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Static Power System Simulation using Python

Dr. Bogdan Dobrica

University of Bucharest, email: bdobrica@gmail.com

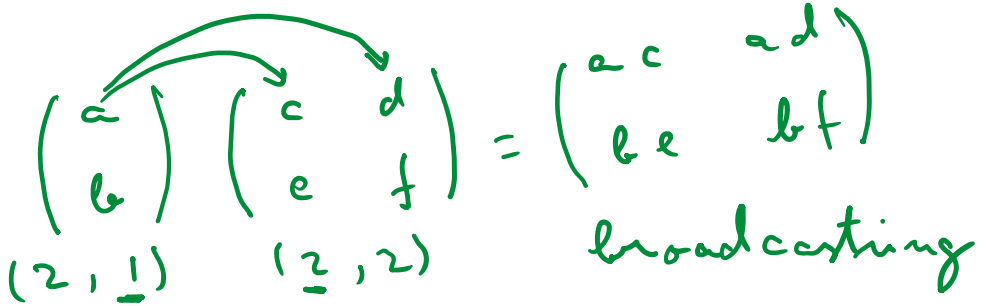
Why do we need Power Systems Simulations?

- More hybrid power systems are being connected to existing grids;
- Grids are legally required to be evaluated statically and dynamically to cover normal and abnormal operating conditions;
- To achieve maximum efficiency, each connected system needs to operate optimally.

Why use Python?

- The equations describing the grid behavior are non-linear and can be solved using numerical methods – hence, Python.

Python Tools



- NumPy – for working doing mathematical operations with matrices;
- Pandas – as we need also an Excel equivalent, right? DATAFRAME
- Jupyter Notebook – for ease of doing programming experiments;
- PyPSA – a readily available static power simulation system for Python;
  - https://pypsa.readthedocs.io/en/latest/ (documentation)
  - https://pypsa.org/ (official website)
- PyPSA-EUR – a collection of models covering European Network of Transmission System Operators.
  - https://pypsa-eur.readthedocs.io/en/latest/ (documentation)

Installing Required Software

- Download Python https://www.python.org/downloads/
  - Recommended version: 3.7
- Open a console and run the following commands:

```
$: python -m pip install –upgrade pip
$: python -m pip install numpy openpyxl pandas notebook pypsa
$: python -m jupyter notebook
```

Jupyter Notebook

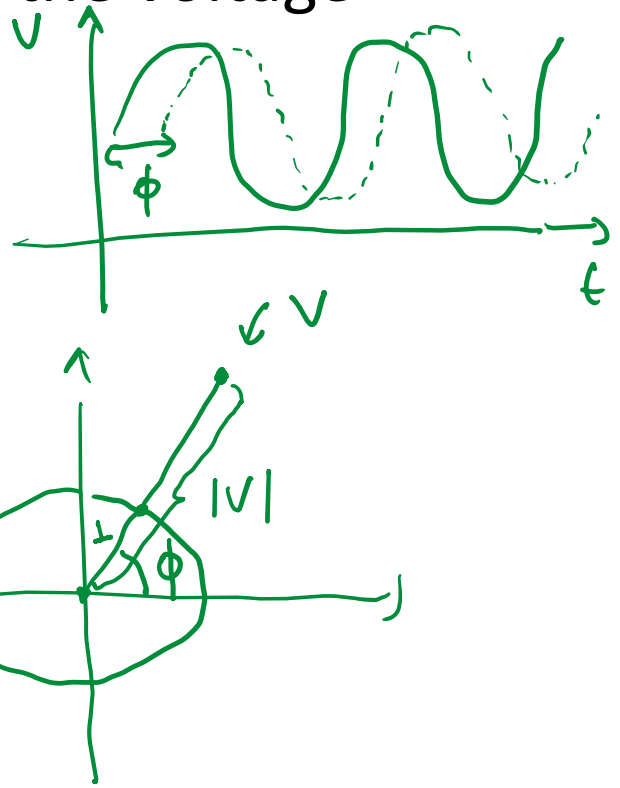
- A web-browser IDE for Python;
- Based on “running cells” – small pieces of code that share their environment:
  - For the current cell you’ll have access to all the objects defined in previously run cells.
- Useful shortcuts:
  - [a] creates a new cell before the current active cell; [b] creates one after
  - [m] on an active cell converts it to a “markup” cell; [y] to go back
  - [CTRL+ENTER] on an active cell runs the cell
  - [d][d] on an active cell, deletes the cell.

