“Emerging approaches in distribution network optimization”
30 Jan 2026 Newcastle

EPICS Tutorial

Workshop

- Hands-on session to give exposure to modeling challenges and solutions in the distribution network space
- Showcase the opportunities to build on collaborative open-source toolboxes for distribution network simulation and optimization
- Showcase workflows using *git* to accomplish effective collaboration
- We will take an approach building on the *JuMP* toolbox in the *Julia* programming language, using off-the-shelf algorithms for simulation and optimization, with a focus on domain-specific applications through *PowerModelsDistribution* and *OpenDSSDirect*

Agenda

- Overall timing 9am - 3pm
  - Part 1: 9am-noon (with coffee break)
    - talks with slides, provide installation guidelines just before lunch
  - lunch noon-1pm
    - You can install VSCode, Julia, git
  - Part 2: 1pm-3pm
    - installfest, mostly guided but self-study, no general presentation

Audience

- We assumed
  - Electrical engineering or computer science background
  - Familiarity with linear algebra and complex numbers
  - Anyone interested in these topics
    - Ph.D. candidates, postdocs, early career researchers, vacation students

- BYOD – Bring your own device (laptop)

Goals

- Help you understand what is happening in Australian distribution networks
- Help you see the opportunities of moving from simulation to optimization thinking
- Generate excitement on scientific collaboration on open-source toolboxes for power systems research
- Give you the confidence to experiment with
  - Distribution network data sets for Australia
  - Modeling capabilities of OpenDSS(direct) and PowerModelsDistribution
  - Optimisation problem statements such as *distribution state estimation and dynamic operating envelope* quantification
- Share slides, background materials and contact details

Talks Content

- Introduction to power sector in Australia
- Challenges in distribution networks
- Modeling challenges
- From simulation to optimization modeling
  - What is mathematical optimisation
  - Multiconductor & multiperiod OPF, SE, DOEs
- Installfest: OpenDSSDirect and PowerModelsDistribution
- Get some examples running? E.g. GPST DOE code or something similar (https://github.com/frederikgeth/GPSTTopic82024/)

Who am I?

- Prof. Fred(erik) Geth
- Bachelor of Science EE/CS, Master of Science & PhD EE-power systems, all at KU Leuven (Belgium)
- PhD 2014 “Battery storage integration in distribution networks”
- Developed an EV integration optimization software tool at Tractebel 2014-2015
- Research lab EnergyVille 2016-2018
- Moved to Newcastle Australia and worked with national lab (CSIRO) 2018-2022
- Startup GridQube in Brisbane 2022 – mid 2025
- Love cycling (bikepacking) and skiing

Who am I?

- Julio Braslavsky
- Electronics Engineer 1989 National University of Rosario, Argentina
- PhD 1996 Electrical Engineering (Control Systems) University of Newcastle, Australia
- Postdoc: Université Catholique de Louvain-la-Neuve 1996 Belgium, University of California Santa Barbara 1997
- Senior Research Scientist CSIRO 2010. Senior Principal Research Scientist 2024
- Love cooking, camping, dancing (tango)

CSIRO

Who am I?

- James Foster
- Mathematics and Science, University of Newcastle, Australia
- PhD 2014 Mathematical Optimisation with Power Flow Applications
- Postdoc: University of Wisconsin-Madison
- Research Scientist CSIRO 2019, Senior Research Scientist CSIRO 2025.
- Love reading, hiking, games with my kids

CSIRO

Who am I?

- Gregor Verbic
- BSc and MSc in Electrical Engineering, University of Ljubljana, Slovenia
- PhD (2003) on voltage stability, University of Ljubljana, Slovenia
- Postdoc: University of Waterloo (2005)
- Moved to Australia in 2010
- Professor of Electrical Engineering at the University of Sydney
- Love everything outdoors

Landscape of electricity networks in Australia

Australian Energy Market Operator (AEMO)

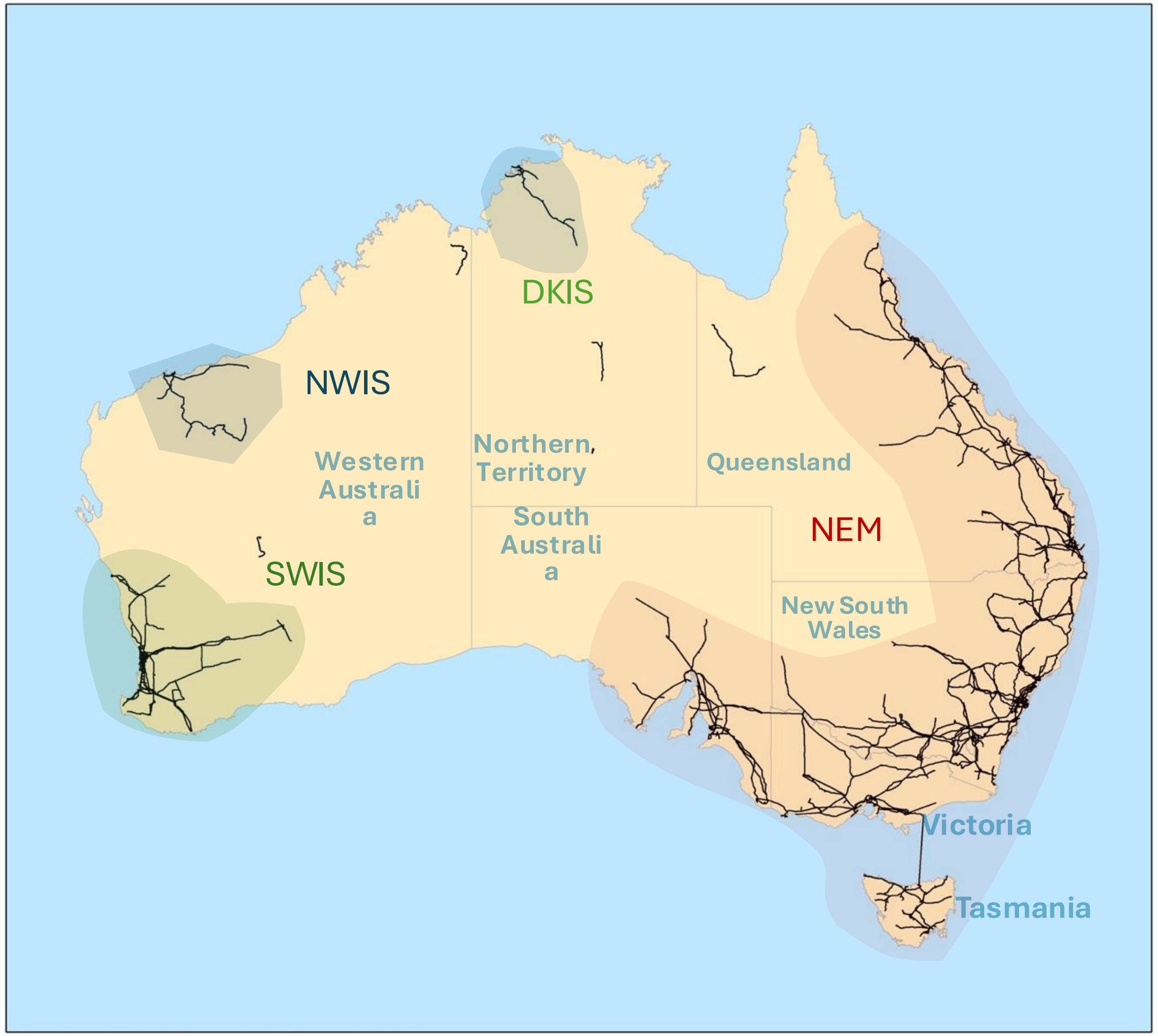
NEM (National Energy Market)
80 GW generation capacity
15 - 35 GW demand
5-minute dispatch energy market
Security constrained economic dispatch with co-optimised ancillary services

AEMO

SWIS (South-West Interconnected System)
5.8 GW generation capacity
Wholesale electricity trading and a capacity market

NWIS (North-West Interconnected System)

DKIS (Darwin-Katherine Interconnected System)
Numerous smaller systems

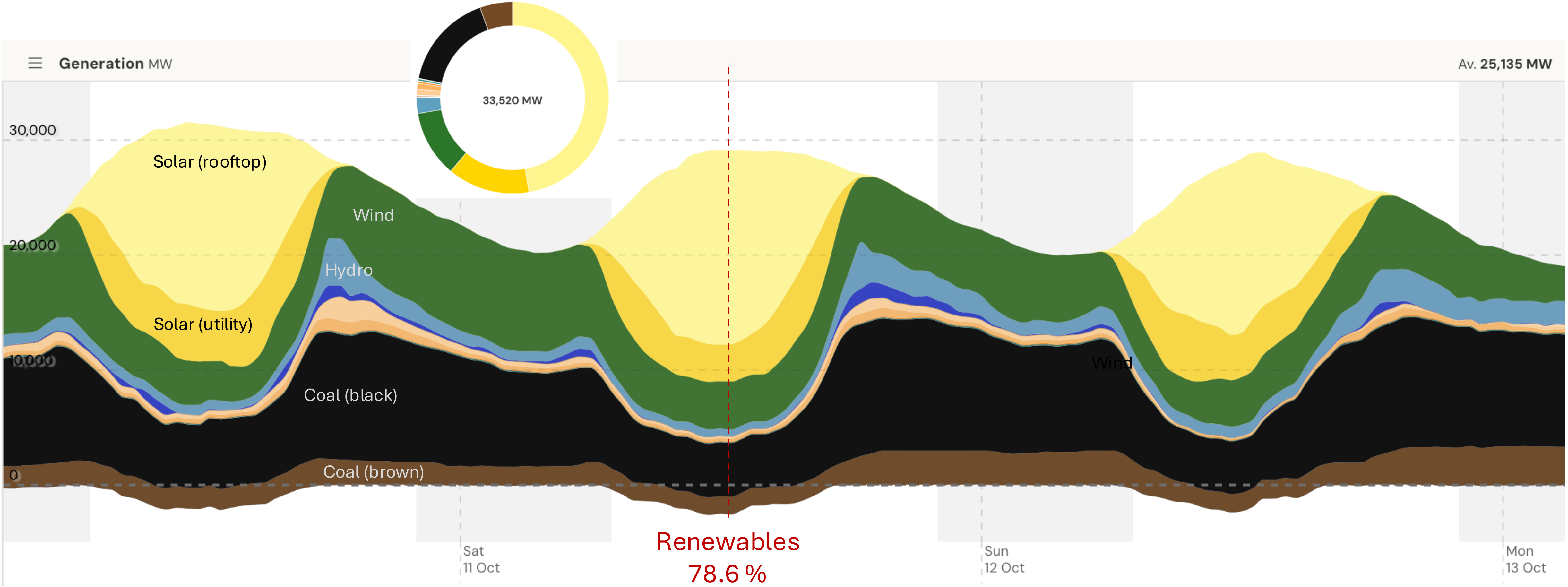


This map was created by Geoscience Australia on: Thursday, 23 February 2017

Renewables are rapidly displacing coal and gas generation

About 40% of Australian homes today have rooftop PV – capable of meeting 50 % underlying energy demand across the NEM in a sunny day

Current national record highest renewables generation over a day on Saturday 11 Oct 2025

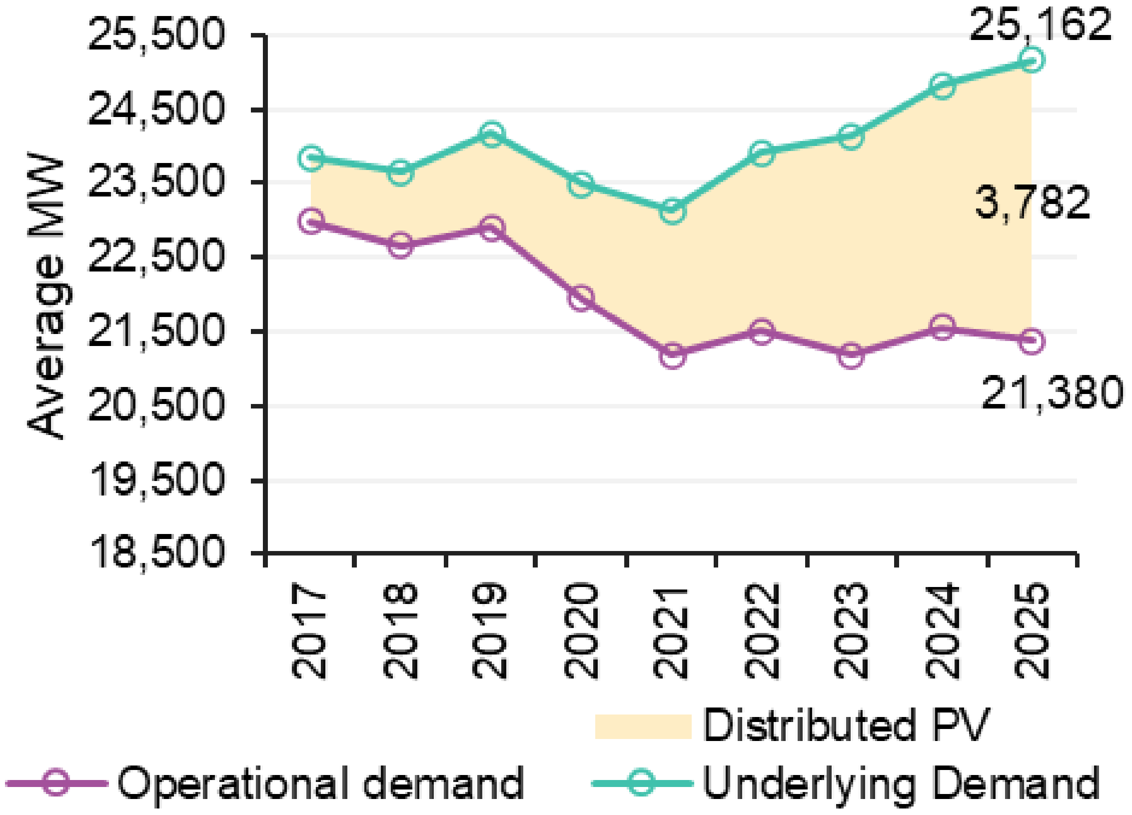


System operational challenges from high-level distributed PV

The growth of distributed PV has been reducing **operational demand** – needed to maintain minimum levels of dispatchable synchronous generation online

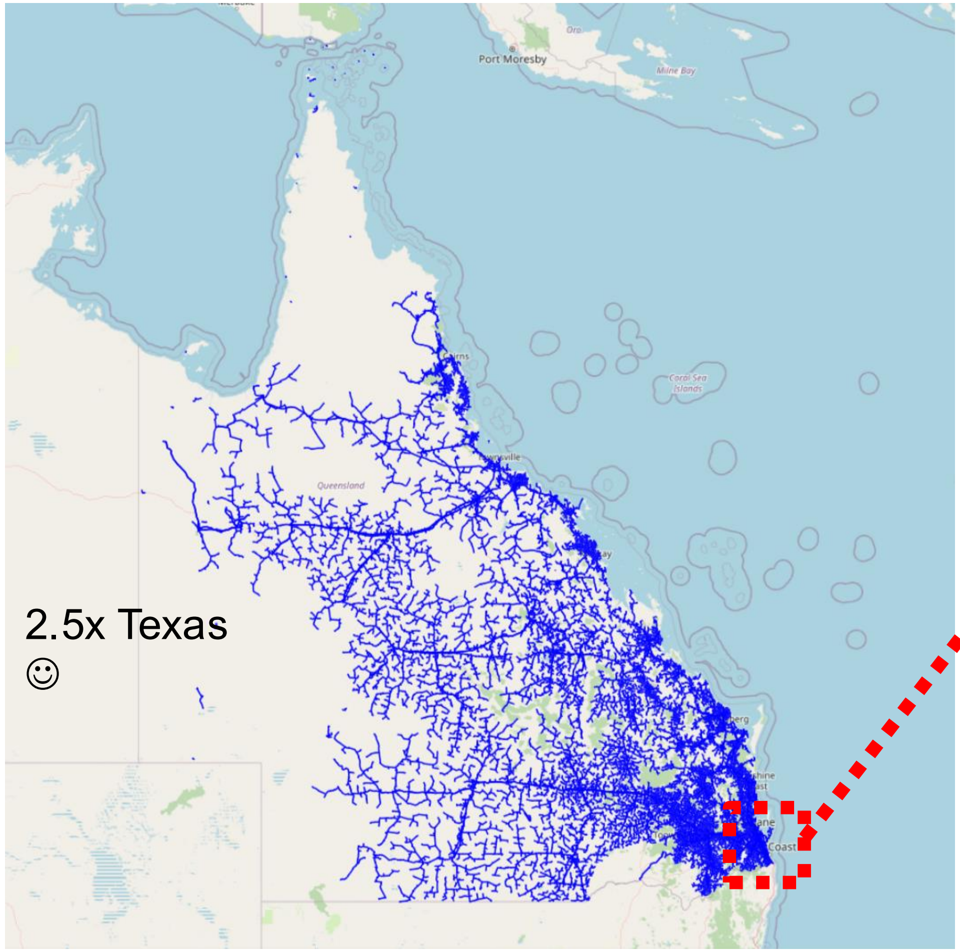
Today less than 5 % of (more than 4 million) rooftop PV inverters in Australia are controllable (standard AS/NZS 4777.2-

