AC/DC power flow aimed at large scale systems

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Large Scale Systems Week

eRoots Analytics

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Contents

Motivation

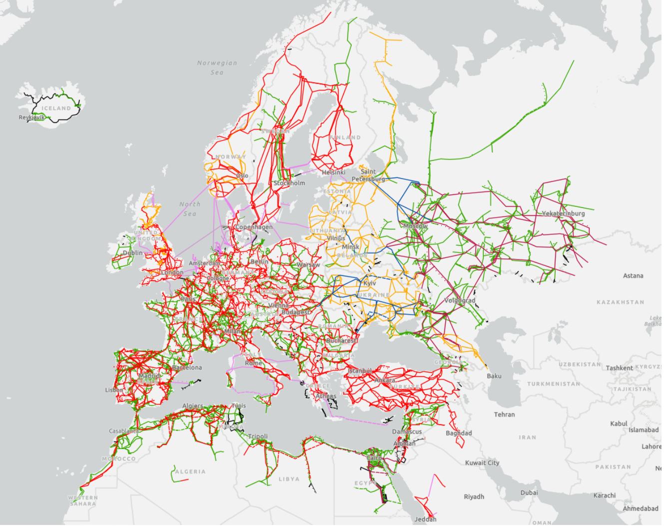

Figure 1: Grid map of Europe, with HVDC links in purple.

Objectives

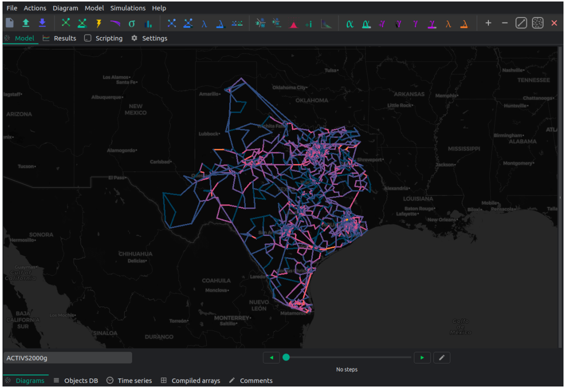

Figure 2: GridCal interface used for power flow analysis in Spain.

- Integrate both AC and DC systems into a unified framework.
- Address the convergence issues found in current methods.
- Model complex components like converters and controllable transformers.
- Implement the method and test its scalability.

Comparison of features

We present a generalised approach to the power flow problem, much more flexible than conventional methods.

Feature	**Traditional**	**Classical**	**Generalised**
Handles AC systems	✓	✓	✓
Remote controls	×	×	✓
Control more than two magnitudes at a bus	×	✓	✓
Controlled branch magnitudes	×	✓	✓
Interconnected AC/DC grids	×	✓	✓
Flexible bus type definition	×	×	✓

Table 1: Comparison between traditional, classical, and generalised power flow.

What is a power grid?

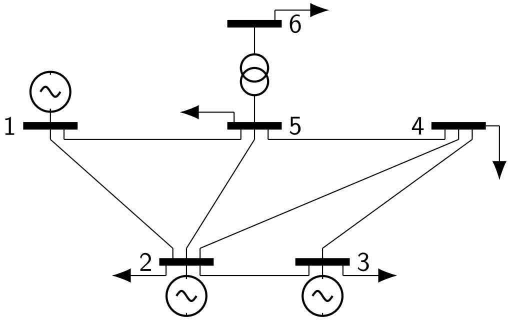

Figure 3: Example grid showing buses linked through branches.

A grid is modeled as an undirected graph the set of buses (nodes) are connected to each other by the set of branches (edges):

- **Buses**: Represent the points in the network where generation, load, or interconnections occur.
- **Branches**: Power lines, transformers and converters, which can be passive or controllable.