AC Power: A Few Considerations

- Considering a simple AC circuit, the general solution for the voltage will give:

$$V = |V|e^{j(\omega t + \phi)} = |V|e^{j\phi}e^{j\omega t} = \tilde{V}e^{jwt}$$

- Where:
  - V is the complex voltage solution to conservation of energy;
  - ω is the solution angular frequency;
  - ϕ is the solution phase, and;
  - t it the time.
- We call the term $\tilde{V}$ a phasor (**phas**e vect**or**)

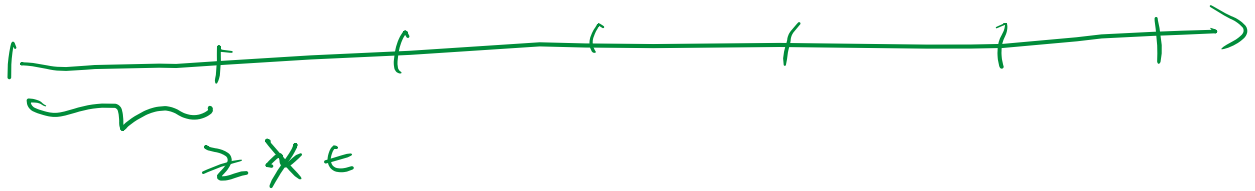


AC Power: Static Analysis

- In a normal power grid, the angular frequency is the same. The phasor becomes the only important factor.
- E.g. Ohm's Law:

$$\underline{V} = \underline{I}\underline{Z} \Leftrightarrow \tilde{V}e^{\omega t} = \tilde{I}\underline{Z}e^{\omega t} \Leftrightarrow \underline{\tilde{V}} = \underline{\tilde{I}}\underline{Z} \Leftrightarrow \underline{\tilde{V}}\underline{Y} = \underline{\tilde{I}}$$

- Where:
  - I is the current, and $\tilde{I}$ is the corresponding phasor;
  - V is the voltage, and $\tilde{V}$ is the corresponding phasor;
  - Z is the impedance / Y is the admittance seen by the generator.
- The equation is time-independent → steady state → static analysis.



AC Power: Phasor Notation

- Power in an AC circuit is given by:

$$\tilde{S} = P + jQ = \tilde{V}\tilde{I}^{\star}$$

- Where:
  - $\tilde{I}^{\star}$ is the complex conjugate of the current phasor;
  - $\tilde{S}$ is the complex power for which $|\tilde{S}|$ is the apparent power and for which
  - $P = Re(\tilde{S})$ is the real power;
  - $Q = Im(\tilde{S})$ is the reactive power.
- The power factor is $\cos(\theta) = \frac{P}{|\tilde{S}|}$

Power Grid

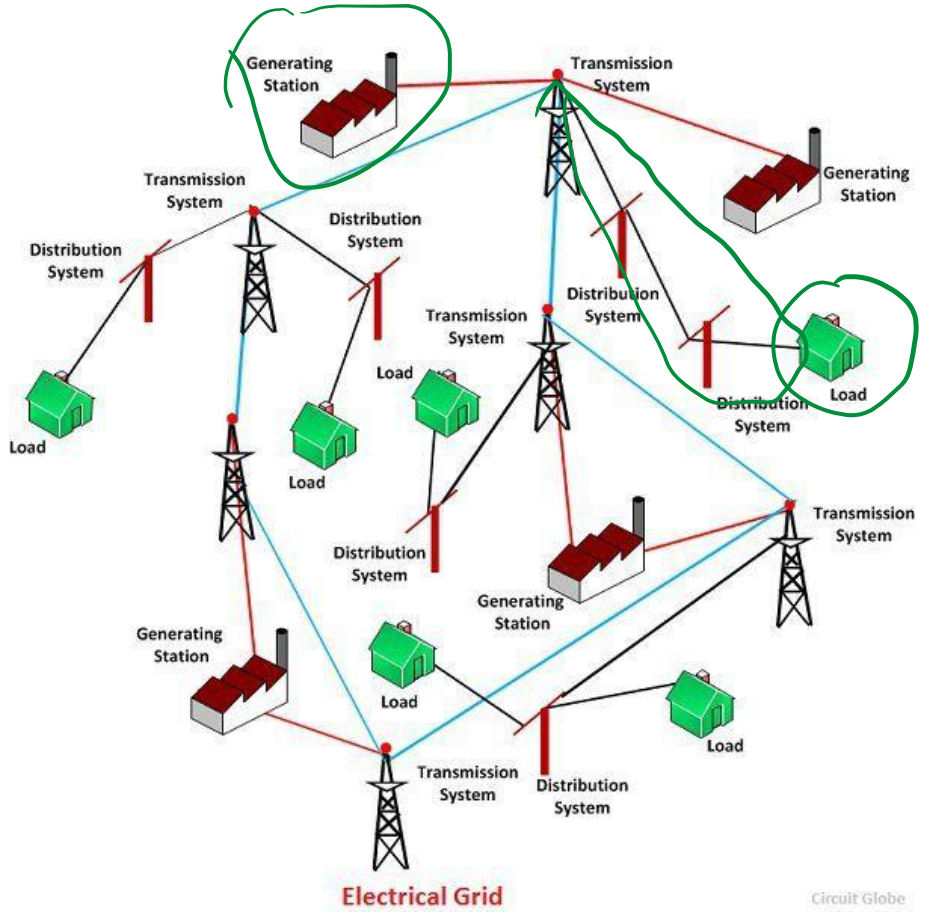
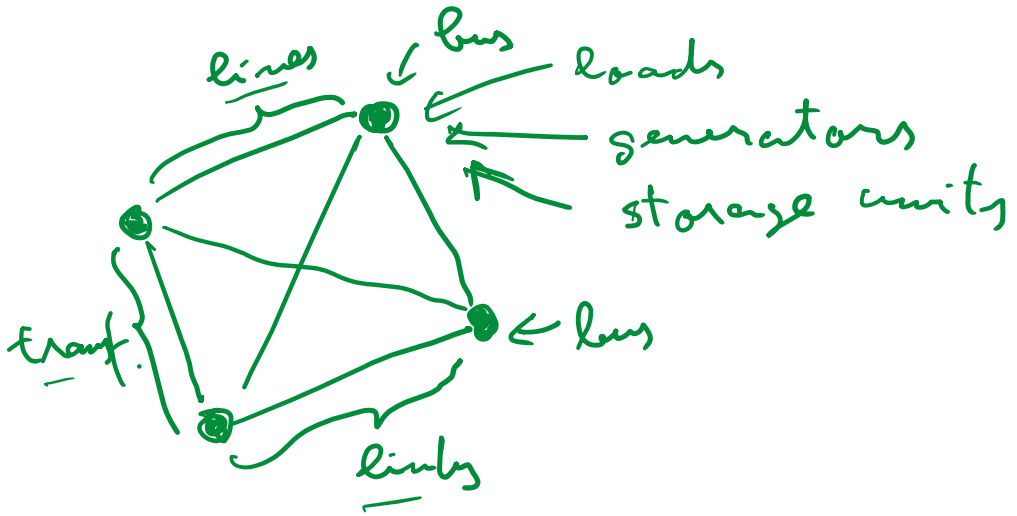