Without mitigating actions, high-PV generation at low-demand times pose risks to voltage and frequency controllability



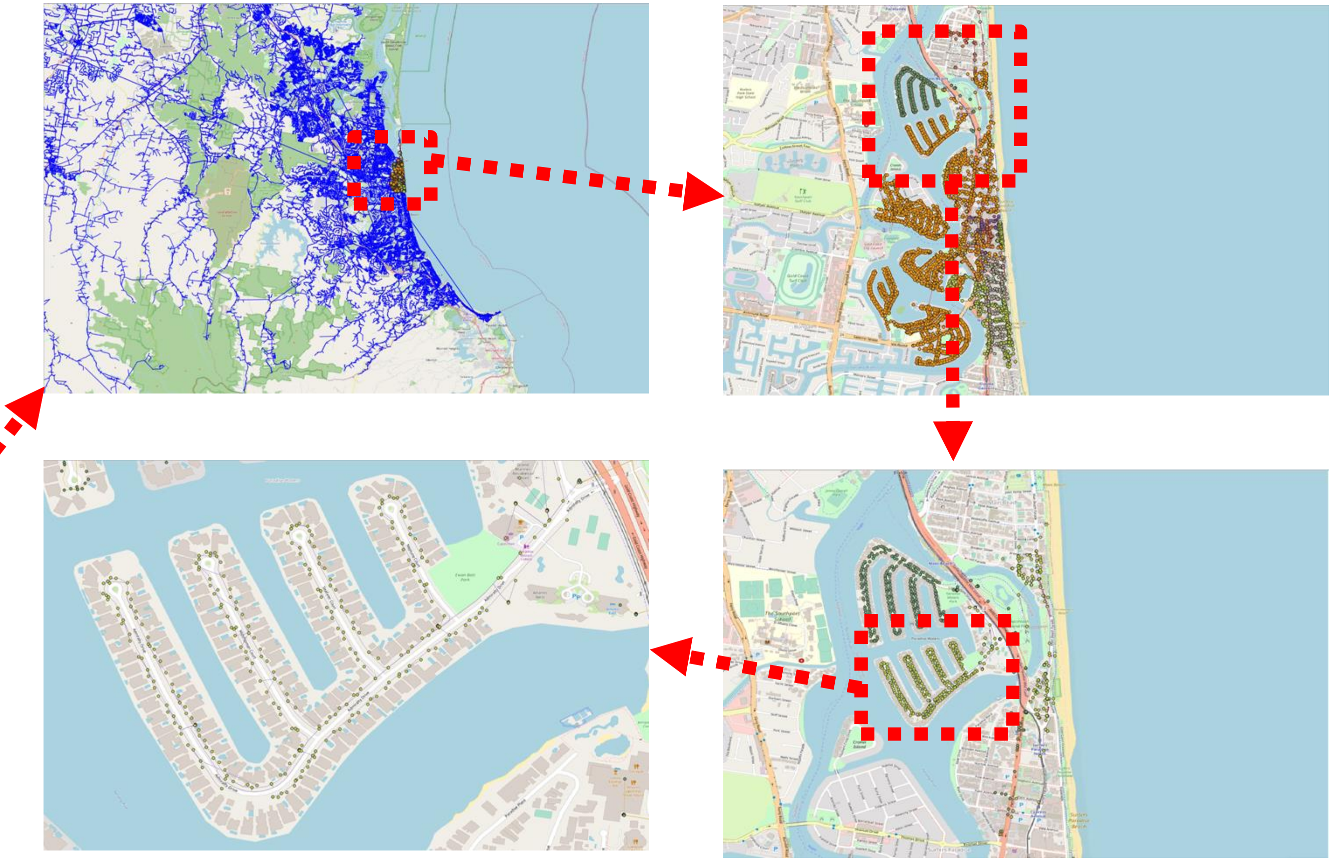
AEMO Quarterly Energy Dynamics (Q1 2025)

Distribution systems (& data sets) are huge



2.5x Texas
☺

~14.5 million objects - ~30 million electrical nodes



Consequences for networks **not** ready for fast growth of DER

“Use as little electricity as possible between four and nine”

Dutch government TV campaign “Flip the switch”

“8,000 companies are currently waiting to be able to feed in electricity, while 12,000 others are waiting for permission to use more power.”

Tennet, the government-owned agency that runs the Netherlands' national grid

Countries Ranked by Watt per person

Rank (by W/person)	Country	Installed Solar (MW, 2024)	Annual Growth (2023–24)	W per person
1	Australia	38,472	15.6%	1,426
2	Netherlands	24,048	13.0%	1,336

https://ourworldindata.org/grapher/solar-electricity-per-capita

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Netherlands' renewables drive putting pressure on its power grid

16 October 2025

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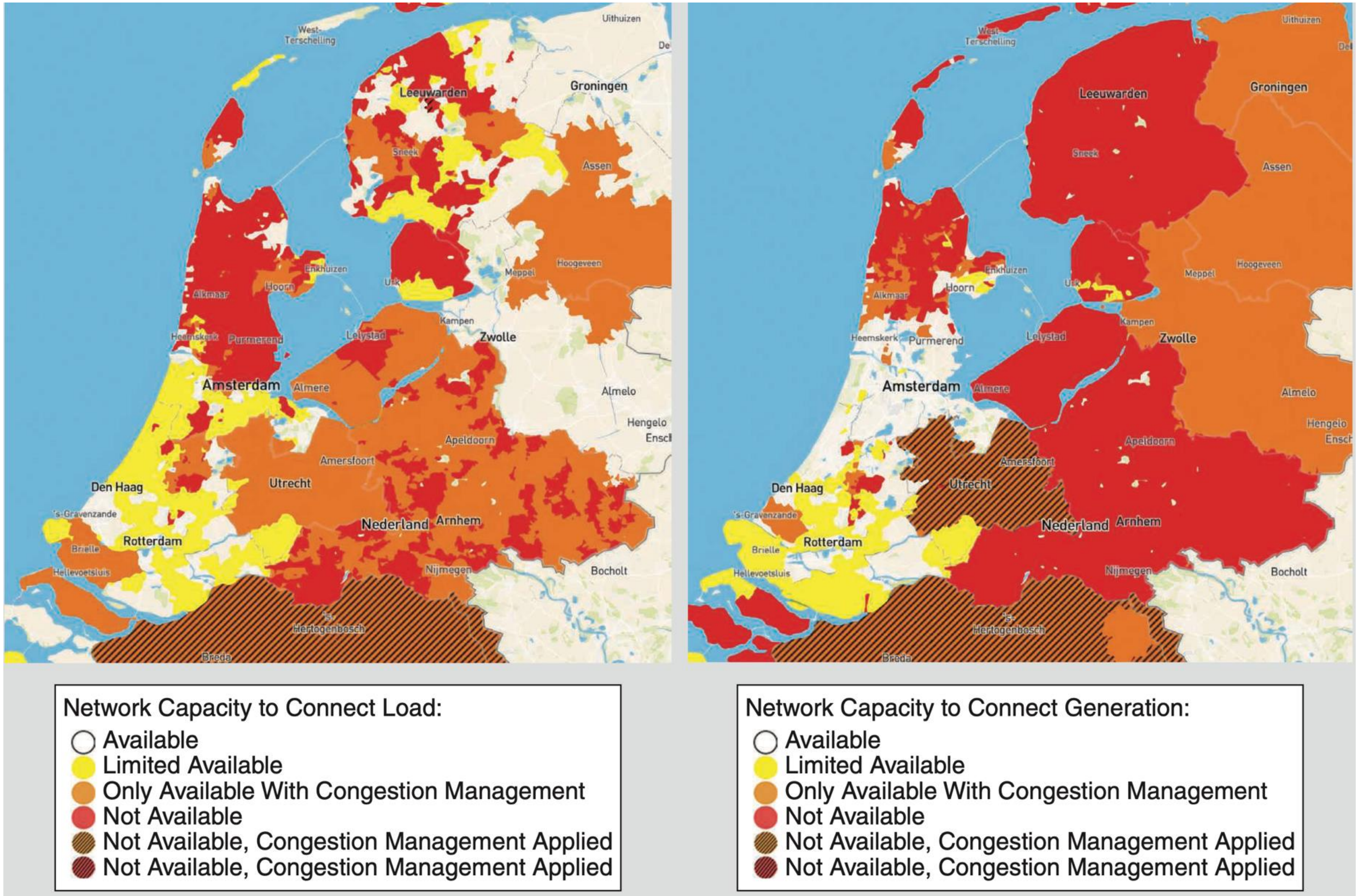
John Laurenson
Business reporter, Rotterdam

The Netherlands has raced to switch to wind and solar power

Distribution network congestion is reality



https://capaciteitskaart.netbeheernederland.nl/

Why focus on distribution systems?

In countries like Australia, **this is where the action is**

- A transformation driven by consumers adoption of DER (Distributed Energy Resources)
- DER bring opportunities and challenges
- Seizing the opportunities and resolving the challenges requires investment and new ways to plan and operate the network

Dynamic operating envelopes (DOEs)

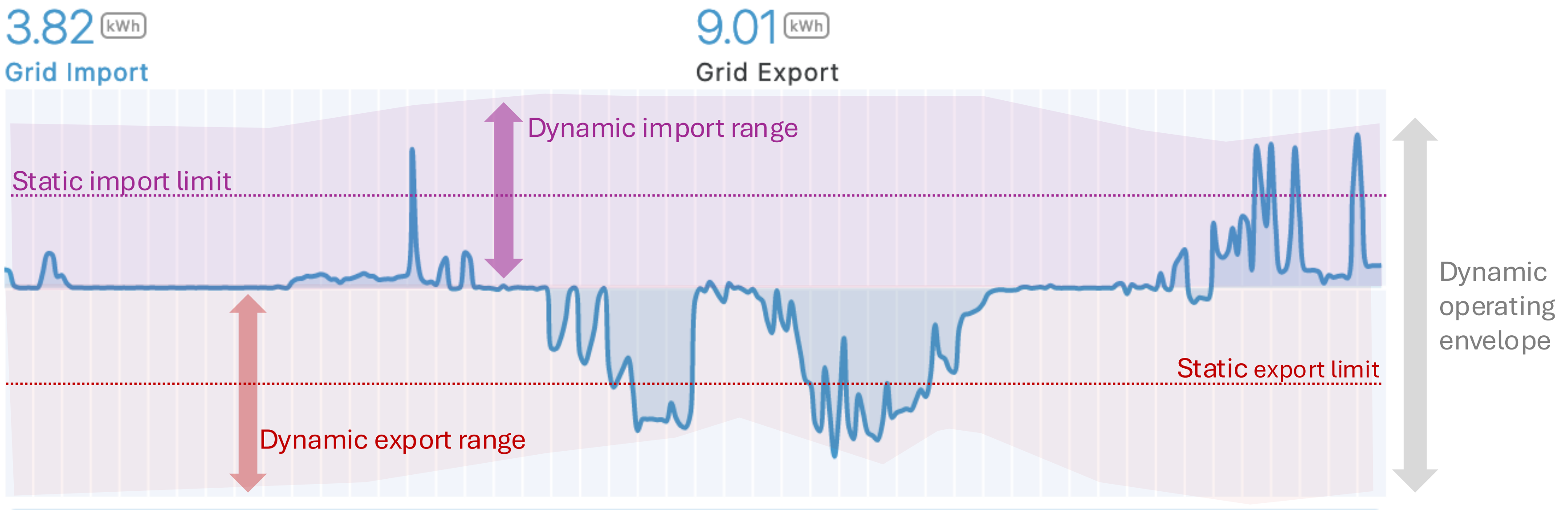
Allow DER to play a greater role in energy markets and the grid

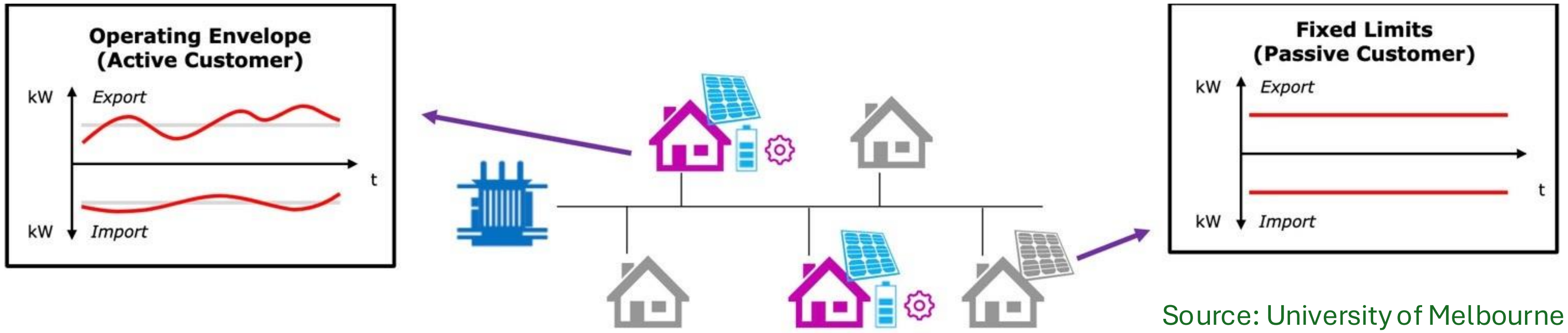
Set dynamically:

1-5-minute intervals,

24 hours in advance

Define time-varying, locational limits to the power that a consumer can import / export to the grid at a given moment



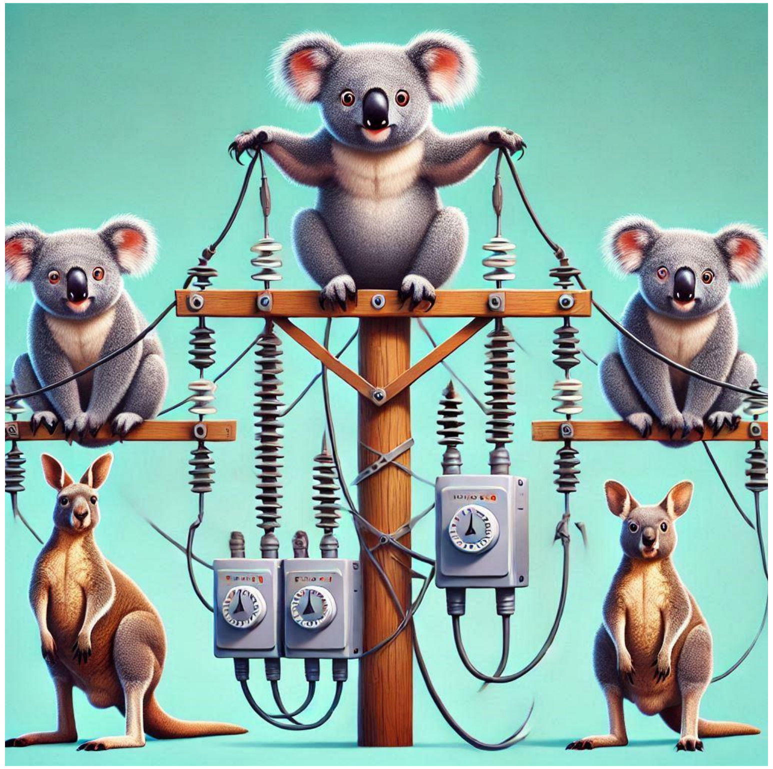


Source: University of Melbourne

DOEs are essential to realise the value of DER at scale

What about Australian networks?