Grid of grids

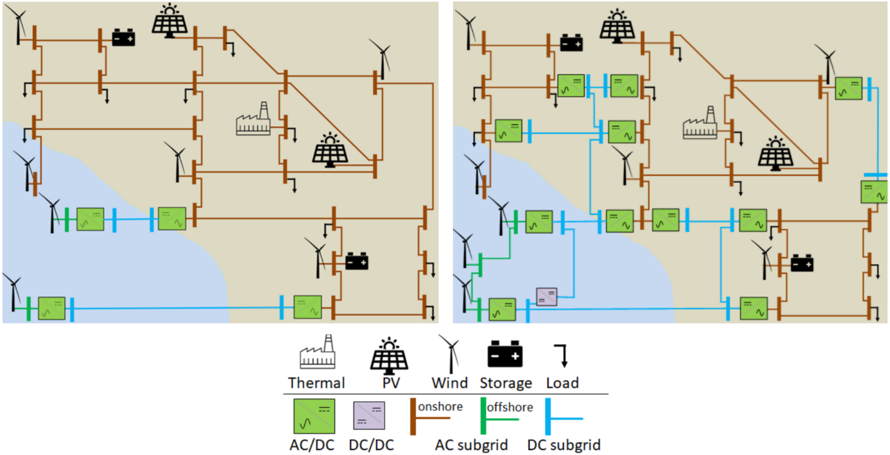

Figure 4: From present grids to future systems.

Voltage Source Converter (VSC)

Voltage source converters (VSCs) interlink AC subsystems with DC subsystems, allowing for controlling two magnitudes. This controllability, while providing more flexibility, also introduces more complexity.

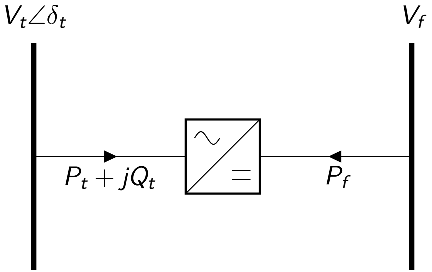

Figure 5: Representation of a VSC.

VSC unification of AC and DC sides

Converters interconnect DC and AC buses. Hence, there are two approaches to the problem:

- **Sequential**: we first solve the AC networks, then the DC networks, merge them, and repeat the calculation → non-scalable
- **Unified**: we solve all AC and DC grids at the same time → much more scalable

The active powers on the f and t sides are related through the power loss equation:

$$\begin{aligned} P_f + P_t &= P_{\text{loss}}, \\ P_f + P_t &= a + b\frac{\sqrt{(P_t)^2 + (Q_t)^2}}{V_t} + c\frac{(P_t)^2 + (Q_t)^2}{V_t^2}. \end{aligned} \tag{1}$$

The power flow problem

- Grid operators are interested in knowing the operating state of the network.
- That is, voltages, currents and powers have to be found everywhere in the grid.
- The underlying equations, which come from the physics, are non-linear in nature.
- Among many solvers, we opt for the Newton-Raphson given its quadratic convergence and scalability properties.

$$\boldsymbol{x} = [\delta, V, \tau, m, P^{\text{zip}}, Q^{\text{zip}}, P_f, P_t, Q_f, Q_t]^T \tag{2}$$

$$\mathbf{g} = [g_{p,ac}, g_{q,ac}, g_{p,dc}, g_{l,acdc}, g_{l,hvdc}, g_{p,hvdc}, g_{p_f,tr}, g_{p_t,tr}, g_{q_f,tr}, g_{q_t,tr}]^T \tag{3}$$

The Newton-Raphson method

- To solve the system using the Newton-Raphson method, we need a Jacobian matrix.
- This matrix contains the partial derivatives of the form $\frac{\partial \mathbf{g}}{\partial \mathbf{x}}$. Two ways to calculate:
  1. Partial differences such as $\frac{\mathbf{g}(\mathbf{x}+h)-\mathbf{g}(\mathbf{x}-h)}{h}$ $\rightarrow$ easier but slower
  2. With previously derived closed-form expressions $\rightarrow$ harder but faster
- The typical Newton-Raphson system is represented as:

$$-\mathbf{J}\Delta\mathbf{x} = \mathbf{g} \tag{4}$$

where:

- $\mathbf{J}$ is the Jacobian matrix.
- $\Delta\mathbf{x}$ is the vector of unknown variations.
- $\mathbf{g}$ is the residual vector of equations.