image source: circuitglobe.com

- A power grid is a network (i.e. graph)
- graph node = power grid bus
- edges = power grid lines / transformers



Power Grid in PyPSA

- The object is called pypsa.Network
- Parameters:

argument	type	unit	default	description
name	string	-	-	unique name
snapshots	list / pd.Index	-	[‘now’]	List of time “moments”
snapshot_weightings	pd.DataFrame	hours	1	How long is a time “moment”
now	any	-	‘now’	Current time “moment”
srid	integer	-	4326	Spatial Reference System Identifier

Power Grid in PyPSA

```
In [1]: import pypsa

        grid = pypsa.Network()

In [ ]:
```

```
In [1]: import pypsa

        grid = pypsa.Network(name = 'My Grid')

In [ ]:
```

AC Power Buses

- A bus is the node at which several components of the power system (e.g. generators, loads, transformers) are connected.
- A bus enforces energy and charge conservation laws.
- A bus has 4 parameters:
  - $|\tilde{V}|$ - the amplitude of the voltage;
  - ϕ – the phase angle of the voltage;
  - $P = Re(\tilde{S})$ – the real power;
  - $Q = Im(\tilde{S})$ – the reactive power.

AC Power Buses: Types

- Based on the availability of the parameters, there are 3 types of buses:

Bus Types	$\lvert\widetilde{V}\rvert$	θ	P	Q
Generator Bus (PV-bus)	known	unknown	known	unknown
Load Bus (PQ-bus)	unknown	unknown	known	known
Slack or Reference Bus	known	known	unknown	unknown

220 V ± 5%

Generator Bus

- Has at least one generator connected to it;
- The voltage amplitude is kept constant by controlling the reactive power.

Load Bus

- There are no generators connected to this bus;
- The load bus voltage can be permitted within a tolerable value (i.e. 5%);
- The phase angle is of little importance for the load.

Slack Bus

- Injects or absorbs active or reactive power from the system;
- Doesn’t have any loads connected to it;
- The phase angle is usually taken as 0;
- The slack bus is an artificial concept in load flow studies as the resistive losses of the system are not know accurately in advance;
- The slack bus is chosen arbitrarily from the busses that meet the conditions (no load, at least one generator);

Buses in PyPSA

- Use pypsa.Network.add(class_name='Bus') to add new buses.
- Parameters:

argument	type	unit	default	description
name	string	-	-	unique name
v_nom	float	kV	1	Nominal voltage
x	float	-	0	Position in the SRID system (longitude)
y	Float	-	0	Position in the SRID system (latitude)
carrier	string	-	AC	The carrier ('AC', 'DC', 'heat', 'gas' etc)
unit	string	-	None	Unit for the bus carrier (usually `MW`)
v_mag_pu_set	string / Series	/unit	1	Voltage magnitude set point.

