High Fidelity, Year Long Power Network Data Sets for Replicable Power System Research

Pascal Van Hentenryck
University of Michigan

IEEE PES Power & Energy Society®
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Team

- Dan Bienstock, Columbia
  - IOE, optimization, discrete mathematics
- James Anderson, Steven Low, Caltech
  - EECS, control, optimization
- Carleton Coffrin, Russell Bent, LANL
  - CS, optimization
- Ian Hiskens, Ferdinando Fioretto, Pascal Van Hentenryck
  - CS, EECS, IOE
- Patrick Panciatici, RTE
  - all of the above

Overview

- Overview
- Desired Fidelity
- GRG Format
- Transformations
- Case Studies

Overview (1)

- High-fidelity modeling of electricity networks
  - components + control systems
- JSON format to capture the required fidelity
  - useful for operators and optimization software
- Real test cases coming from RTE
  - largest transmission operator in Europe
- Transformation tools and scripting
  - node breaker, bus breaker, bus branch
  - per unit transformations
  - rollback

Overview (2)

- Validation, quality control, and metrics
  - validation of modeling and parameters
  - characterization of problem complexity
- Synthetic test cases
  - graph manipulation, exploiting the structure
- Disaggregation and obfuscation
  - preserving privacy in time series
- Repository
  - replicable research

JSON Format

- Capture electrical power system with high fidelity
  - components, constraints, corrective actions, …
- Cognizant of computational issues
  - the distance to solvers must be small
  - the translation should be efficient computationally
- Extensibility
  - the format can easily accommodate new components, attributes, …
- Standard, modern, and reusable technology
  - JSON is becoming ubiquitous

Targeted Audience

- No unique audience
  - operators running the system
  - developers of the underlying solvers
- Operators
  - would like to see the physical organization of the network
    - A substation is a meaningful concept and should be preserved
  - would like to see actual units for
    - e.g., voltage magnitudes
- Tool developers
  - would like to start from a representation which is as close as possible to the solver needs