- MV is typically three-wire three-phase or single-wire earth return (SWER)
  - Overhead lines and underground cables
  - No transposition of lines
- LV feeder (backbone) is typically three-phase four-wire OH/UG
  - Laterals to customers single or three-phase
  - Split-phase 2x230V when downstream of SWER
- Multi-earthed neutral grounding philosophy
  - <1 Ohm at sub, <10 Ohm at customer connection



Batteries

- Home batteries and large scale well

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RENEW ECONOMY

CLEAN ENERGY NEWS AND ANALYSIS

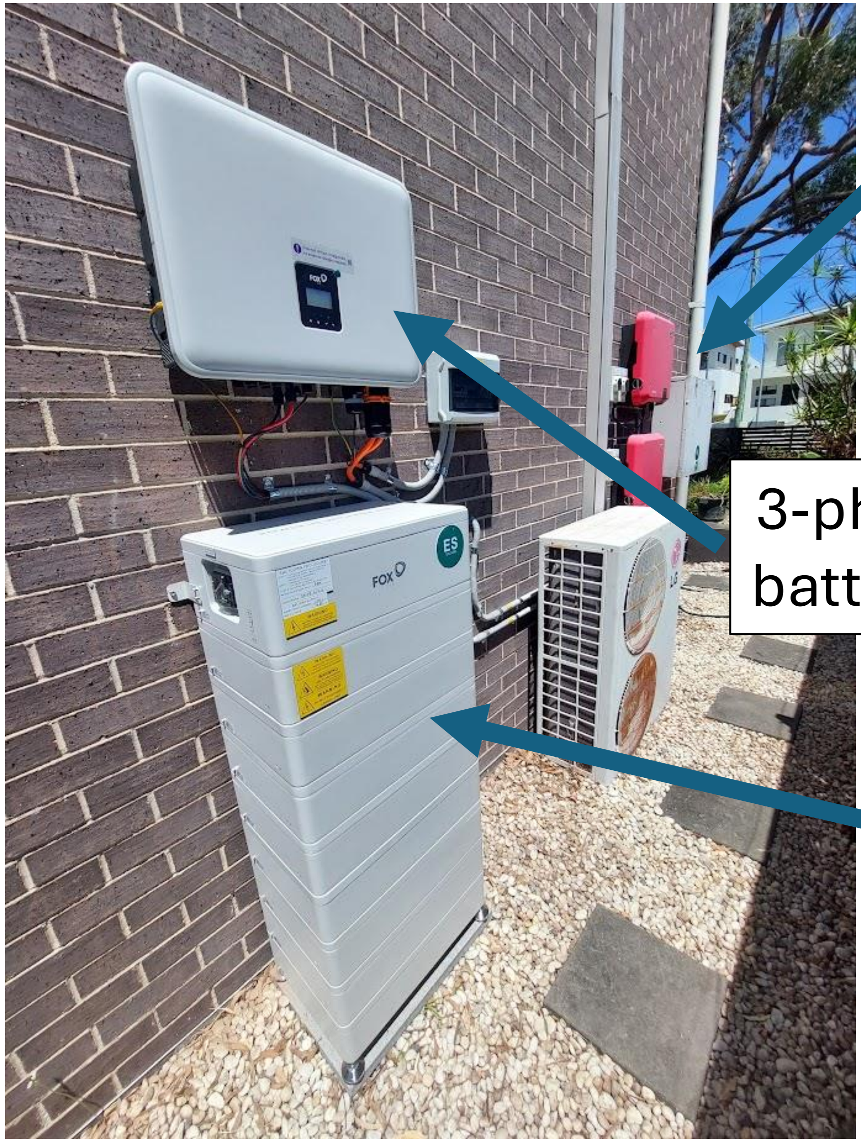
Thursday, January 29, 2026

Home Wind Solar Storage Electrification Commentary Podcasts Maps All | The Driven

Home » Commentary » Home battery installations will match the scale of Snowy Hydro scheme – in a single year

Home battery installations will match the scale of Snowy Hydro scheme – in a single year

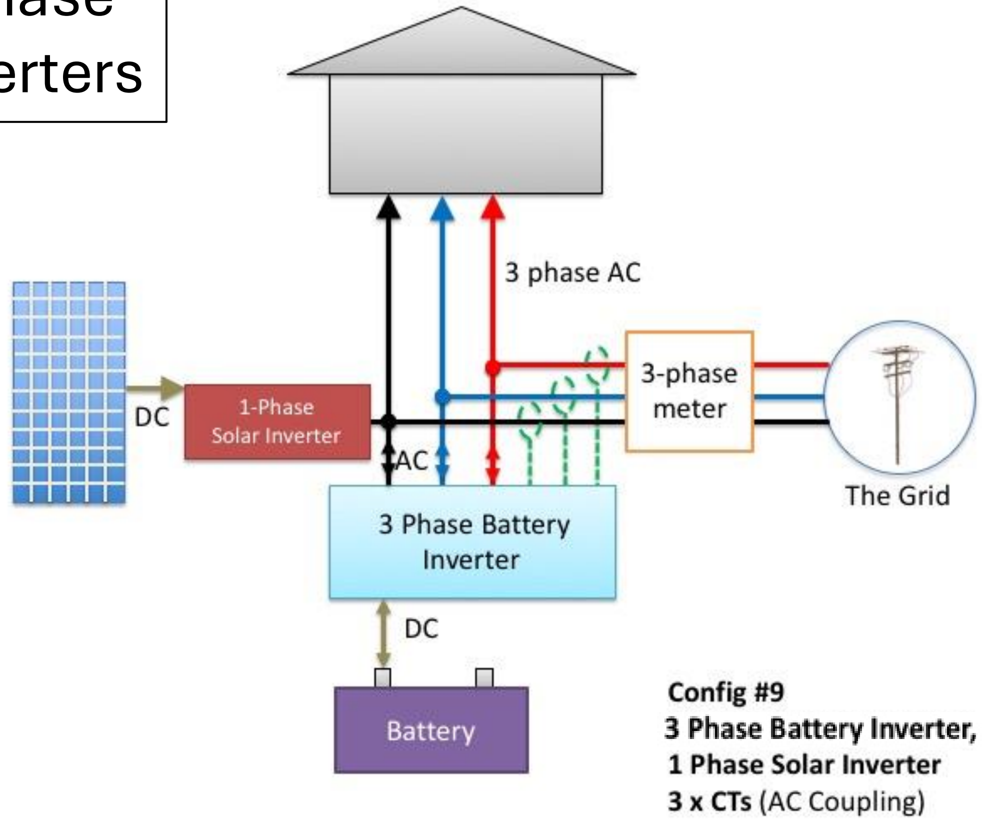
Three-phase battery inverter with a single-phase solar inverter



2 single-phase 5kW PV inverters

3-phase 15kW battery inverter

42 kWh battery



solarquotes.com.au

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 achieveable*
- *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

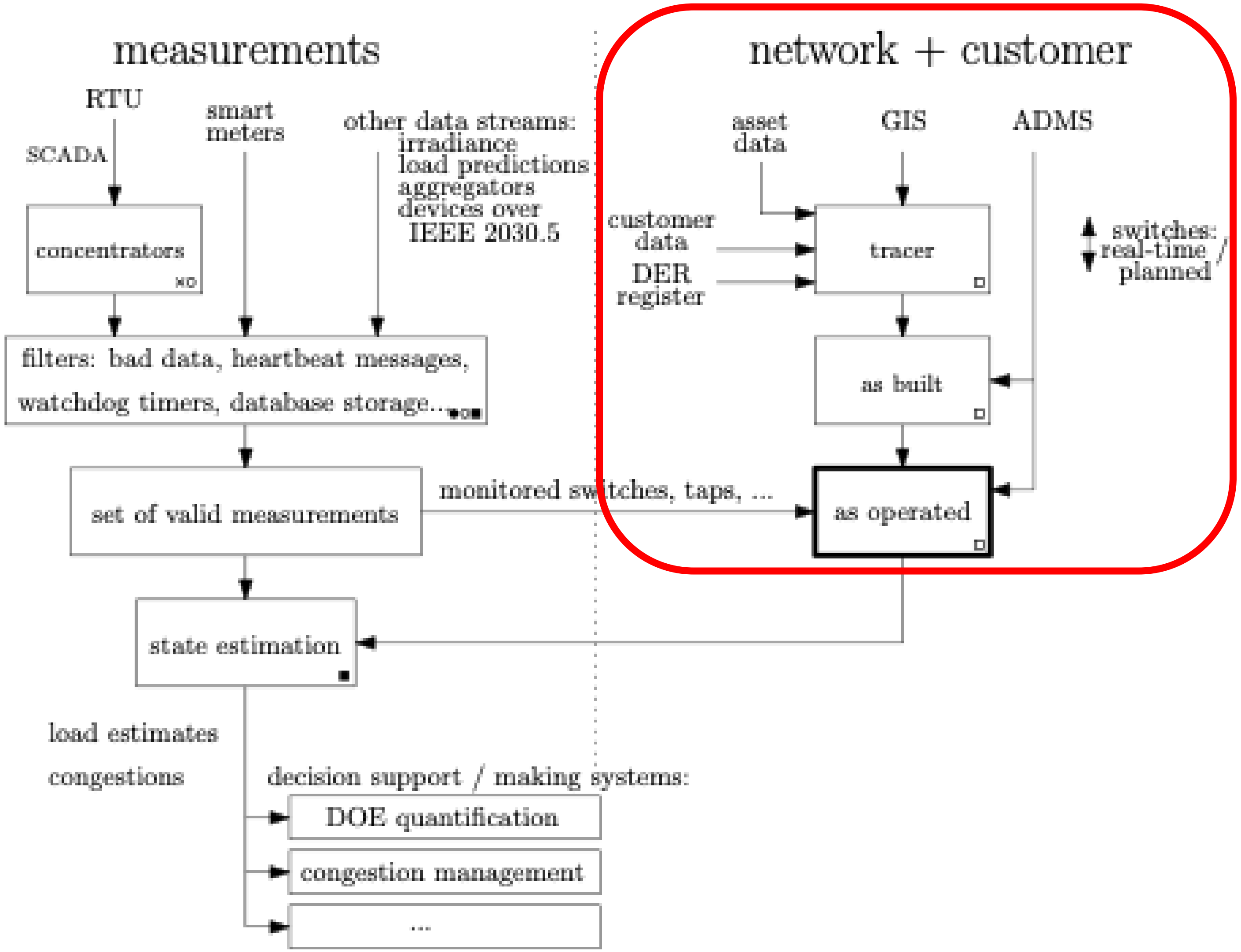
	Issue	Implications and risks
1	Missing phase labels (loads, transformers, etc.)	Inaccurate per-phase power flows, voltage unbalance inexact.
2	Switch states & user-branch connections	See issue 1 + impossible to determine how many consumers are connected to a transformer (aggregate values at feeder head 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

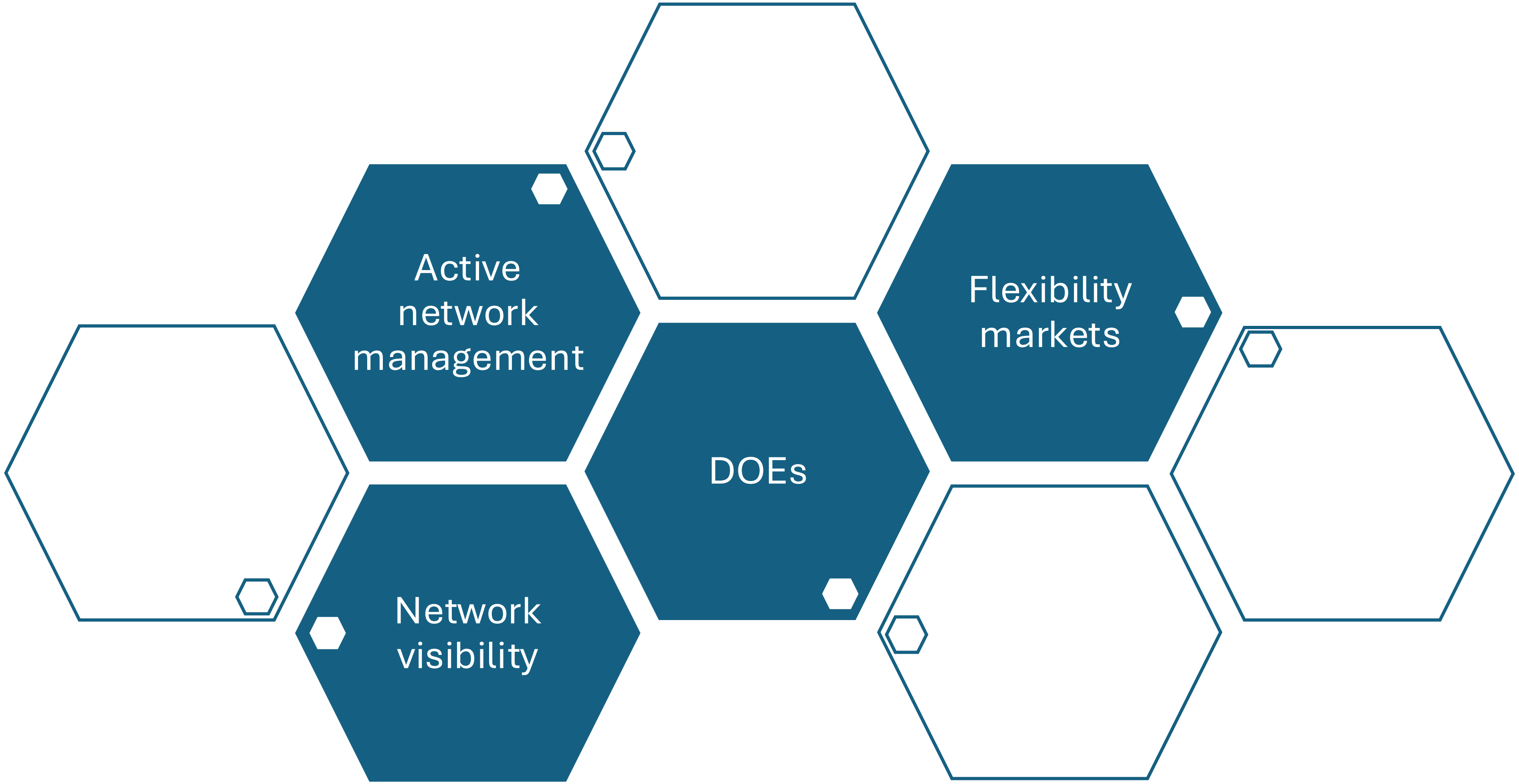
Recommendations

- 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



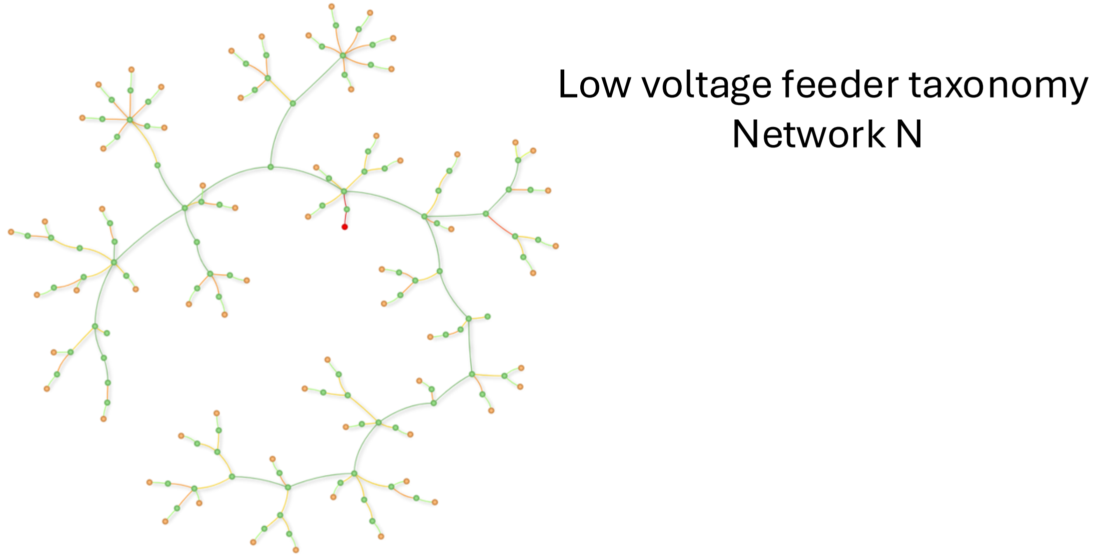
Enablers

- Open standards & interoperability
  - For communication (CSIP-Aus)
  - For modeling (CIM)