Buses in PyPSA

In [1]:
```
import pypsa

grid = pypsa.Network(name = 'My Grid')
grid.add(
    class_name = 'Bus',
    name = 'Bus #1',
    v_nom = 0.22,
    x = 44.4268,
    y = 26.1025
)
```

In [2]:
```
grid.buses
```

Out[2]:

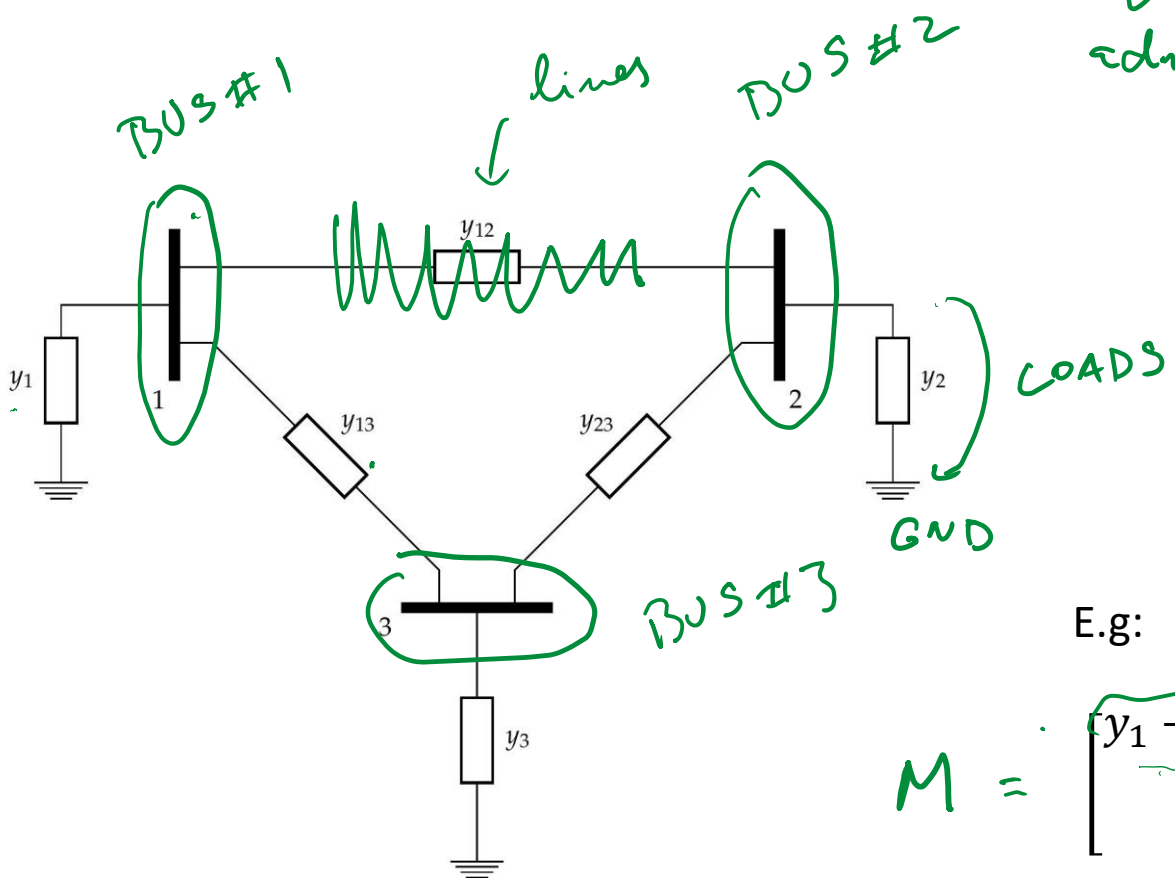
attribute	v_nom	type	x	y	carrier	unit	v_mag_pu_set	v_mag_pu_min	v_mag_pu_r
Bus #1	0.22		44.4268	26.1025	AC	None	1.0	0.0	

Bus Admittance Matrix

$Y = \frac{1}{Z}$ ← imp

↓ adm

$\tilde{I} = M \tilde{V}$



$$Y_{il} = \begin{cases} y_i + \sum_{\substack{k=1 \\ k \neq l}}^{N} y_{ik}, i = l \\ -y_{il}, i \neq l \end{cases}$$

$y_{il} = 0 \Leftrightarrow$ bus i is not connected to bus l.