Overview

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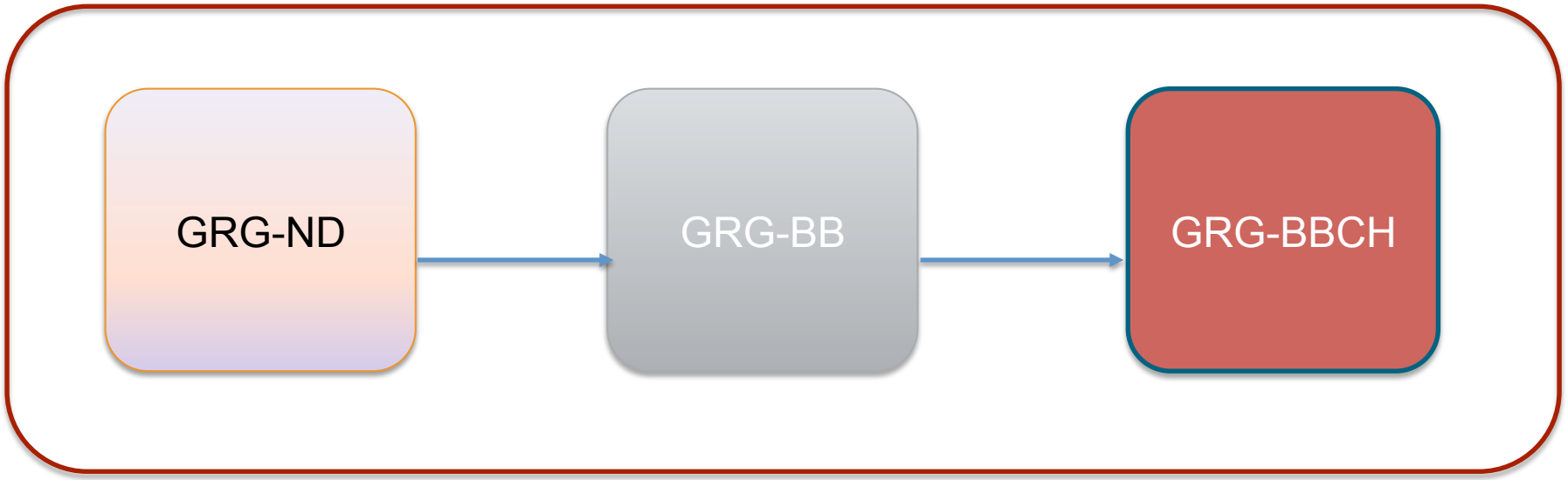
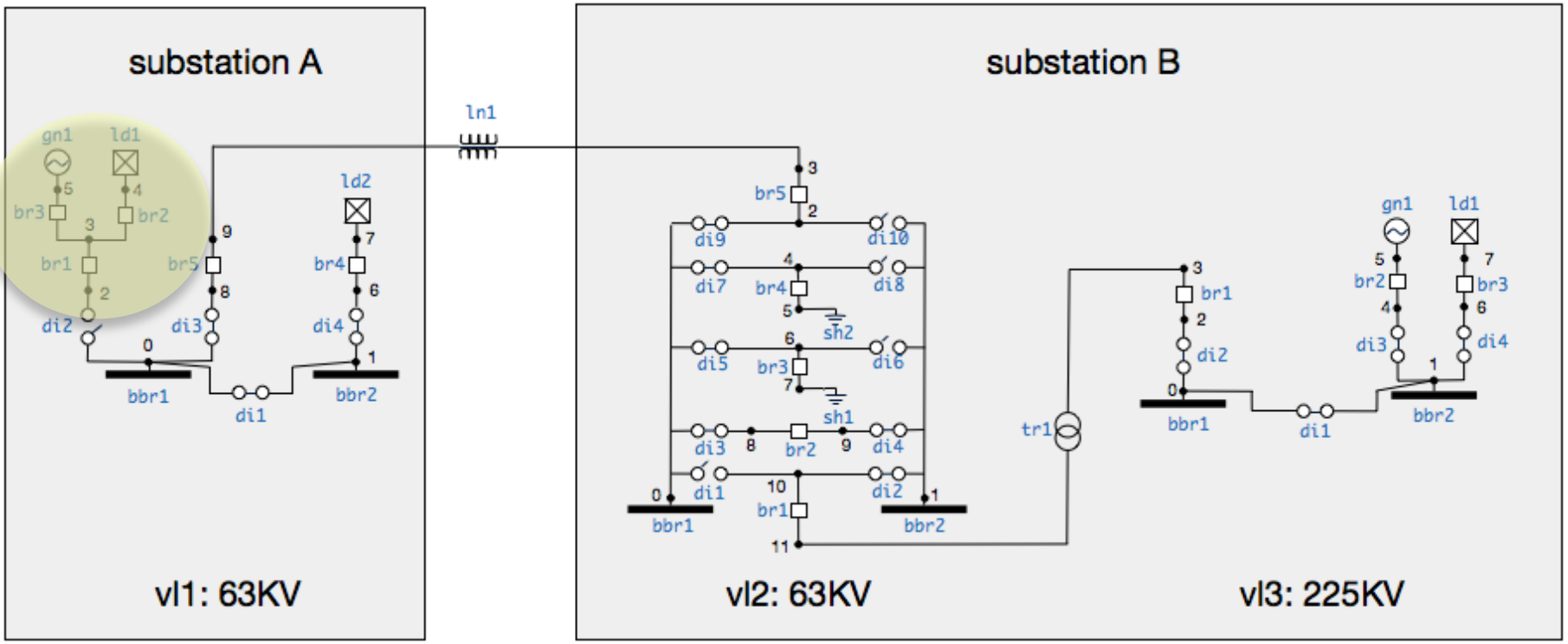
Philosophy