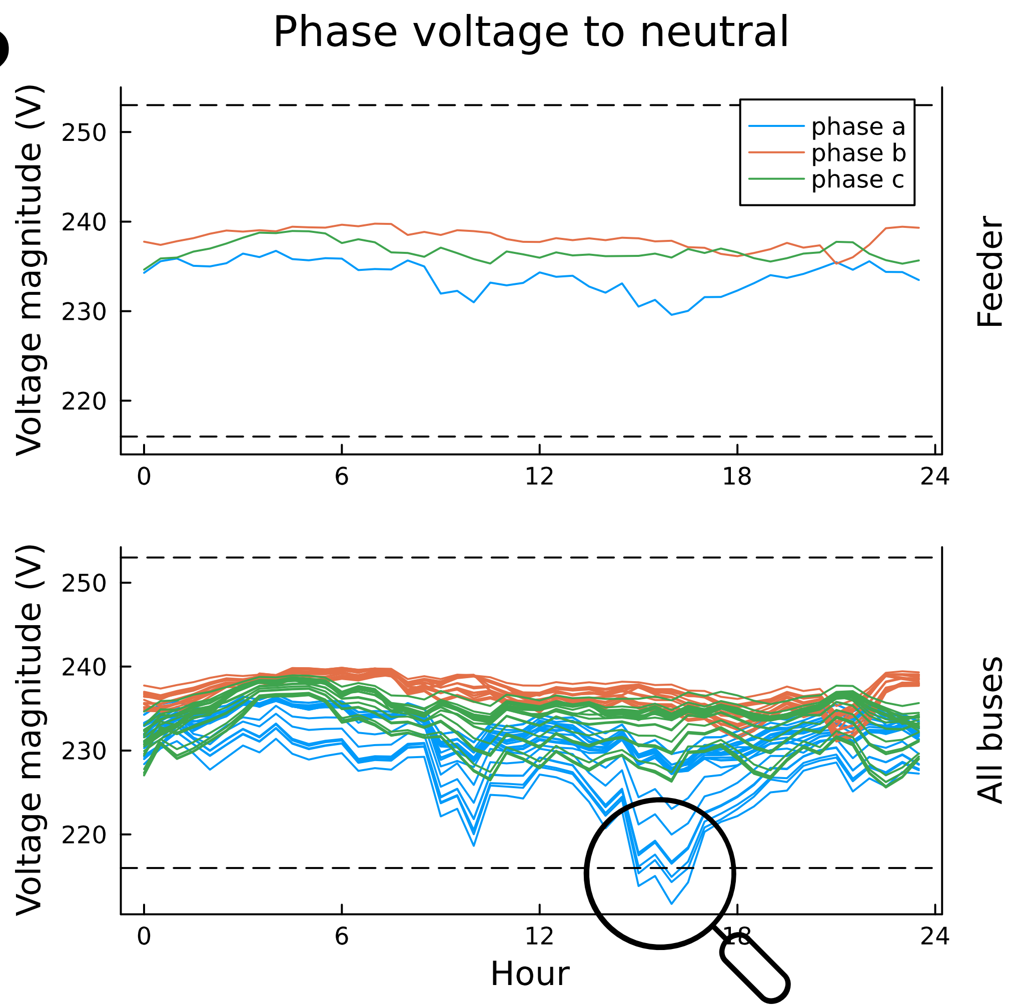
- Open source tools & collaboration
  - Validated, auditable power engineering decision support software

What is phase unbalance?

- A distribution network with unbalanced loads



- 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

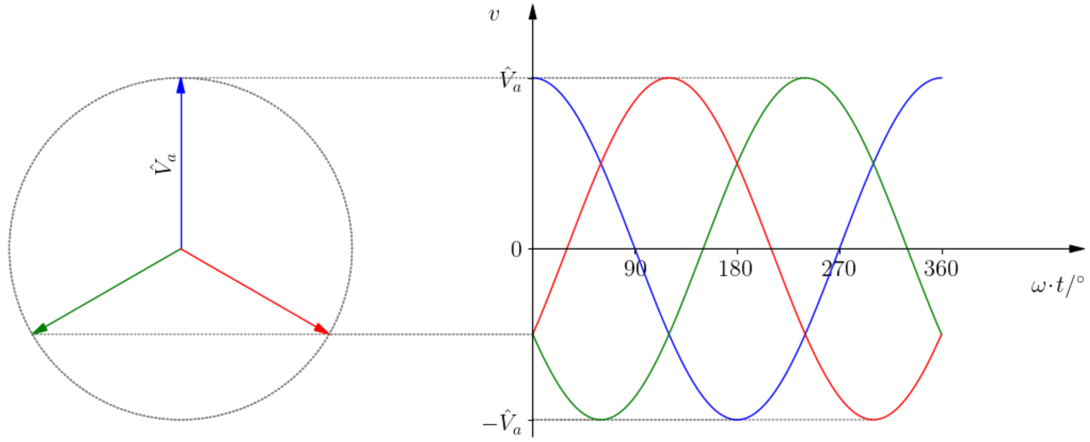
$v = |v| \cos(\omega t + \angle v)$

Complex cartesian

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

Phasor polar

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



3 scalars into ....

$v_a = |v_a| \angle v_a$
$v_b = |v_b| \angle v_b$
$v_c = |v_c| \angle v_c$

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:

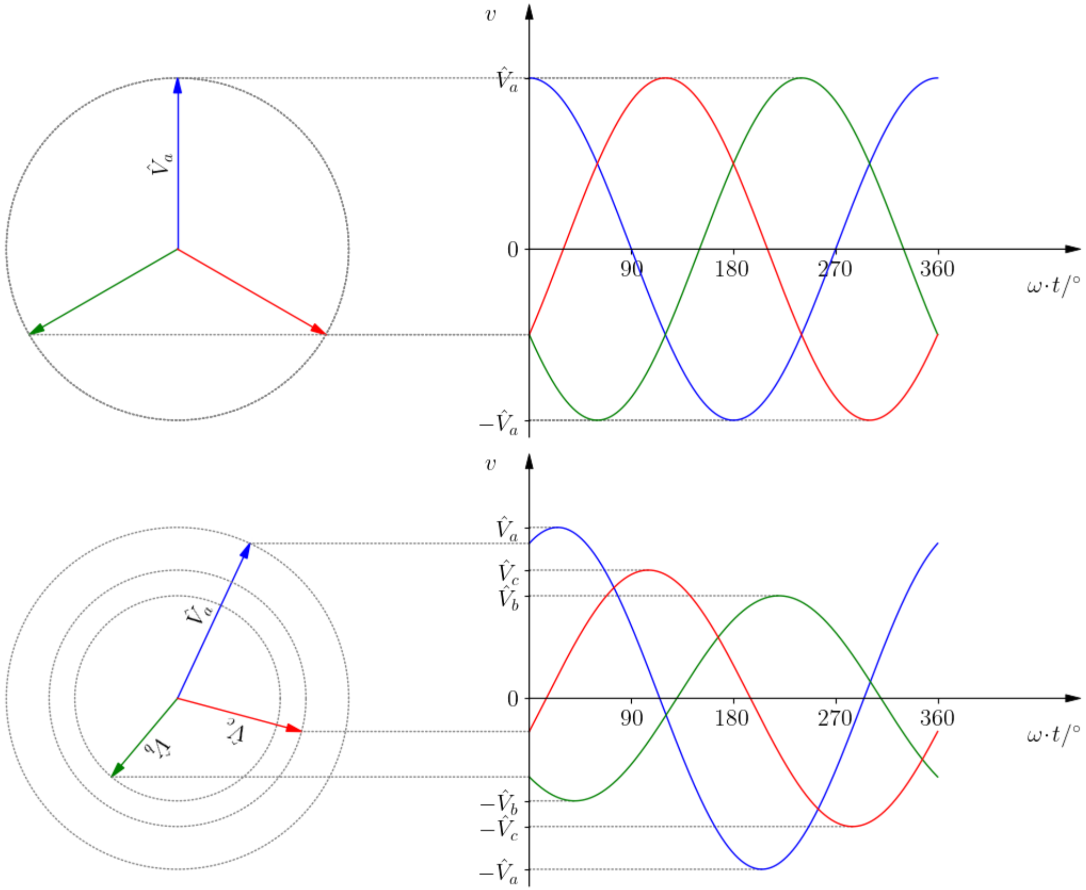
- phase angle difference between the phases different from 120°
- different magnitudes

Unbalance implies ineffective use of the network's transfer capacity

- avoidable network losses
- worse voltage drop/increase

Balanced

Unbalanced



Balanced and unbalanced phasors
Symmetrical components

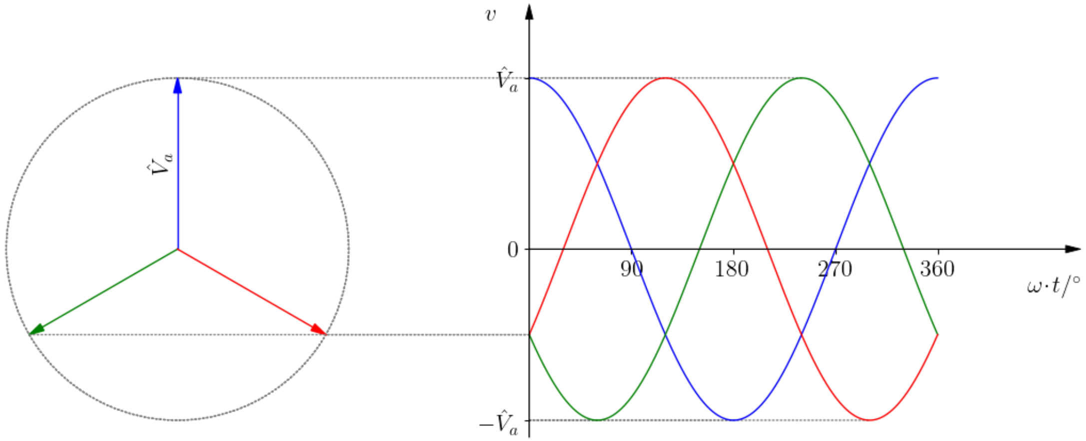
Zero sequence

Positive sequence

Negative sequence

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

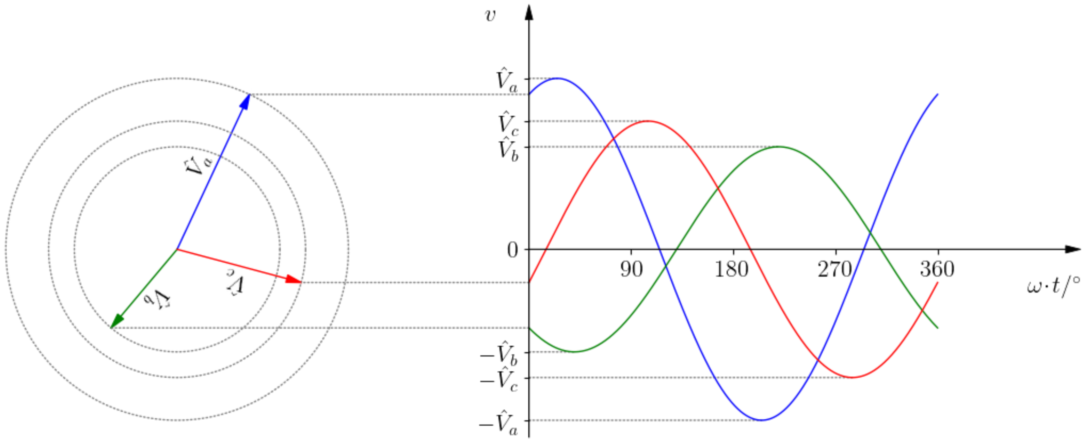
Balanced



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

$$\begin{bmatrix} V0 \\ V1 \\ V2 \end{bmatrix} = \begin{bmatrix} 0.0842 + 0.2538im \\ 0.7315 + 0.0078im \\ 0.0906 + 0.1611im \end{bmatrix} \qquad \begin{vmatrix} V0 \\ V1 \\ V2 \end{vmatrix} = \begin{bmatrix} 0.2674 \\ 0.7316 \\ 0.1848 \end{bmatrix}$$

Unbalanced



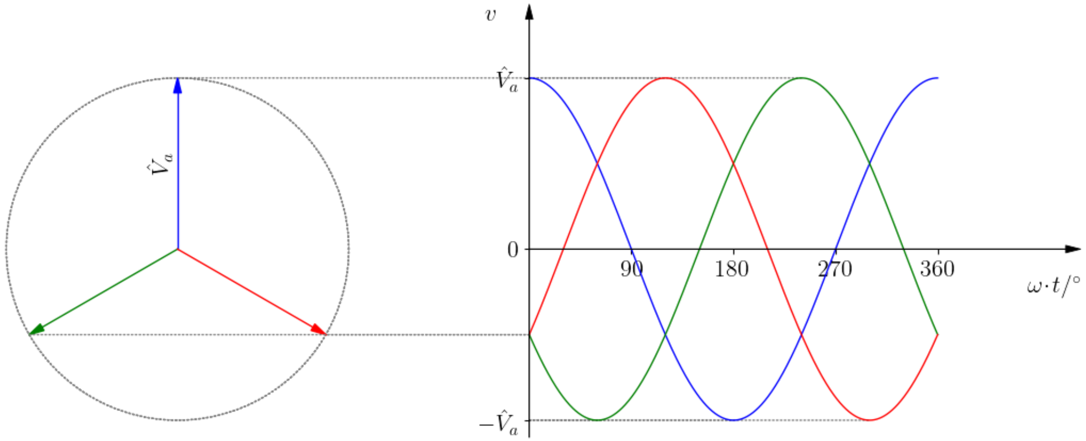
Balanced and unbalanced phasors
Symmetrical components

Zero sequence → $V0$

Positive sequence → $V1$

Negative sequence → $V2$

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



Balanced

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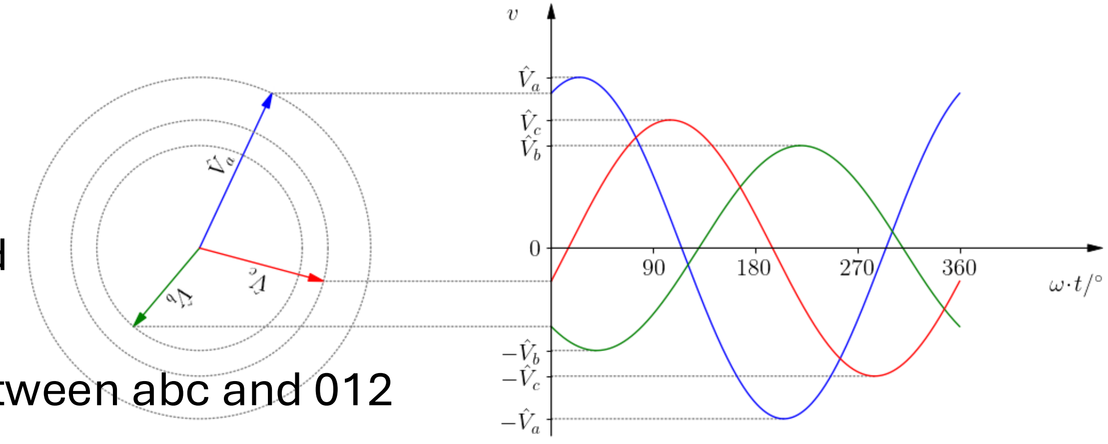