Rules for solvability

To ensure solvability in generalized power flow, the following rules are defined:

- Each subgrid must have at least one reference for voltage magnitude and angle.
- Control of a remote bus is allowed.
- No two devices can control the same nodal voltage.
- Buses can have up to 4 controlled magnitudes in AC subsystems and 2 in DC subsystems.

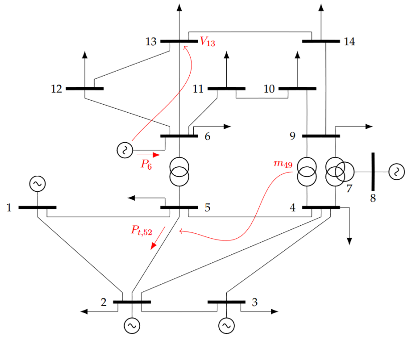

Figure 6: Scheme of the IEEE 14-bus grid with remote controls.

Installation

The three requisites are:

1. Python 3.10 or 3.11.
2. VSCode.
3. GridCal wheels.

Python installation

- For instance, download Python 3.10.9 from https://www.python.org/downloads/release/python-3109/.
- Make sure to add Python to the PATH.

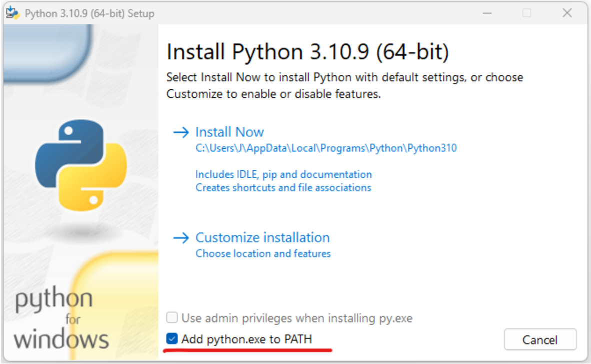

Figure 7: Python installation.

VSCode installation

- Download VSCode from https://code.visualstudio.com/.
- Install the Python extension.

Figure 8: Python VSCode extension.

GridCal installation

- Create a virtual environment in VSCode: Ctrl+Shift+P, then Python: Create Environment.
- Activate with `"./.venv/Scripts/Activate"`.
- Install the latest alpha GridCal release: `pip install GridCal==5.3.0a3`.
- Verify the installation with `pip list`.

Open the interface:

- Windows:

```
python -c "from GridCal.ExecuteGridCal import runGridCal; runGridCal()"
```

- Unix:

```
python3 -c "from GridCal.ExecuteGridCal import runGridCal; runGridCal()"
```

GUI usage: modelling


```
python -c "from GridCal.ExecuteGridCal import runGridCal; runGridCal()"
```

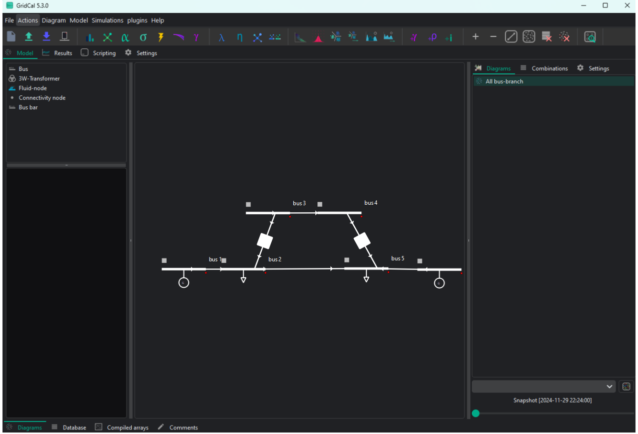

Figure 9: Visualization of the 6-bus grid through the GUI.