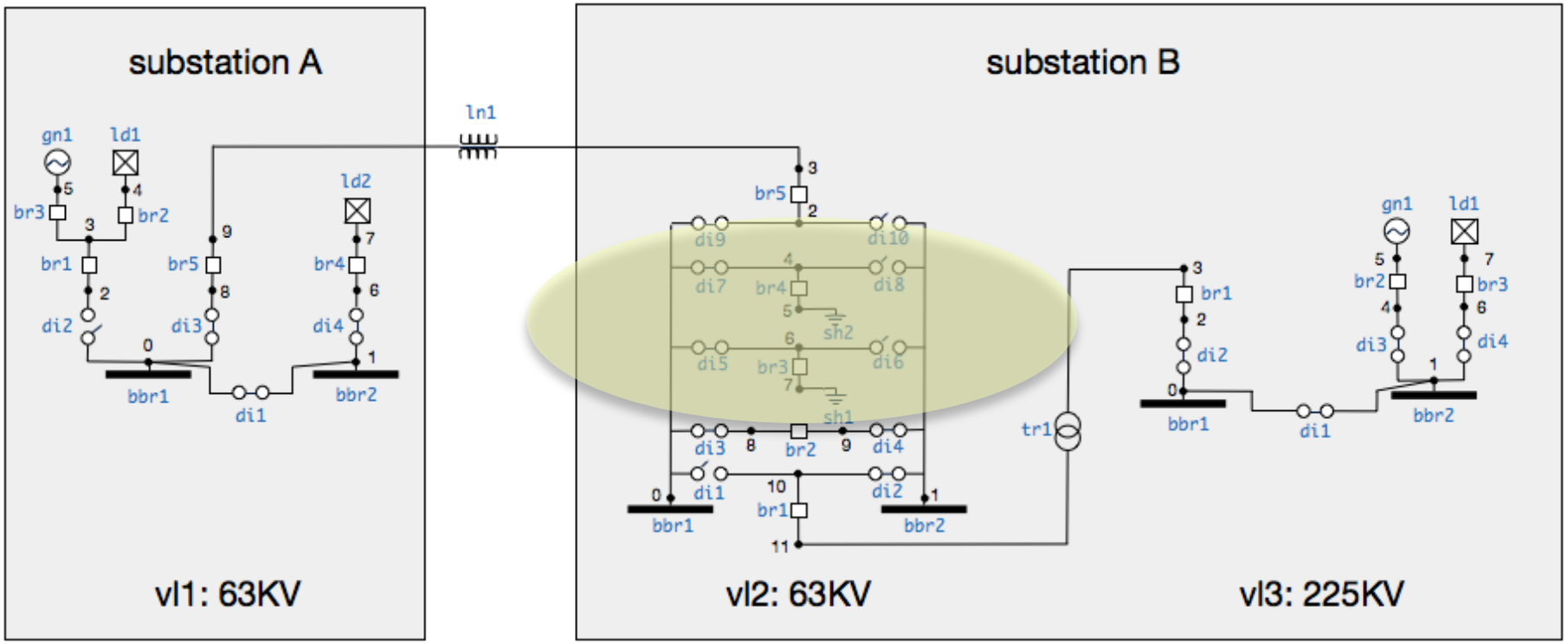


Node Breaker Bus Breaker Bus Branch

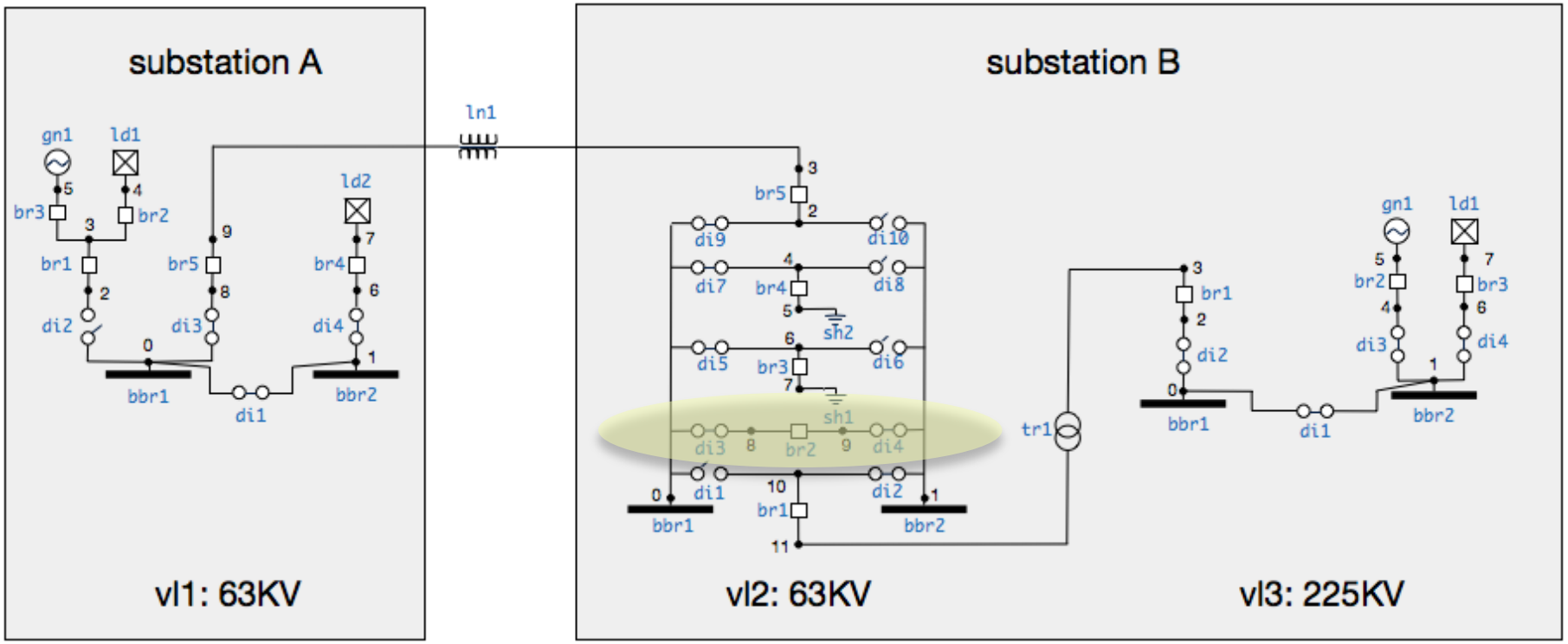
GRG-NB: The Physical Network