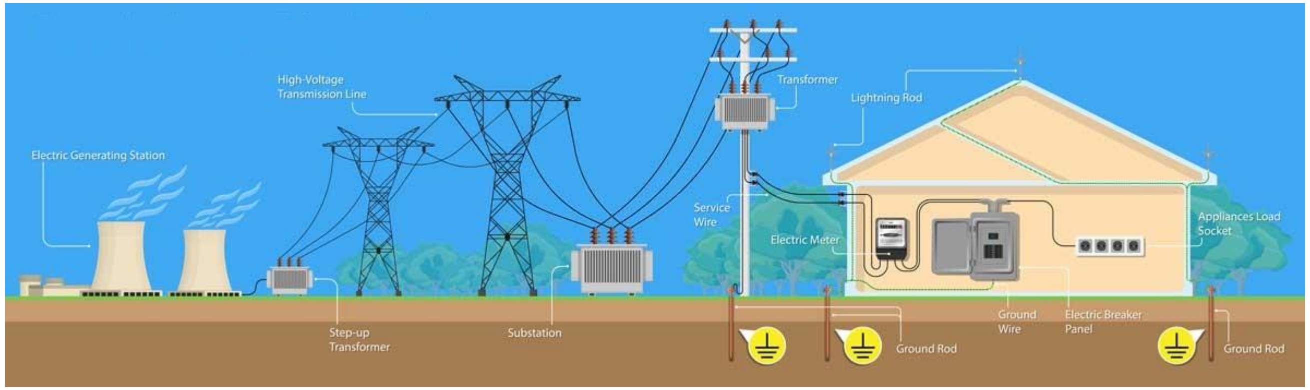
Unbalanced

Note:

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

Neutral conductor grounding

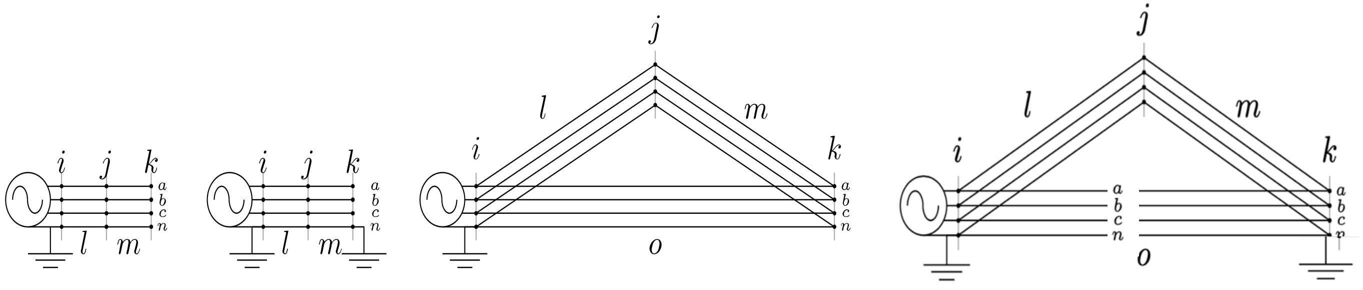
- Bonding the neutral conductor voltage to the potential of the earth.
  - Never close to perfect, or
  - Very expensive to bring it close to zero impedance



Neutral conductor grounding

- 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**

Network neutral grounding configuration variants



single-grounded radial

multi-grounded radial

single-grounded meshed.

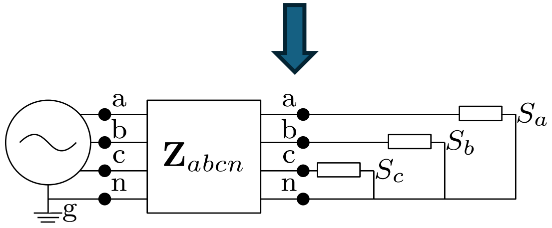
multi-grounded mesh

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

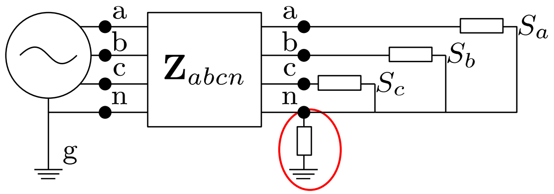
Neutral conductor grounding

- 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**

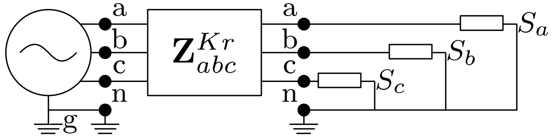
4-wire network



No ground
No grounding of neutral at load bus



Solid grounding
Grounding of neutral at load bus

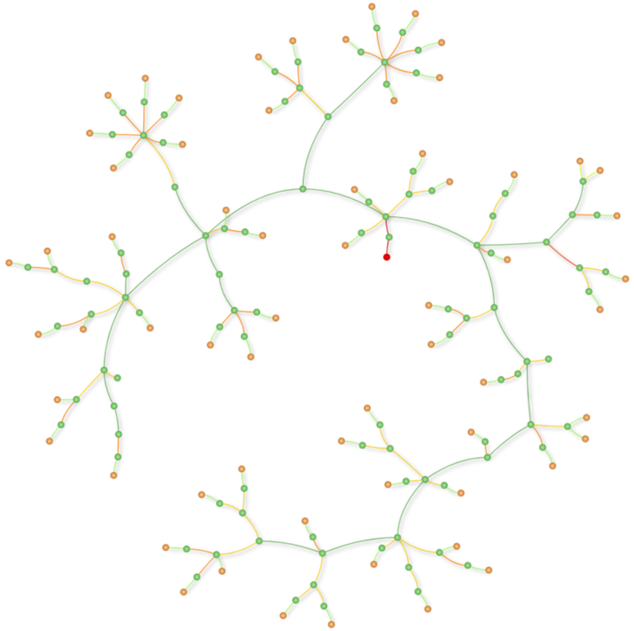


Perfect grounding
Grounding of neutral at load bus

Neutral conductor grounding

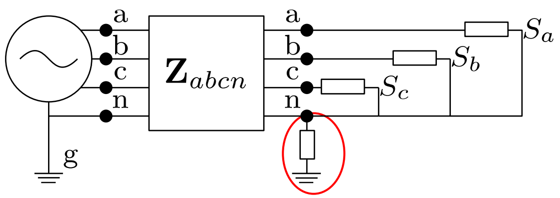
Assume all LV nodes have solid grounding.

This is still an **optimistic** model.



The smaller the network, the more difference in neutral grounding

Neutral to ground impedance



Solid grounding

Neutral conductor grounding

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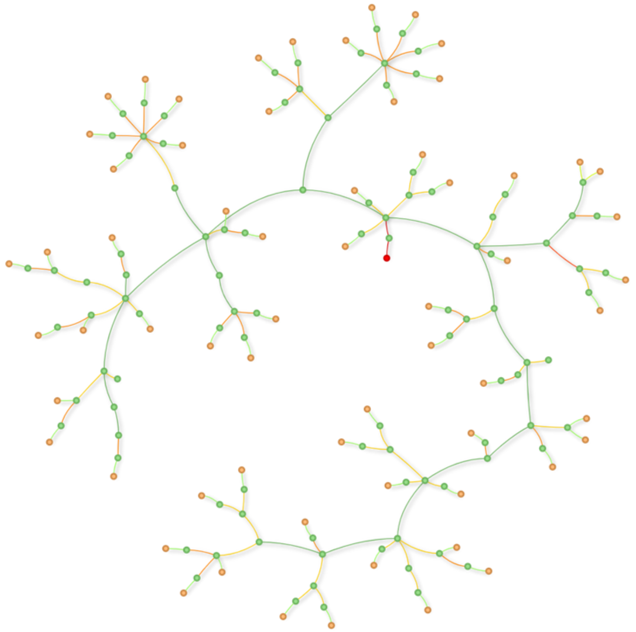

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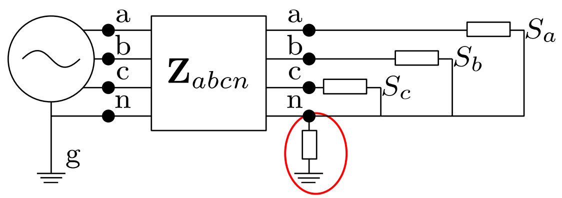
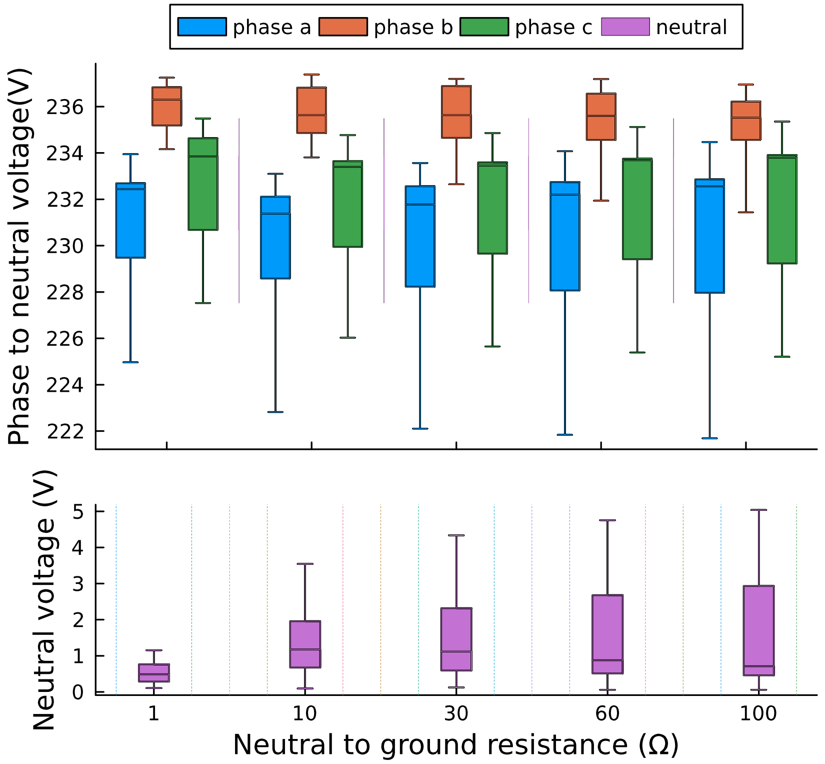
Neutral to ground impedance



Solid grounding

Impact of neutral to ground resistance



Neutral conductor grounding

Assume all LV nodes have solid grounding.

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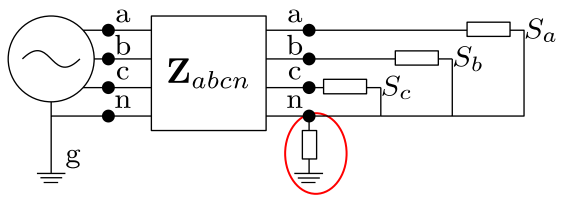
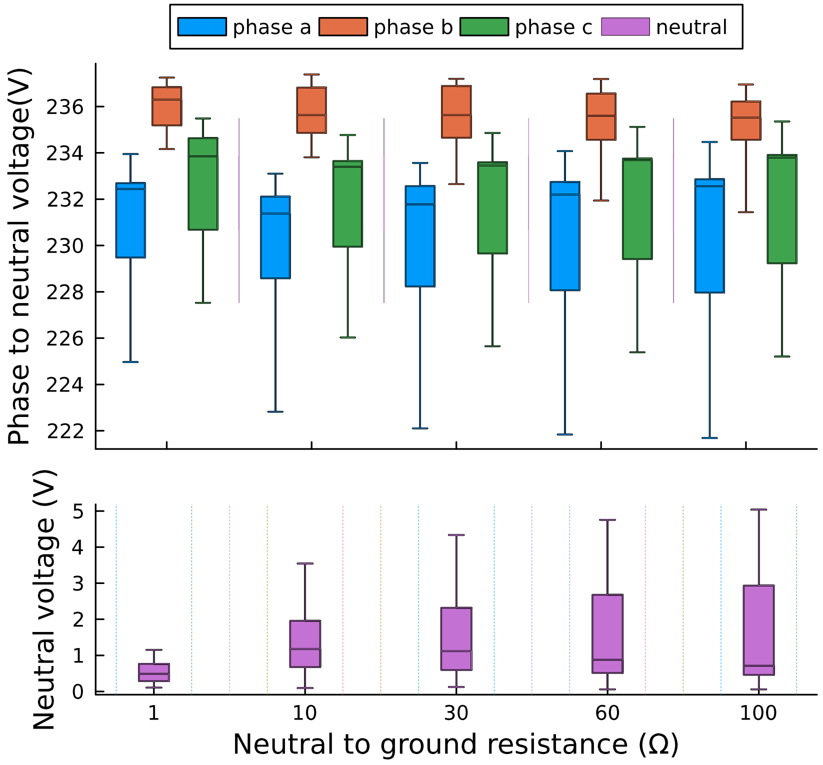
Neutral to ground impedance



Solid grounding

Impact of neutral to ground resistance

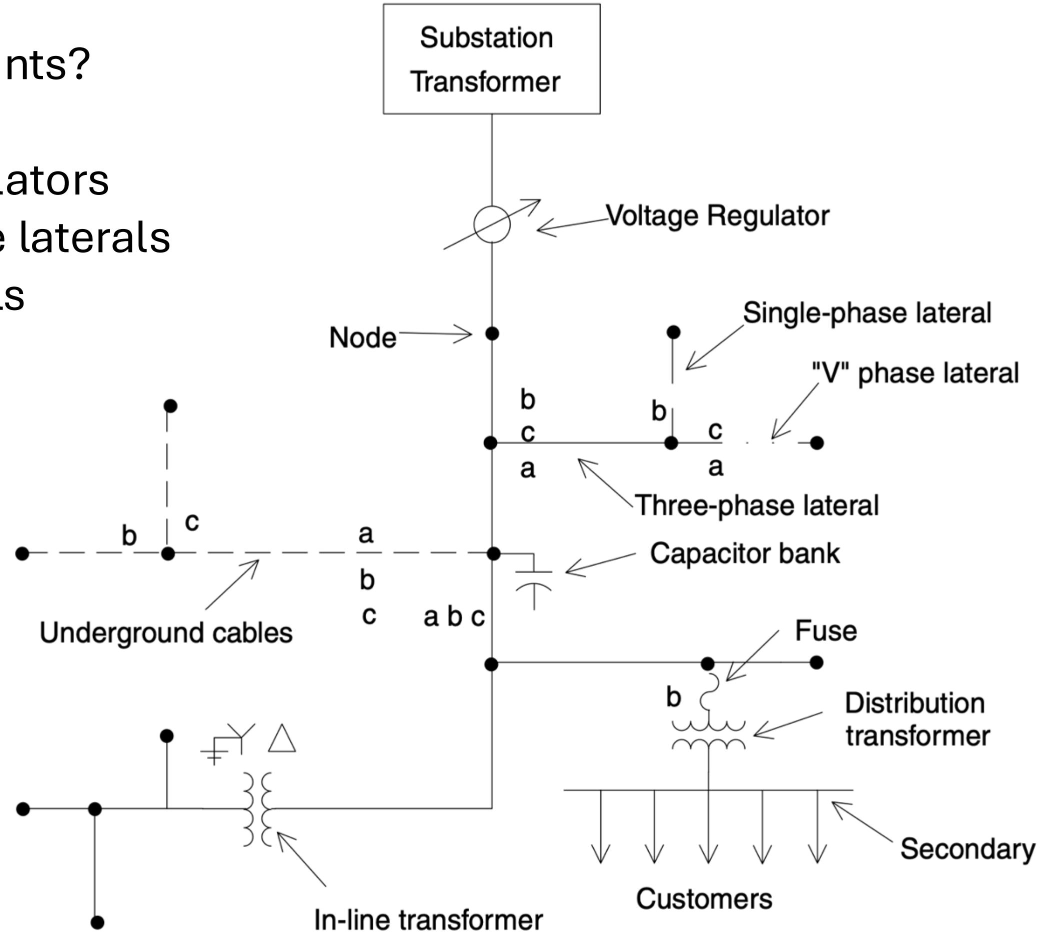


- A non-zero neutral conductor voltage decreases the power you can transfer before you hit the limits
  - significant under-estimation of voltage magnitude problems
  - over or under-estimation of voltage unbalance