- Go over the complete database.
- Check the controls of the generators.
- Check the controls of the VSCs. What to expect?

GUI usage: solving

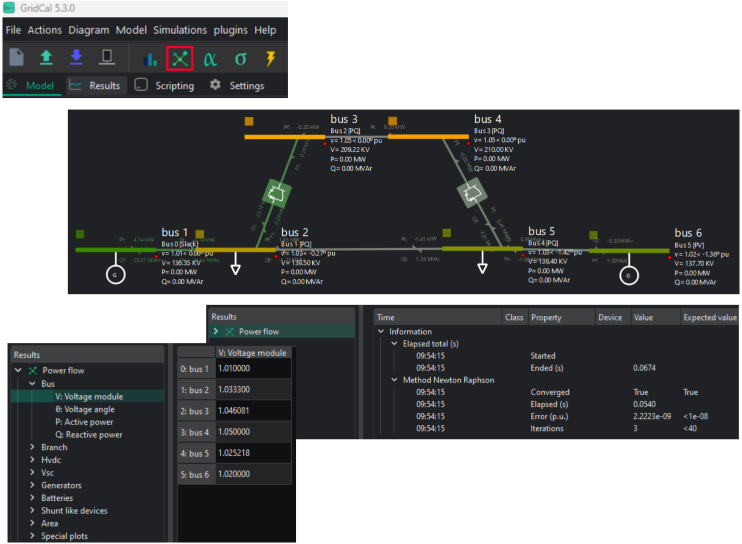

Figure 10: GUI simulation execution, solver selection and results visualization on the 6-bus grid.

A few questions

Solver selection:

- Run the power flow with both the Newton-Raphson and the Gauss-Seidel.
- How many iterations do we need in both?
- What is the computational time?

Control setting:

- What if the two converters control active power?
- What if the two converters control voltage on the DC side?

Scripting: modelling

- Let's move into our code editor.

```python
import numpy as np
import GridCalEngine as gce
from GridCalEngine.enumerations import ConverterControlType

# Grid instantiation
grid = gce.MultiCircuit()

# Define buses
bus1 = gce.Bus(name='B1', Vnom=135, is_slack=True)
...

```

Scripting: solving

- Let's move into our code editor.

```
pf_driver = gce.PowerFlowDriver(grid=grid)
pf_driver.run()
Vm = pf_driver.results.voltage
Va = np.angle(pf_driver.results.voltage, deg=True)

```

Challenges of advanced cases

- The 6-bus case had 1 AC and 1 DC subsystem.
- Transnational grids are composed of many AC and DC grids.
- Real grids may also have controllable transformers.

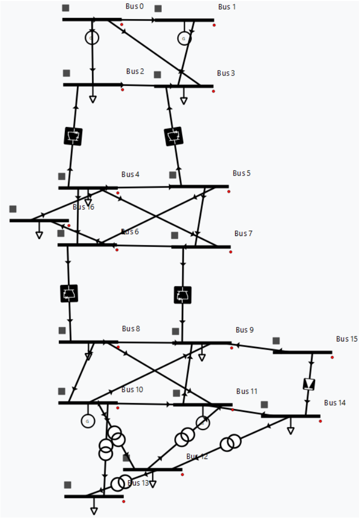

Figure 11: Interconnected AC systems overview.

Issues in the 17-bus cases

What issues are we facing?