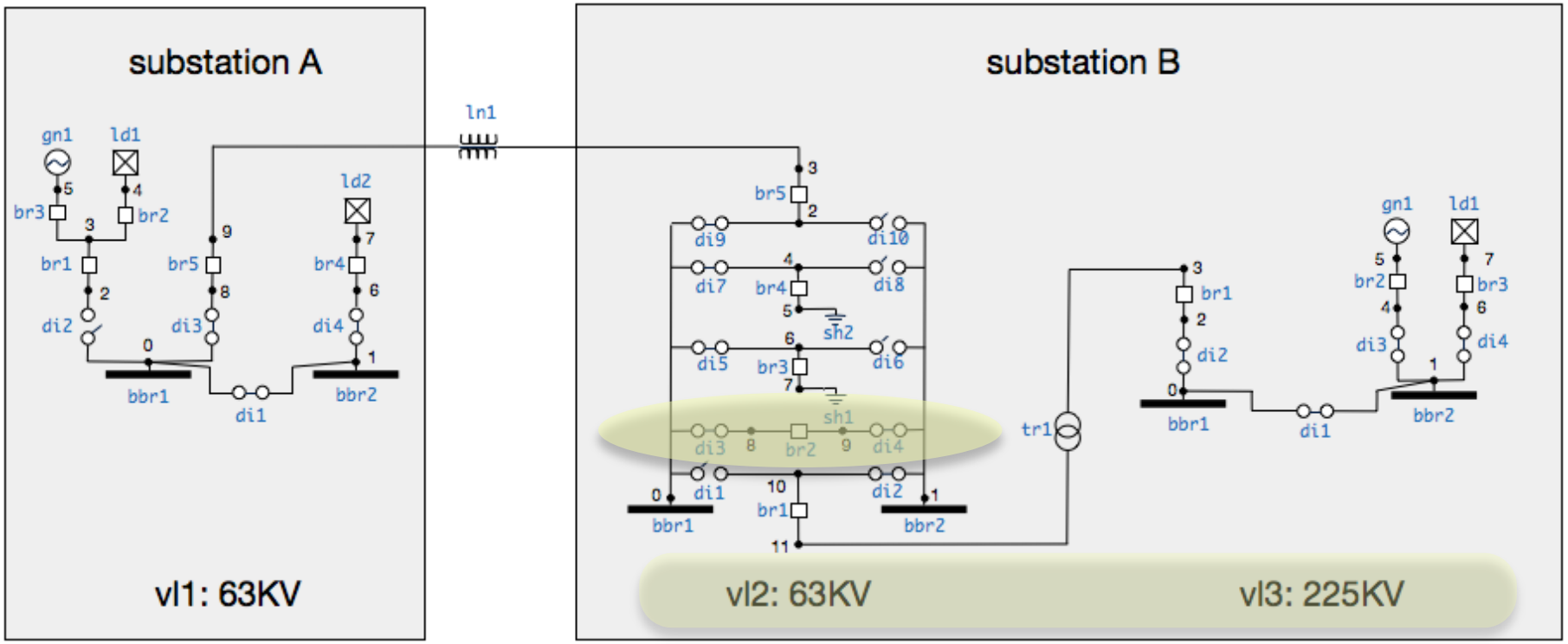
GRG-NB: The Physical Network



GRG-NB: The Physical Network



GRG-NB: The Physical Network