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

i

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

- 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

Bus / terminals / branches

i

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

i

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

- 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

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)

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

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

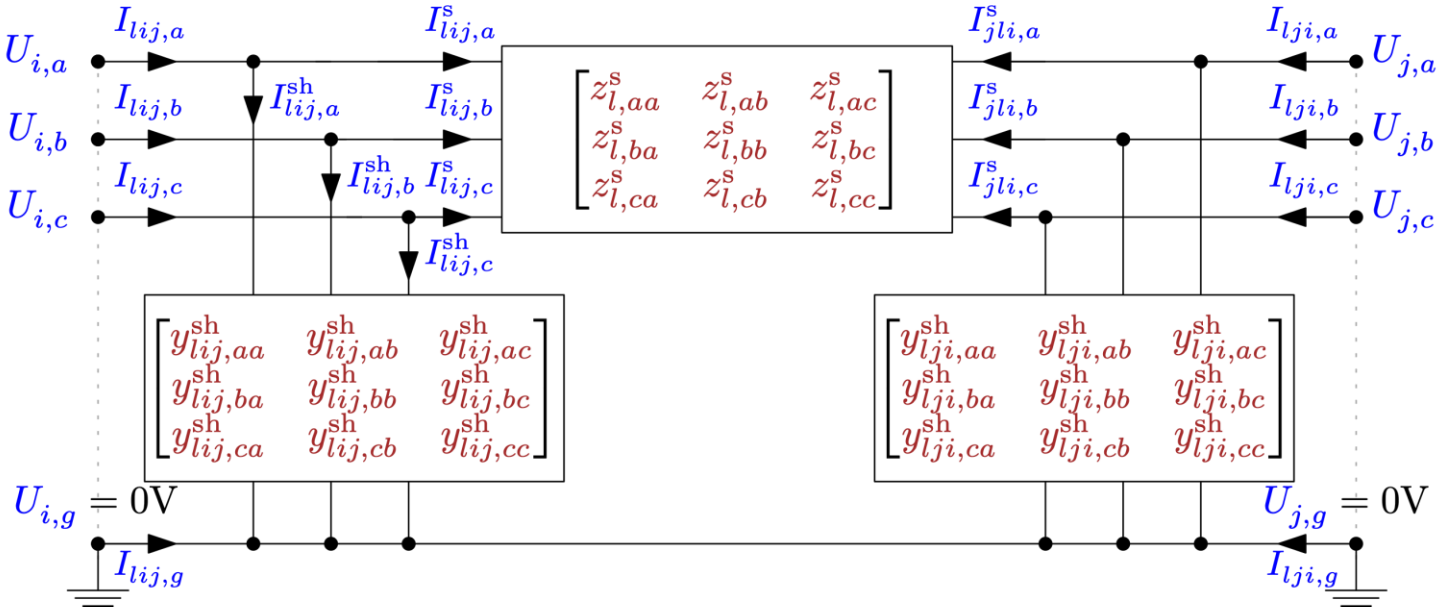
i

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

i

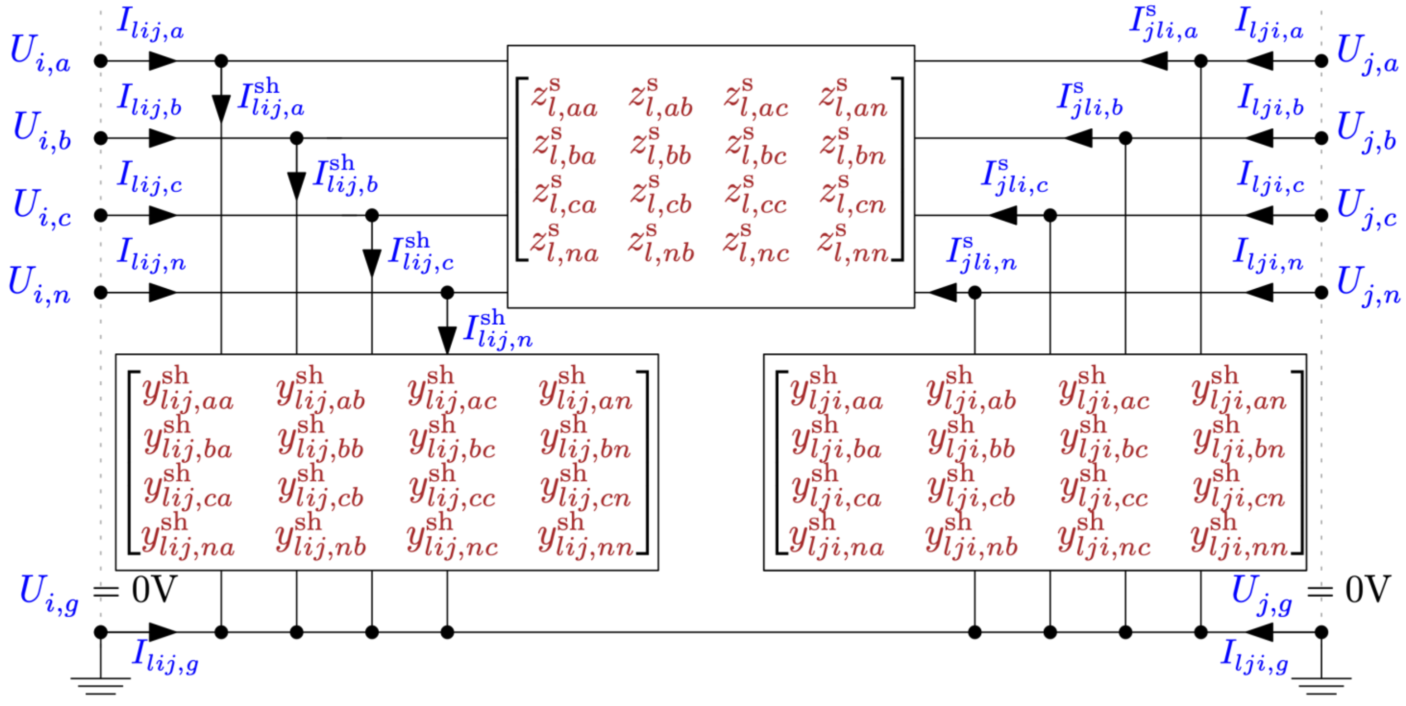
- a
- b phases
- c
- n neutral
- g ground

3-wire branch



2 x 3 x 9 real parameters per branch

4-wire branch



2 x 3 x 16 real parameters per branch

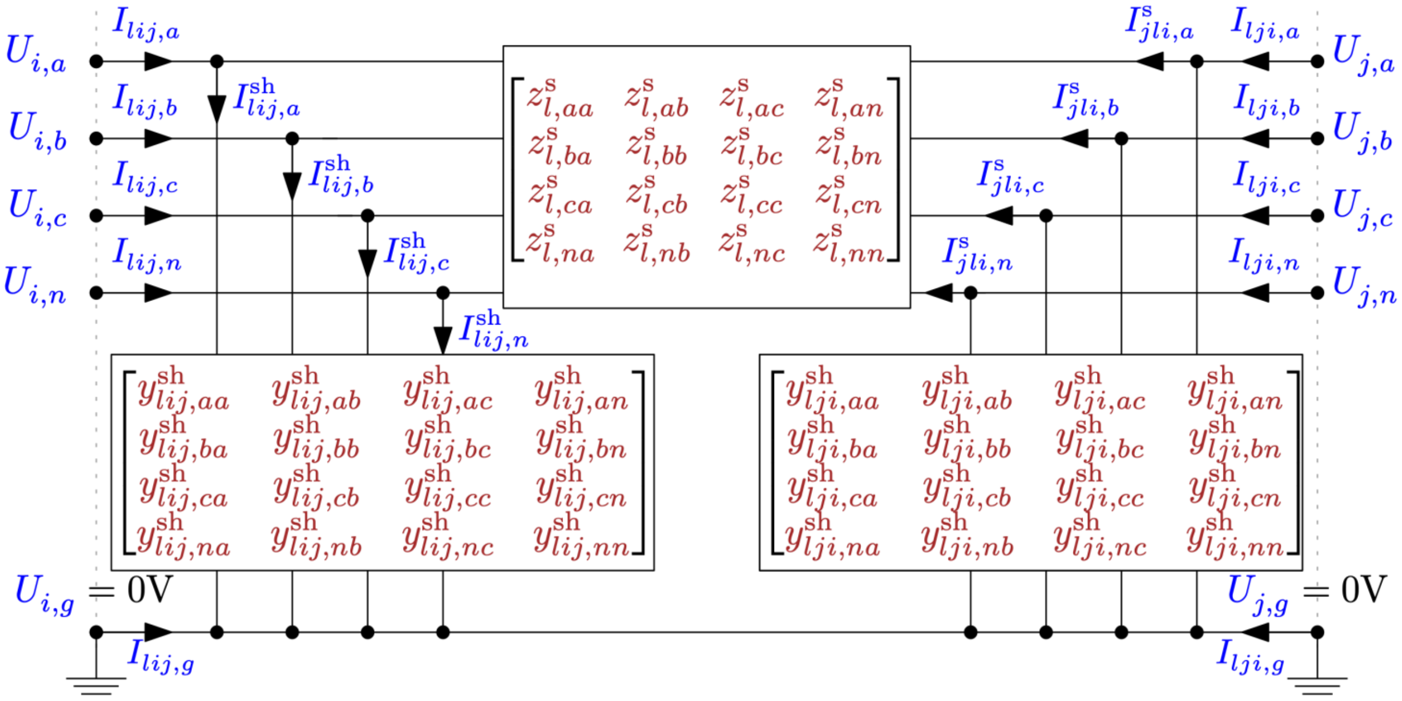
4-wire branch

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



4-wire branch

- 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

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

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

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

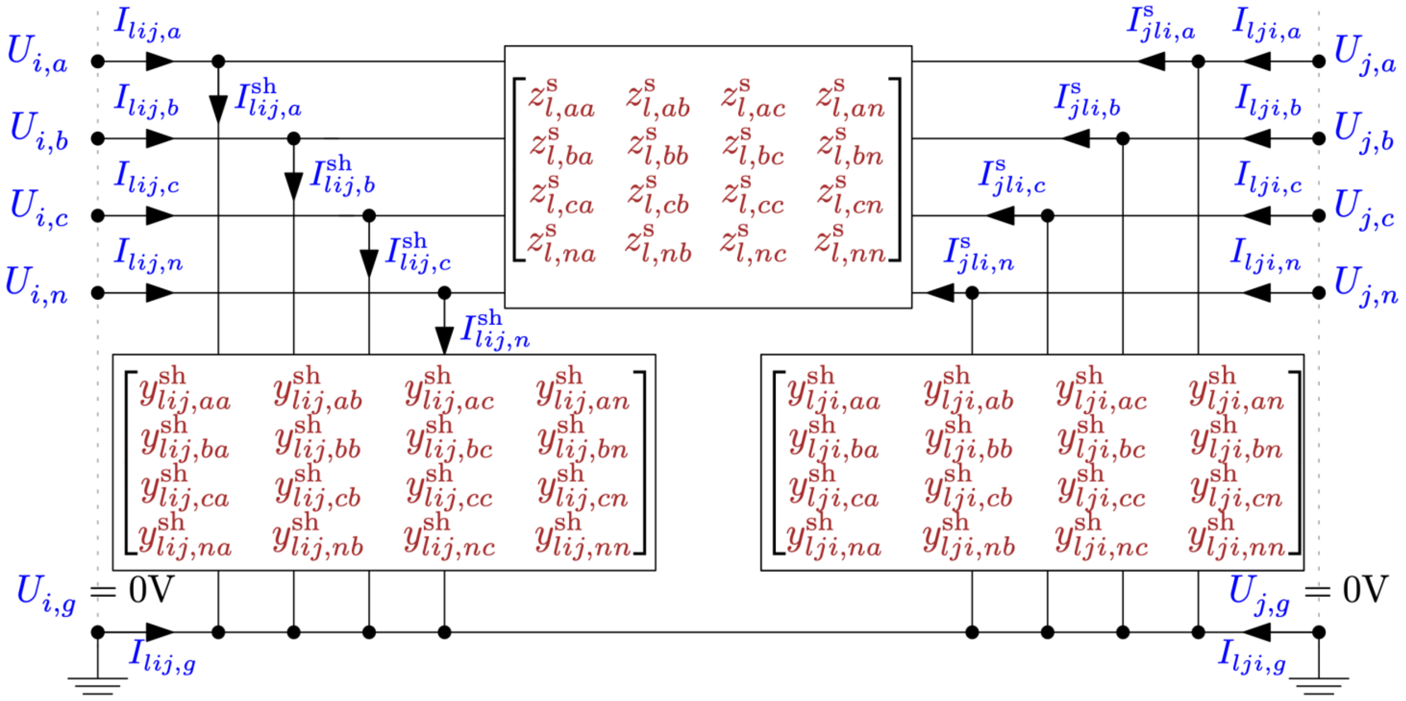
$$\mathbf{I}_{lij}^s = -\mathbf{I}_{lji}^s$$

Bounds

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

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

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

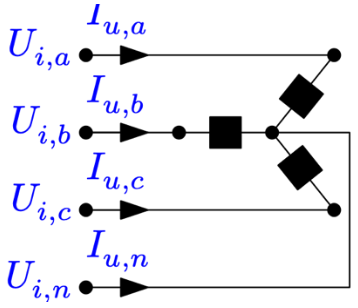


Loads

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.

$$\mathbf{U}_i \circ (\mathbf{I}_u)^* = \mathbf{S}_u^{\text{ref}} = \mathbf{P}_u^{\text{ref}} + j\mathbf{Q}_u^{\text{ref}},$$

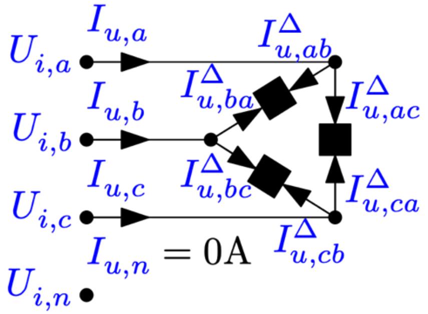


- Configuration
  - Delta
  - Wye
- Model
  - Constant power
  - Constant current
  - Constant impedance
  - Exponential
  - ...