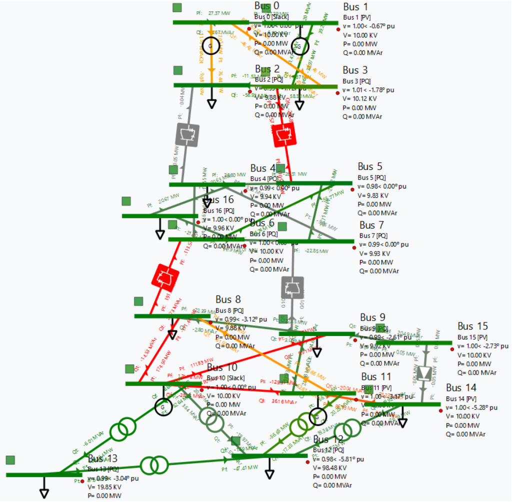

Figure 12: Default interconnected AC system results.

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Fixing issues in the 17-bus cases

Some potential fixes include:

- Adjust the transformer control setpoints.
- Change the VSCs control modes.
- Modify the VSCs control setpoints.
- Regulate the generators voltage reference.

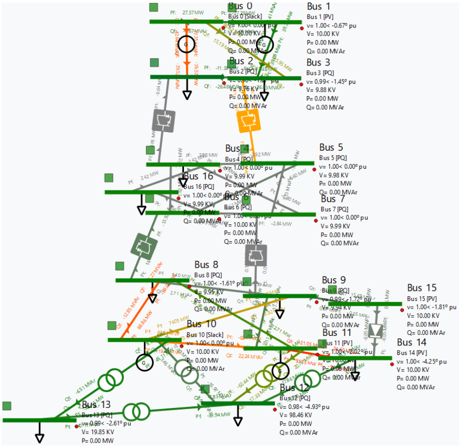


Figure 13: Interconnected AC systems with a feasible solution.

Transformer control

Despite being less flexible than VSCs, some transformers are also controllable:

- m: the tap module can regulate V_m and Q
- τ: the tap angle can adjust P

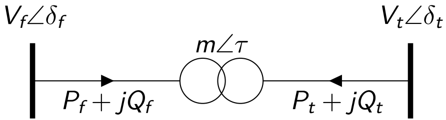


Figure 14: Representation of a controllable transformer.

- Let's increase $V_{m,13}$ to 1.019876 p.u..
- Is it reasonable to have $0.9 \leq m \leq 1.0$?

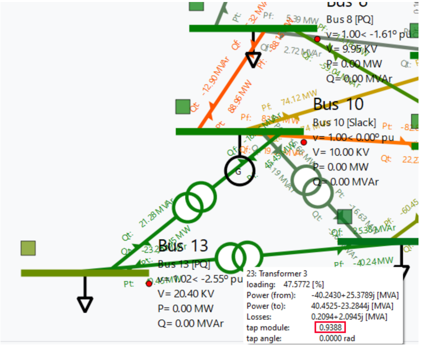


Figure 15: Transformer controlling V_m with m.

What is a large system?

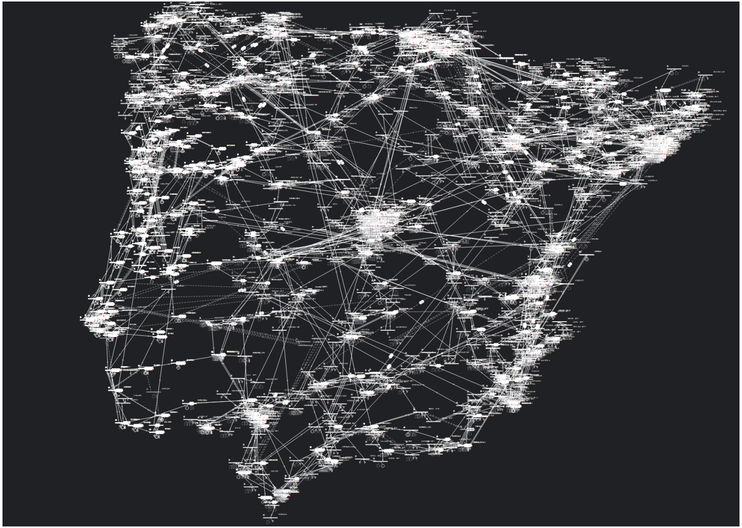


Figure 16: Grid topology of the Iberian system.