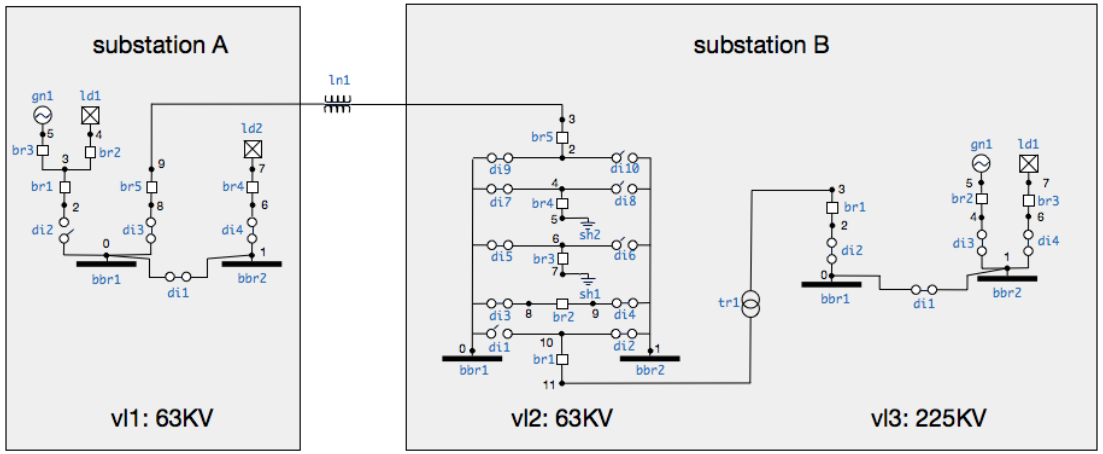


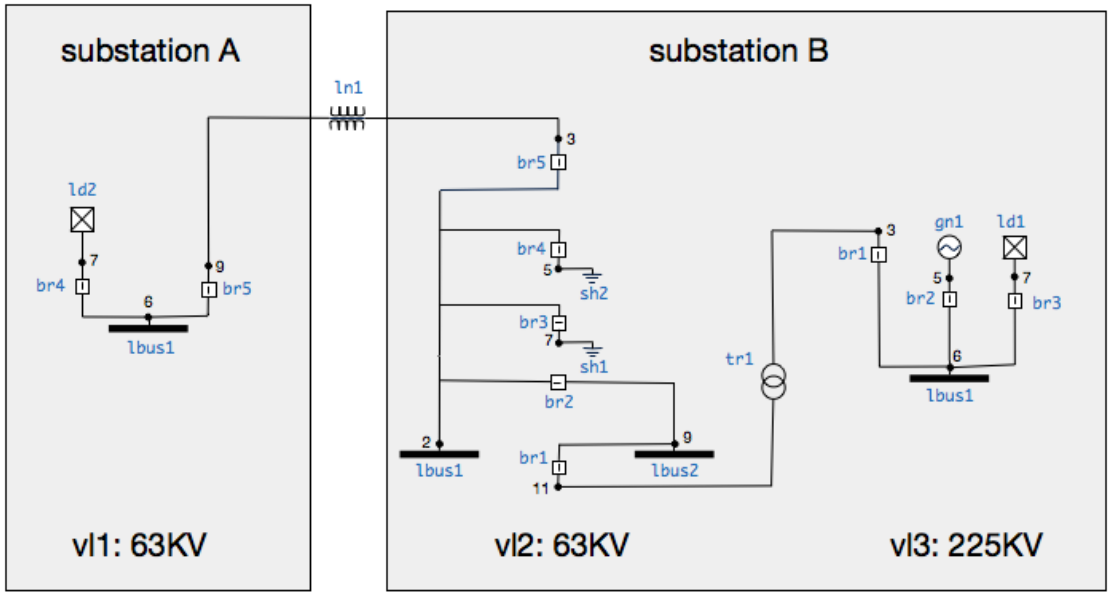
GRG Formats

	Node-breaker	Bus-breaker	Bus-branch
Topology	yes	yes	no
Breakers	yes	yes	no