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

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

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



[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"]

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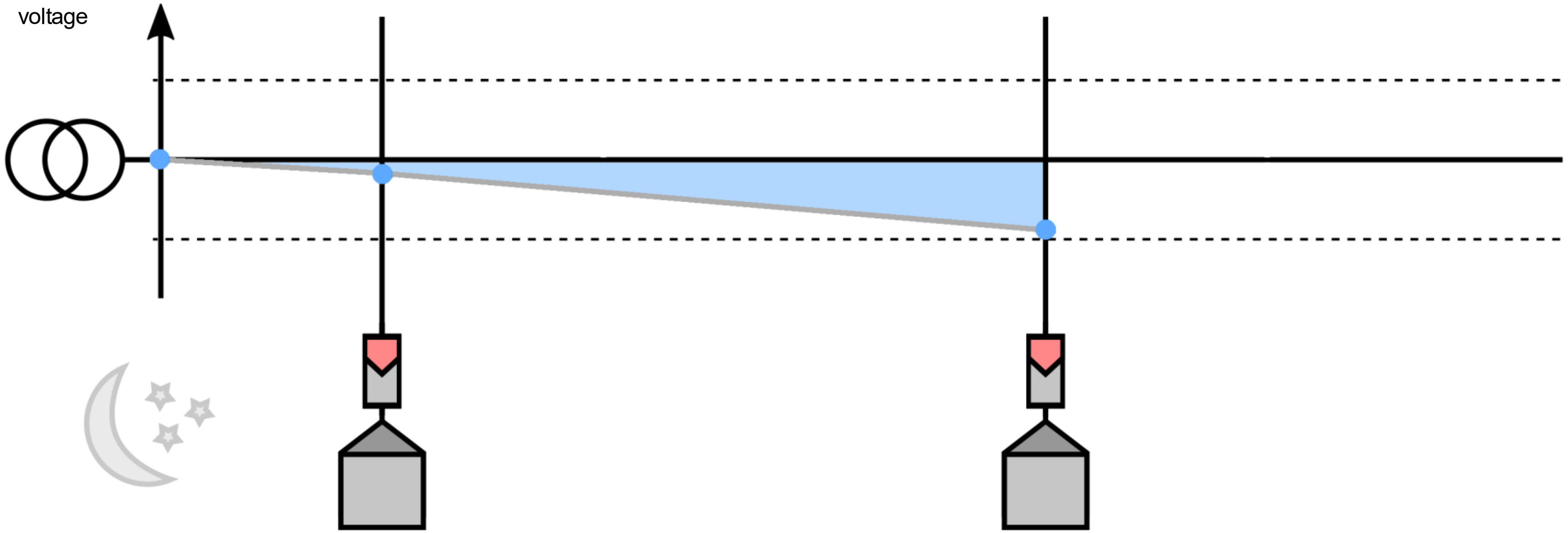
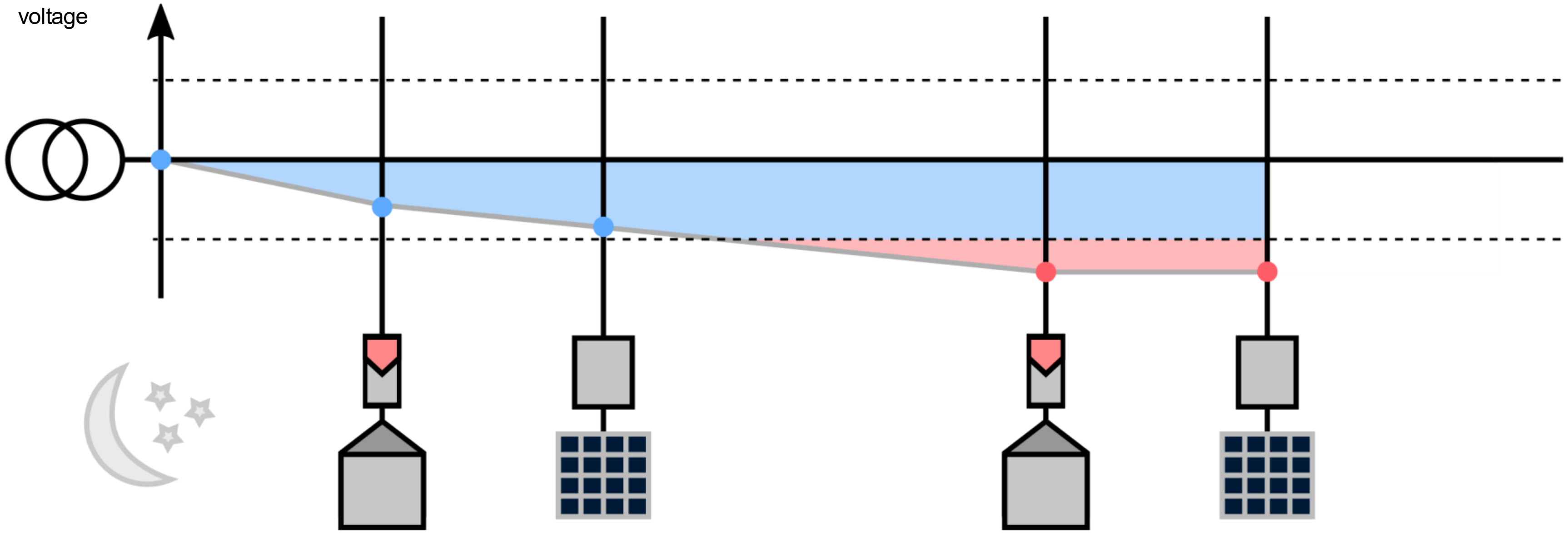
From simulation to optimization models

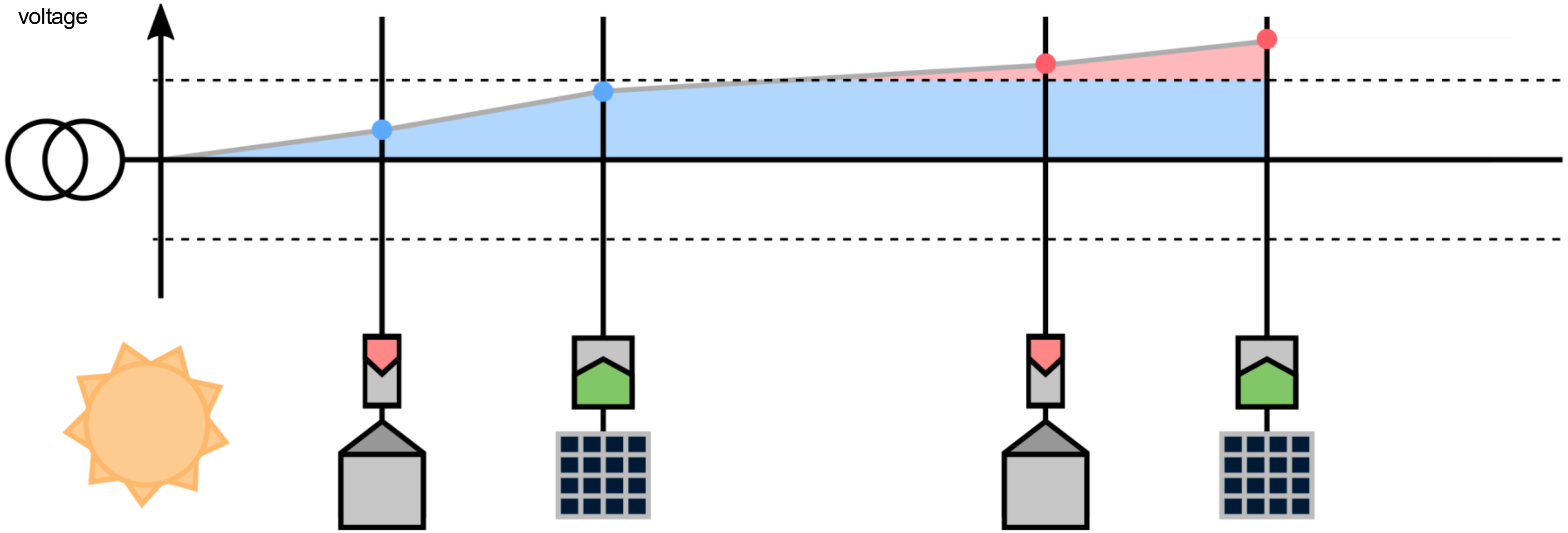
distribution networks



distribution networks

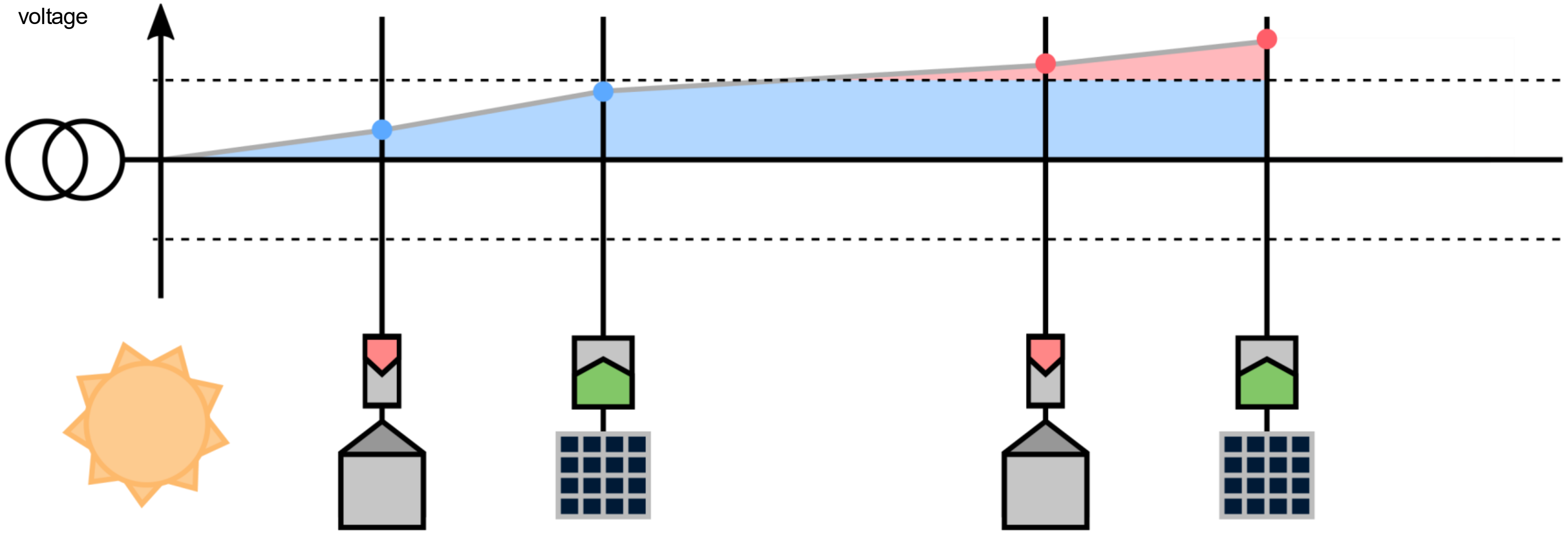


distribution networks



distribution networks

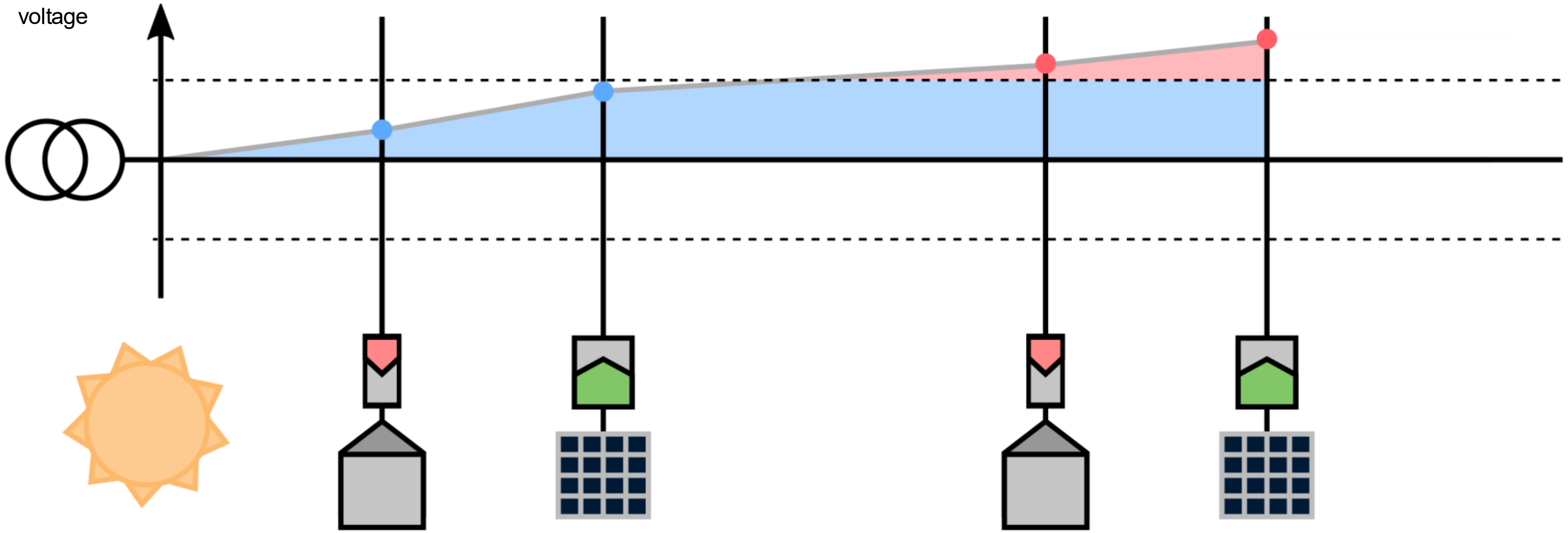
PASSIVE SOLUTION
reinforce the network (more copper)



distribution networks

ACTIVE

ACTIVE SOLUTION
- PV curtailment
- EV charging coordination
- **batteries**
- ...



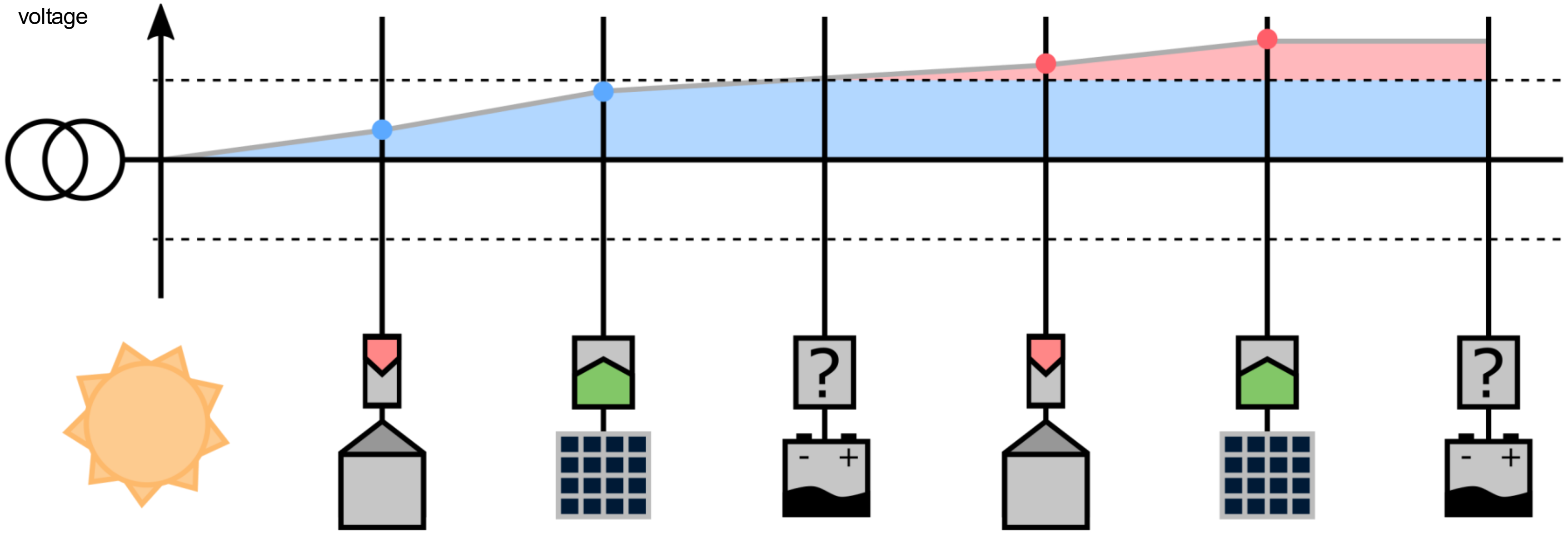
in presence of distributed control, e.g. volt-var/watt PV inverters

distribution networks

ACTIVE

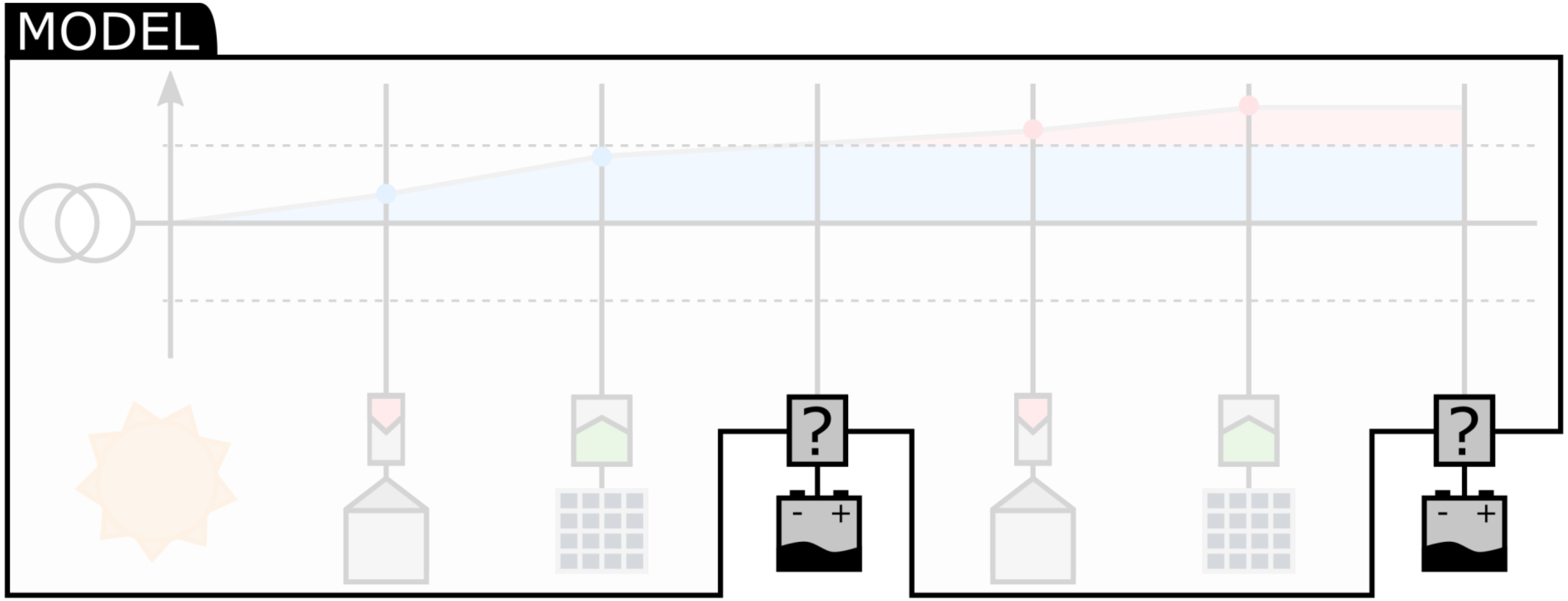
ACTIVE SOLUTION

- PV curtailment
- EV charging coordination
- **batteries**
- ...