What is a large system?

- Note: open the grid of Las Palmas to exemplify.

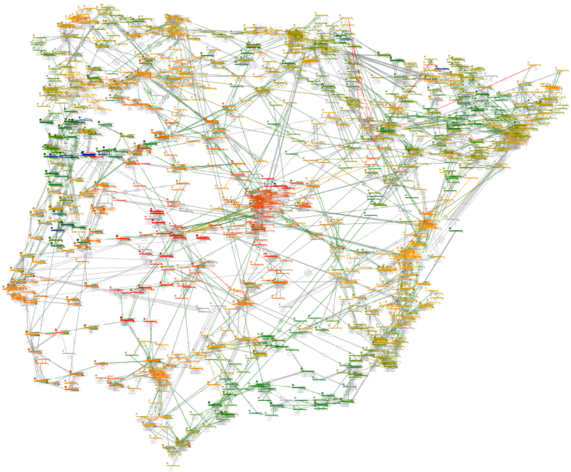


Figure 17: Solved power flow for the Iberian system.

IEEE 118-bus operational overview

- Are voltage magnitudes correct?
- Are branch loadings within limits?
- How could an AC/DC link help?

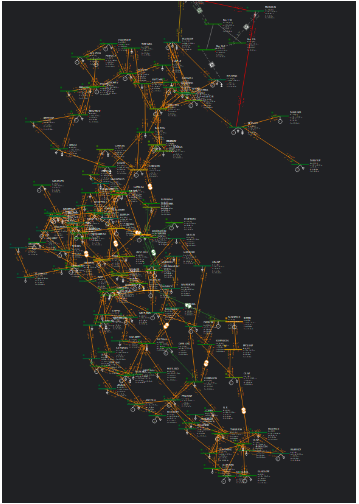
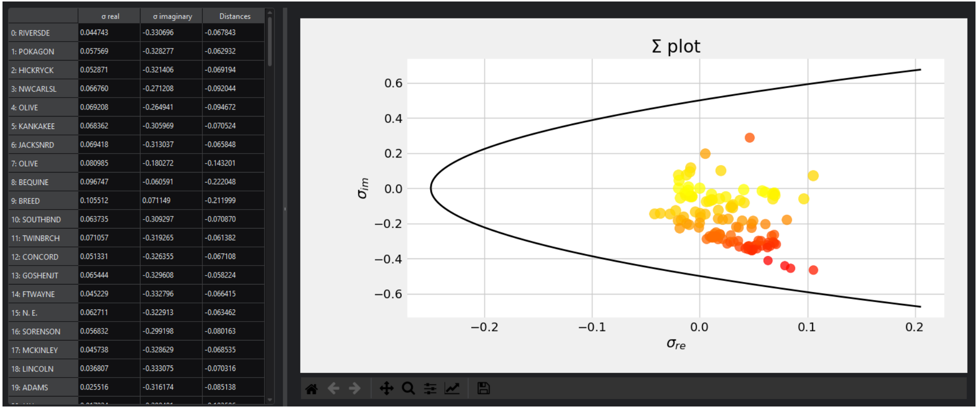


Figure 18: Original operation of the IEEE 118-bus grid.