E.g:

$$M = \begin{bmatrix} y_1 + y_{12} + y_{13} & -y_{12} & -y_{13} \\ -y_{12} & y_2 + y_{12} + y_{23} & -y_{23} \\ -y_{13} & -y_{23} & y_3 + y_{13} + y_{23} \end{bmatrix}$$

BUS #	1	2	3
1	-	0	-
2	0	-	-
3	-	-	-

Bus Equations

- In a system with N buses, for each bus $i \in \overline{1, N}$:

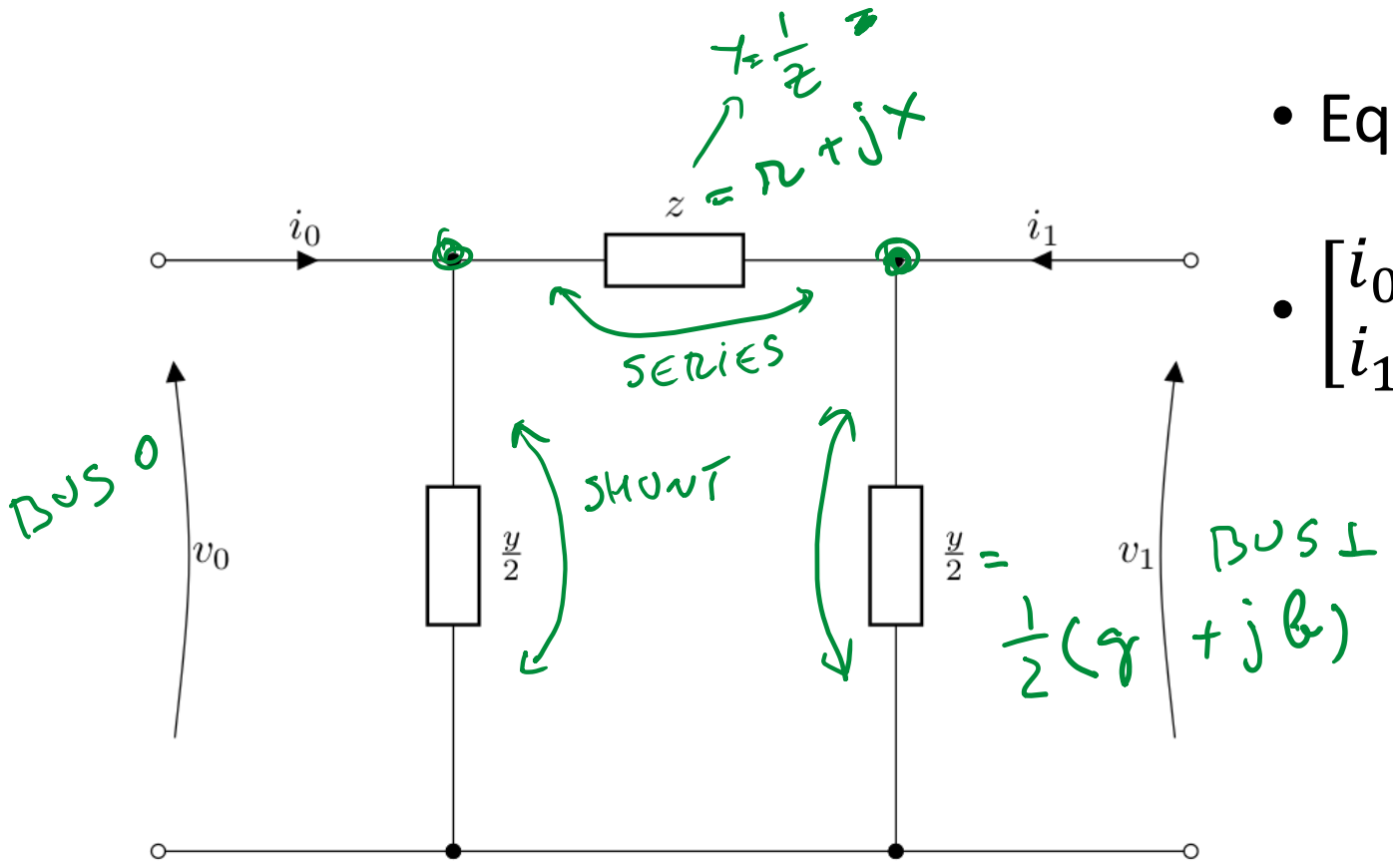
$$\begin{cases} P_i = \sum_{k=1}^{N} |\widetilde{V_i}||\widetilde{V_k}|(Re(Y_{ik})\cos(\phi_i - \theta_k) + Im(Y_{ik})\sin(\phi_i - \theta_k)) \\ Q_i = \sum_{k=1}^{N} |\widetilde{V_i}||\widetilde{V_k}|(Re(Y_{ik})\sin(\phi_i - \theta_k) - Im(Y_{ik})\cos(\phi_i - \theta_k)) \end{cases}$$

- Y is the bus admittance matrix, θ_i is the phase angle on bus i;
- P_i, Q_i are the active and reactive powers from bus i.