distribution networks

ACTIVE



ACTIVE SOLUTION
- PV curtailment
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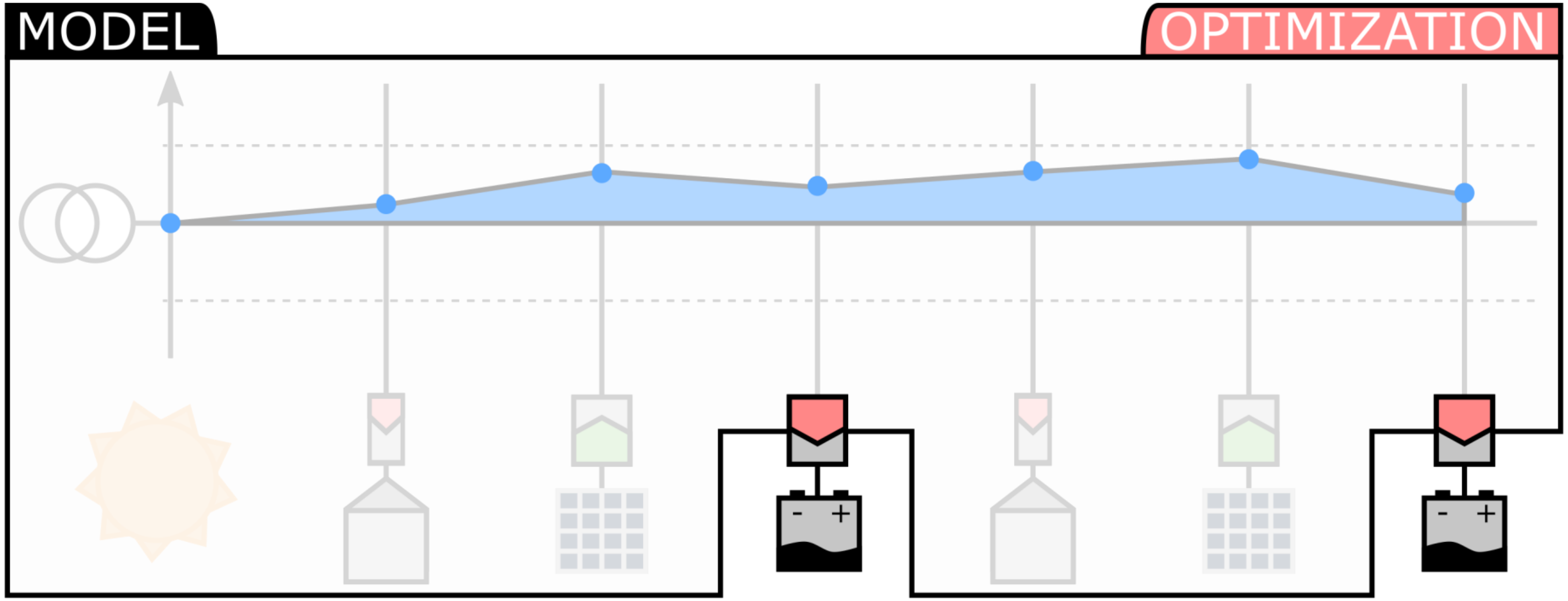
- **batteries**
- ...

distribution networks

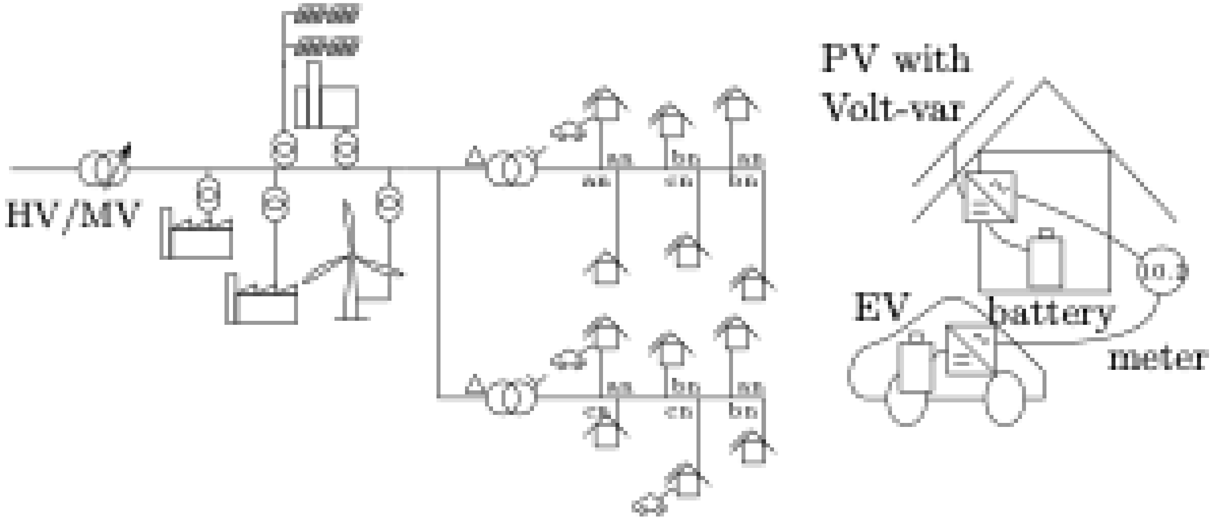
ACTIVE

ACTIVE SOLUTION

- PV curtailment
- EV charging coordination
- **batteries**
- ...



OPF?



OPF example

min. cost of dispatch
s.t. network physics
- operating limits: S, V, I
- devices: EV, PV, battery
- inverter control

outcome:
- feasible dispatch & network within operating limits

Feasible set of canonical problem

- System of complex-value nonlinear matrix equations
  - In practice additional complexity to avoid padding for lines with fewer wires
- Reformulations in lifted variables (I -> UI^H=S, V->VV_H=W) may enable better linearization or convexification
- Transformers need detailed treatment, delta-connected loads etc

complex variables

$$\mathbf{U}_i = \begin{bmatrix} U_{i,a} \\ U_{i,b} \\ U_{i,c} \\ U_{i,n} \end{bmatrix} \quad \mathbf{I}_{lij} = \begin{bmatrix} I_{lij,a} \\ I_{lij,b} \\ I_{lij,c} \\ I_{lij,n} \end{bmatrix} \qquad \mathbf{U}_i^{\perp} = \begin{bmatrix} U_{i,an} \\ U_{i,bn} \\ U_{i,cn} \end{bmatrix} = \underbrace{\begin{bmatrix} 1 & 0 & 0 & -1 \\ 0 & 1 & 0 & -1 \\ 0 & 0 & 1 & -1 \end{bmatrix}}_{\mathbf{M}^{\perp}} \underbrace{\begin{bmatrix} U_{i,a} \\ U_{i,b} \\ U_{i,c} \\ U_{i,n} \end{bmatrix}}_{\mathbf{U}_i}$$

bounds

$$0 \le \underbrace{\begin{bmatrix} U^{\min}_{i,a} \\ U^{\min}_{i,b} \\ U^{\min}_{i,c} \\ 0 \end{bmatrix}}_{\mathbf{U}_i^{\min}} \le \begin{bmatrix} |U_{i,a}| \\ |U_{i,b}| \\ |U_{i,c}| \\ |U_{i,n}| \end{bmatrix} \le \underbrace{\begin{bmatrix} U^{\max}_{i,a} \\ U^{\max}_{i,b} \\ U^{\max}_{i,c} \\ U^{\max}_{i,n} \end{bmatrix}}_{\mathbf{U}_i^{\max}} \qquad 0 \le \begin{bmatrix} |I_{lij,a}| \\ |I_{lij,b}| \\ |I_{lij,c}| \\ |I_{lij,n}| \end{bmatrix} \le \underbrace{\begin{bmatrix} I^{\max}_{lij,a} \\ I^{\max}_{lij,b} \\ I^{\max}_{lij,c} \\ I^{\max}_{lij,n} \end{bmatrix}}_{\mathbf{I}^{\max}_{lij}}$$

KCL

$$\forall i: \underbrace{\sum_{lij} \mathbf{I}_{lij}}_{\text{lines}} + \underbrace{\sum_{wij} \mathbf{I}_{wij}}_{\text{switches}} + \underbrace{\sum_{id} \mathbf{I}_d}_{\text{loads}} - \underbrace{\sum_{ig} \mathbf{I}_g}_{\text{generators}} + \underbrace{\sum_{ih} \mathbf{Y}_h \mathbf{U}_i}_{\text{shunts}} = 0$$

Ohm's law

$$\mathbf{I}_{lij} = \mathbf{Y}^{\text{sh}}_{lij} \mathbf{U}_i + \mathbf{I}^{\text{s}}_{lij}$$

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

demand

$$\mathbf{S}_d^{\perp} = \mathbf{U}_i^{\perp} (\mathbf{I}_d[\mathcal{P}])^{\text{H}}$$

dispatchable generation

$$\mathbf{S}_g = \mathbf{P}_g + j\mathbf{Q}_g = \mathbf{U}_i (\mathbf{I}_g)^{\text{H}}$$

$$\mathbf{P}_g^{\min} \le \text{diag}(\mathbf{P}_g^{\perp}) \le \mathbf{P}_g^{\max}$$

$$\mathbf{Q}_g^{\min} \le \text{diag}(\mathbf{Q}_g^{\perp}) \le \mathbf{Q}_g^{\max}$$

PowerModelsDistribution.jl

- Toolbox with 3-wire and 4-wire *optimization* models in various variable spaces
- Supports majority of components from OpenDSS, OpenDSS parser for base case definitions
- Supports multiperiod optimization too
- Separates data, models and algorithms

PowerModelsDistribution.jl: An Open-Source Framework for Exploring Distribution Power Flow Formulations

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***Abstract*—In this work we introduce PowerModelsDistribution, a free, open-source toolkit for distribution power network optimization, whose primary focus is establishing a baseline implementation of steady-state multi-conductor unbalanced distribution network optimization problems, which includes implementations of Power Flow and Optimal Power Flow problem types. Currently implemented power flow formulations for these problem types include AC (polar and rectangular), a second-order conic relaxation of the Branch Flow Model (BFM) and Bus Injection Model (BIM), a semi-definite relaxation of BFM, and several linear approximations, such as the simplified unbalanced BFM. The results of AC power flow have been validated against OpenDSS, an open-source "electric power distribution system simulator", using IEEE distribution test feeders (13, 34, 123 bus and LVTestCase), all parsed using a built-in OpenDSS parser. This includes support for standard distribution system components as well as novel resource models such as generic energy storage (multi-period) and photovoltaic systems, with the intention to add support for additional components in the future.**

***Index Terms*—nonlinear optimization, convex optimization, AC optimal power flow, Julia Language, Open-Source**

design. While the number of mathematical formulations for distribution system modeling has increased, few open-source tools are yet available, and none that enable rapid development of the newest formulations and optimization problems, to the best of our knowledge.

B. The Development of PowerModels

Recently, in response to an explosion of the number of power flow approximations and relaxations appearing in the literature for transmission networks, PowerModels [1] was offered as a free, open-source toolkit for the optimization of steady-state power transmission networks. Written in Julia, a high-level high-performance programming language for numerical computing, and utilizing JuMP [2], PowerModels provides a powerful expansive modeling layer for optimization; PowerModels is engineered to decouple problem specifications, *e.g.*, Optimal Power Flow (OPF) or Optimal Transmission Switching (OTS), from formulations, *e.g.*, AC or second-order cone (SOC) relaxations. This decoupled design allows

	IEEE13	IEEE34	IEEE123	LVTestCase t=500	LVTestCase t=1000
δ	5.1E-8	1.4E-7	1.3E-8	3.2E-8	3.3-8
$\min \lvert U\rvert_{ip}$	0.9750	0.9166	0.9858	1.0353	1.0226
$\max \lvert U\rvert_{ip}$	1.0686	1.0500	1.0437	1.0499	1.0496

- <1E-7 relative error in all variables!

Nondimensionalisation

- Physical equations ($V_j = V_i - Z_l I_{lij}$) have units attached
  - $V_i, V_j - \mathrm{V}, \mathrm{Z_l} - \Omega, \mathrm{I_{lij}} - \mathrm{A}$
  - I.e. so do the circuit laws
- Most Linear algebra routines work with floating point numbers *without* units
- Libraries may have support for propagating units
  - E.g. https://github.com/JuliaPhysics/Unitful.jl works together with JuMP in https://github.com/trulsf/UnitJuMP.jl
  - This comes at some processing and code complexity cost
- When we do computations using standard linear algebra routines, we have to do the nondimensionalization ourselves.
  - $V_j/1V = V_i/1V - \left(\frac{Z_l}{1\Omega}\right)\left(\frac{I_{lij}}{1A}\right)$ this is now a purely mathematical equation
  - Pick a reference value for each SI base unit (that you need) and derive all other bases for all quantities you use $\frac{V_j}{V_{base}} = \frac{V_i}{V_{base}} - \left(\frac{Z_l}{Z_{base}}\right)\left(\frac{I_{lij}}{I_{base}}\right), V_{base} = x\,V, Z_{base} = y\Omega, \mathrm{I_{base}} = \frac{\mathrm{x}}{\mathrm{y}}\mathrm{A}$
  - Divide all quantities by their corresponding bases

Nondimensionalisation vs per-unit

- Bases can massively impact the numerical magnitudes
- E.g. Normalizing by 1 J in the context of power systems leads to high magnitudes, generally we think in terms of a MW x b h, i.e. a 3.6E9 J base
- 1 V vs 1 kV, 1s vs 1h, …

- Per unit conversion is a specific choice of nondimensionalization based on common engineering practice / culture
- In power systems we 1) choose a power base 2) match the voltage base to the expected voltage / reference voltages, often line-to-line 3) pick time base of 1h 4) derive all other units from those.
- OpenDSS does not do any calculations in per unit, it calculates everything in V/A!
  - Ax=b type solvers are very numerically robust (e.g. KLU in Sundials.jl)
  - Some transformer parameters are specified in pu of their own power rating and primary voltage, this gets turned back into SI quantities.
- PMD does use nondimensionalisation, as we believe this may still be advantageous for numerical *optimization* solvers
- Note that admittance matrices across multiple voltage levels have very different magnitudes for the entries, and even more so if there are data artefacts (lines with superfluous buses)