \begin{bmatrix} I_{d,a} \\ I_{d,b} \\ I_{d,c} \end{bmatrix} \leftarrow \begin{bmatrix} (S_{d,a} / U_{i,a})^* \\ (S_{d,b} / U_{i,b})^* \\ (S_{d,c} / U_{i,c})^* \end{bmatrix}$$

$$I_{d,n} \leftarrow -(I_{d,a} + I_{d,b} + I_{d,c})$$

$$U_i \circ (I_u)^* = S_u^{\text{ref}} = P_u^{\text{ref}} + jQ_u^{\text{ref}}$$



[F. Geth, S. Clayes, R. Heidari, "On the Implementation of the Fixed Point Iteration Current Injection Method to Solve Four-Wire Unbalanced Power Flow in PowerModelsDistribution.jl"]