Lines

- Lines are transmission and distribution lines. In the network (graph) language they represent edges between the network's nodes.
- One line can connect two busses, both either AC or DC.
- Standard line properties can be found here:
  - https://pandapower.readthedocs.io/en/latest/std_types/basic.html

Line Model



- Equation:
- $$\begin{bmatrix} i_0 \\ i_1 \end{bmatrix} = \begin{bmatrix} \frac{1}{z} + \frac{y}{2} & -\frac{1}{z} \\ -\frac{1}{z} & \frac{1}{z} + \frac{y}{2} \end{bmatrix} \begin{bmatrix} v_0 \\ v_1 \end{bmatrix}$$

Lines in PyPSA

- Use pypsa.Network.add(class_name='Line') to add new lines.
- Parameters:

argument	type	unit	default	Description
name	string	-	-	unique name
bus0	string	-	-	The name of the 1st connected bus
bus1	string	-	-	The name of the 2nd connected bus
type	string	-	-	e.g. '149-AL1/24-ST1A 10.0'
x	float	Ω	0	Series reactance: z = r + jx
r	float	Ω	0	Series resistance: z = r + jx
g	float	S	0	Shunt conductivity: y = g + jb
b	float	S	0	Shunt susceptance: y = g + jb

Lines in PyPSA

In [1]:
```
import pypsa

grid = pypsa.Network(name = 'My Grid')
grid.add(
    class_name = 'Bus',
    name = 'Bus #1',
    v_nom = 0.22,
    x = 44.4268,
    y = 26.1025
)
grid.add(
    class_name = 'Bus',
    name = 'Bus #2',
    v_nom = 0.22,
    x = 44.9367,
    y = 26.0129
)
```

In [2]:
```
grid.add(
    class_name = 'Line',
    name = 'Line #1',
    bus0 = 'Bus #1', bus1 = 'Bus #2',
    x = 0.1, r = 0.01
)
grid.lines
```

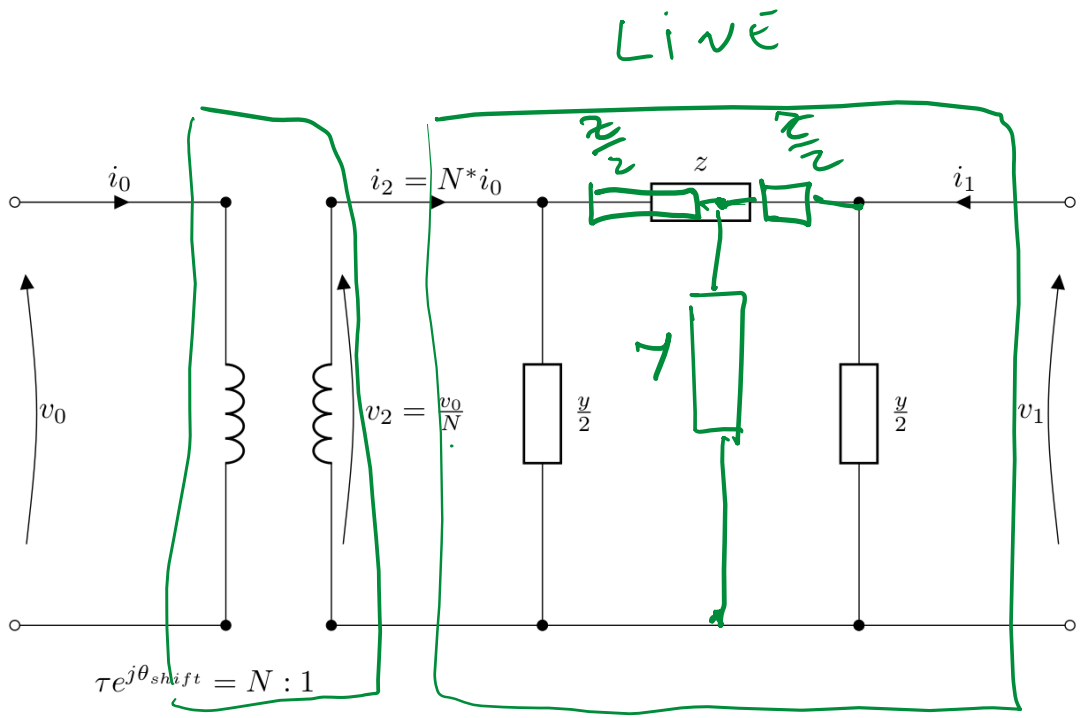
Out[2]:

attribute	bus0	bus1	type	x	r	g	b	s_nom	s_nom_extendable	s_nom_min	...	v_ang_min	v_ang_max
Line #1	Bus #1	Bus #2		0.1	0.01	0.0	0.0	0.0	False	0.0	...	-inf	inf

Transformers

- Transformers are edges In the network (graph) language that connect two different AC busses with different voltages.
- There are two physical models for a transformer:
  - “t” configuration, having two series impedances and one shunt admittance;
  - “pi” configuration, having two shunt admittances and one series impedance.
- Standard transformer types are available here:
  - https://pandapower.readthedocs.io/en/latest/std_types/basic.html#transformers