HELM analysis



	σ real	σ imaginary	Distances
0: RIVERSDE	0.044743	-0.330696	-0.067843
1: POKAGON	0.057569	-0.328277	-0.062932
2: HICKRYCK	0.052871	-0.321406	-0.069194
3: NWCARLSL	0.066760	-0.271208	-0.092044
4: OLIVE	0.069208	-0.264941	-0.094672
5: KANKAKEE	0.068362	-0.305969	-0.070524
6: JACKSNRD	0.069418	-0.313037	-0.065848
7: OLIVE	0.080985	-0.180272	-0.143201
8: BEQUINE	0.096747	-0.060591	-0.222048
9: BREED	0.105512	0.071149	-0.211999
10: SOUTHBND	0.063735	-0.309297	-0.070870
11: TWINBRCH	0.071057	-0.319265	-0.061382
12: CONCORD	0.051331	-0.326355	-0.067108
13: GOSHENJT	0.065444	-0.329608	-0.058224
14: FTWAYNE	0.045229	-0.332796	-0.066415
15: N. E.	0.062711	-0.322913	-0.063462
16: SORENSON	0.056832	-0.299198	-0.080163
17: MCKINLEY	0.045738	-0.328629	-0.068535
18: LINCOLN	0.036807	-0.333075	-0.070316
19: ADAMS	0.025516	-0.316174	-0.085138

Figure 19: HELM's Sigma plot showing showing the complicated feasibility of the systems.

Voltage and branch loading profiles

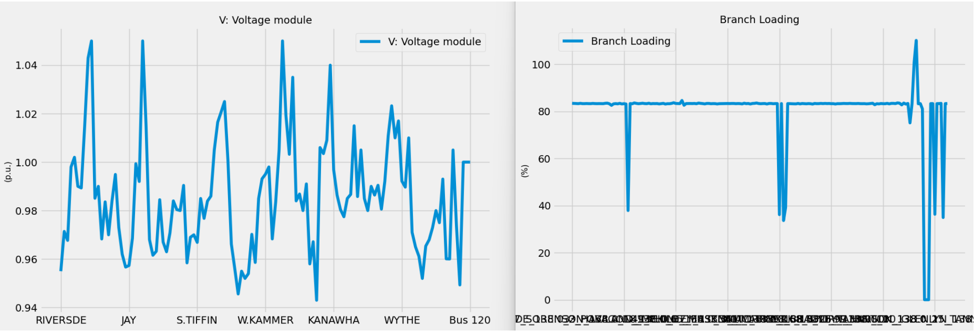


Figure 20: Voltage and branch loadings for the whole IEEE 118-bus system.

VSCs control management

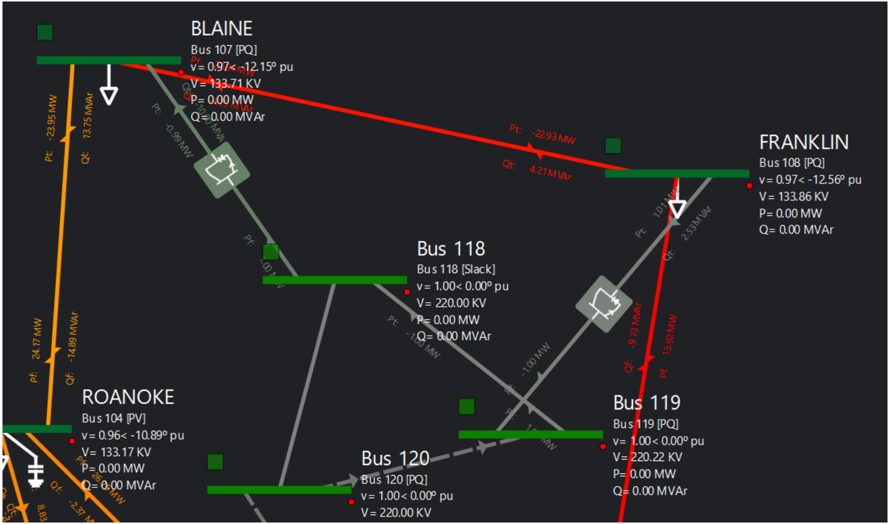


Figure 21: Potential AC/DC link configuration.

Conclusions

- AC/DC converters require a new approach to their modelling.
- The Newton-Raphson method is the go-to algorithm due to its convergence properties.
- Setting the right AC/DC controls is key towards achieving a convergent case.
- Importance of relying on a GUI.

For more information:

- info@eroots.tech
- https://gridcal.readthedocs.io/en/latest/

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