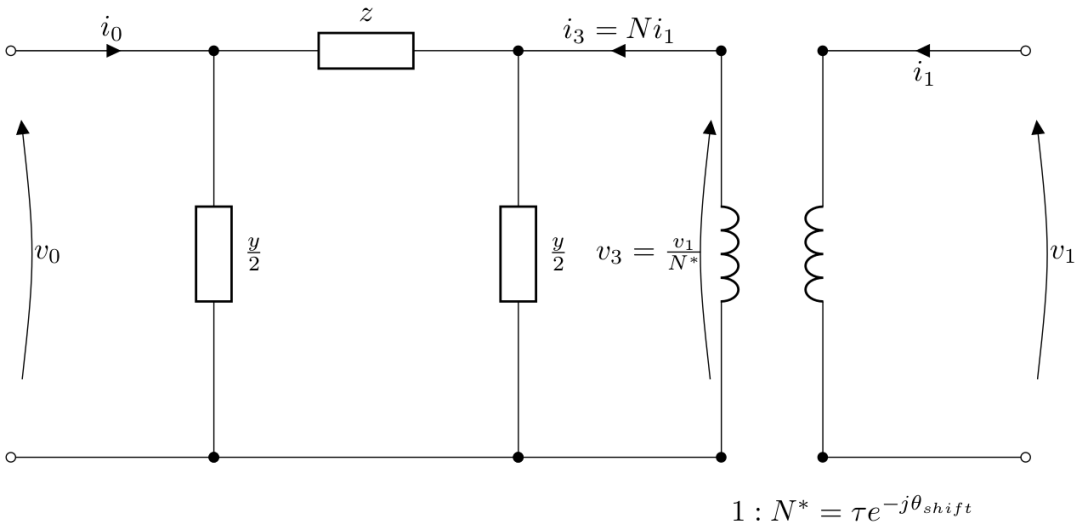
Transformer Models (I)



- Equation:
- $$\begin{bmatrix} i_0 \\ i_1 \end{bmatrix} = \begin{bmatrix} \frac{1}{z} + \frac{y}{2} & -\frac{1}{z}\frac{1}{\tau e^{-j\theta}} \\ -\frac{1}{z}\frac{1}{\tau e^{j\theta}} & \left(\frac{1}{z} + \frac{y}{2}\right)\frac{1}{\tau^2} \end{bmatrix} \begin{bmatrix} v_0 \\ v_1 \end{bmatrix}$$

$pi = \pi$

Transformer Models (II)



- Equation:
- $$\begin{bmatrix} i_0 \\ i_1 \end{bmatrix} = \begin{bmatrix} \left(\frac{1}{z} + \frac{y}{2}\right)\frac{1}{\tau^2} & -\frac{1}{z}\frac{1}{\tau e^{-j\theta}} \\ -\frac{1}{z}\frac{1}{\tau e^{j\theta}} & \frac{1}{z} + \frac{y}{2} \end{bmatrix} \begin{bmatrix} v_0 \\ v_1 \end{bmatrix}$$

Transformers in PyPSA

- Use pypsa.Network.add(class_name='Transformer')

argument	type	unit	default	Description
name	string	-	-	unique name
bus0	string	-	-	The name of the 1st connected bus
bus1	string	-	-	The name of the 2nd connected bus
type	string	-	-	e.g. '0.63 MVA 20/0.4 kV'
x / r	float	Ω	0	Series: z = r + jx
g / b	float	S	0	Shunt: y = g + jb
tap_ratio	float	/unit	1	Ratio of per unit voltages at each bus
tap_side	int	-	0	Which tap is connected directly to a bus
phase_shift	float	degree	0	Voltage phase angle shift.

Links

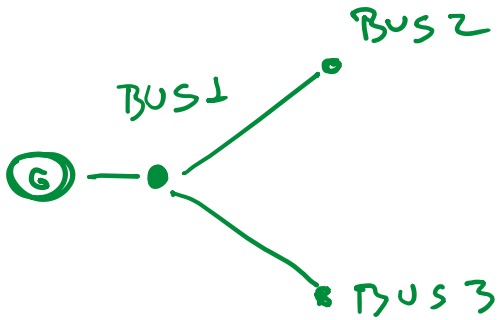
- Links are edges between arbitrary carrier buses.
- They are useful for defining converters between two different carriers (e.g. ‘AC’ to ‘DC’, ‘Wind’ to ‘AC’, etc.).
- The main parameter is the conversion efficiency between the connected buses.
- The efficiency can be set as a time dependent series.

Links in PyPSA

- Use pypsa.Network.add(class_name='Link') to add new lines.
- Parameters:

argument	type	unit	default	Description
name	string	-	-	unique name
bus0	string	-	-	The name of the 1st connected bus
bus1	string	-	-	The name of the 2nd connected bus
carrier	string	-	-	Energy carrier transported. E.g. 'DC'
efficiency	float / Series	-	1	Efficiency of converting from bus0 to bus1
p_nom	float	MVA	0	Limit of power which can pas through.
p_nom_min	float	MVA	0	If p_nom is expandable, its min value.
p_nom_max	float	MVA	inf	If p_nom is expandable, its max value.

Generators



- Generators attach to a single bus and can feed in power.
- It converts energy from its carrier to the carrier-type of the bus to which it is attached.
- Generators can be:
  - conventional generators, providing power anywhere withing a given range;
  - environment-dependent generators, providing power withing limits set as time series.
- For generators, if $P > 0$ the generator is supplying active power to the bus and if $Q > 0$ it is supplying reactive power (i.e. behaving like a capacitor).

Generators in PyPSA (1)

- Use pypsa.Network.add(class_name='Generator')
- Parameters:

argument	type	unit	default	Description
name	string	-	-	unique name
bus	string	-	-	The name of the connected bus
control	string	-	-	The control strategy 'PQ', 'PV', 'Slack'.
carrier	string	-	-	Energy carrier used. E.g. 'gas', 'coal'
p_nom_expandable	bool	-	False	Flag that defines if the power is expandable
p_nom	float	MVA	0	Nominal power.
p_nom_min	float	MVA	0	If p_nom is expandable, its min value.
p_nom_max	float	MVA	inf	If p_nom is expandable, its max value.

Generators in PyPSA (2)

- Use pypsa.Network.add(class_name='Generator')
- Parameters:

argument	type	unit	default	Description
p_min_pu	float / Series	/unit	-1	Min power output per unit of p_nom
p_max_pu	float / Series	/unit	1	Max power output per unit of p_nom
p_set	float	MW	0	Active power set point.
q_set	float	Mvar	0	Reactive power set point.
marginal_cost	float / Series	/MWh	0	Production cost of 1MWh
capital_cost	float	/MW	0	Cost of expanding capacity with 1MW
efficiency_store	float	/unit	1	Efficiency of storage energy.
efficiency_dispatch	float	/unit	1	Efficiency of stored energy dispatching.

percent

0

0

NO STORAGE

Generators in Python with PyPSA

In [3]:
```
grid.add('Generator', 'My gen',
            bus='My bus #0',
            p_set = 100,
            control = 'PQ')

grid.generators
```

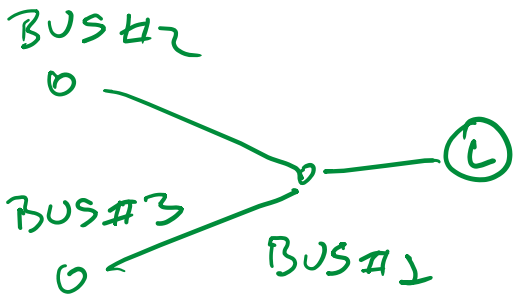
Out[3]:

attribute	bus	control	type	p_nom	p_nom_extendable	p_nom_min	p_nom_max	p_min_pu	p_max_pu	p_set	...	shut_down_cost	min_up_time	min_down_ti
My gen	My bus #0	PQ		0.0	False	0.0	inf	0.0	1.0	100.0	...	0.0	0	

1 rows × 30 columns

Loads

- The load attaches to a single bus and consumes power as a PQ load.
- If $P > 0$ the load is consuming active power from the bus and if $Q > 0$ it is consuming reactive power (i.e. behaving like an inductor).



Loads in PyPSA

- Use pypsa.Network.add(class_name='Generator')
- Parameters:

argument	type	unit	default	Description
name	string	-	-	unique name
bus	string	-	-	The name of the connected bus
carrier	string	-	-	Energy carrier used. E.g. 'AC', 'DC'
p_set	float / Series	MW	0	Active power consumption set point.
q_set	float / Series	Mvar	0	Reactive power consumption set point.
sign	float	-	-1	1 = consumer / -1 = generator

Loads in Python with PyPSA

In [4]:
```
grid.add('Load','My load',
             bus='My bus #1',
             p_set=100)

grid.loads
```

Out[4]:

attribute	bus	carrier	type	p_set	q_set	sign
My load	My bus #1			100.0	0.0	-1.0

Check for Model Convergence

```
In [5]: grid.pf()
```

```
INFO:numexpr.utils:NumExpr defaulting to 8 threads.
INFO:pypsa.pf:Performing non-linear load-flow on AC sub-network SubNetwork 0 for snapshots Index(['now'], dtype='obje
ct')
INFO:pypsa.pf:Newton-Raphson solved in 2 iterations with error of 0.000000 in 0.016957 seconds
```

```
Out[5]: {'n_iter':      0
         now  2,
         'error':                 0
         now  1.164135e-10,
         'converged':         0
         now  True}
```

Model Solutions

In [6]:
```
grid.lines_t.p0
```

Out[6]:

	My line #0	My line #1	My line #2
now	66.667585	-33.333333	-33.333563

In [7]:
```
grid.buses_t.v_ang*180/np.pi
```

Out[7]:

	My bus #0	My bus #1	My bus #2
now	0.0	-0.007892	-0.003946

In [8]:
```
grid.buses_t.v_mag_pu
```

Out[8]:

	My bus #0	My bus #1	My bus #2
now	1.0	0.999986	0.999993

Thank you!