Disconnectors	yes	no	no
Bus type	busbar	logical bus	bus

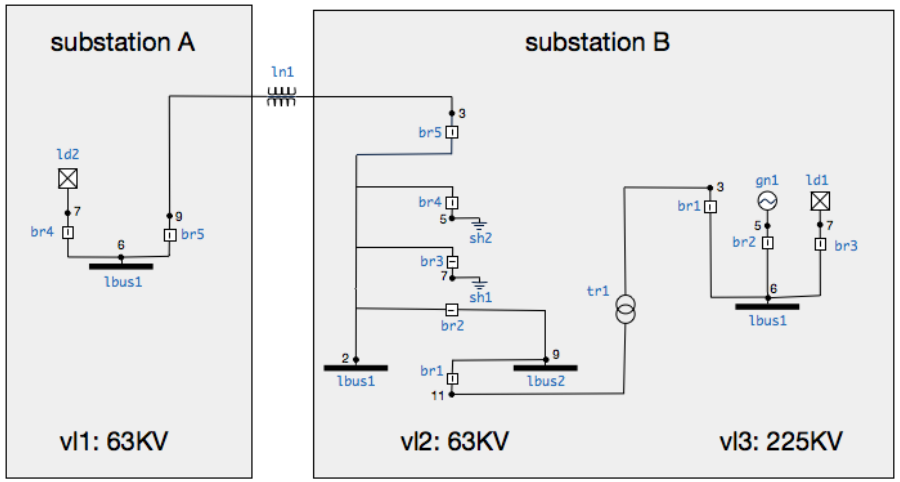
- GRG-NB and GRG-BB
  - topology optimization
  - NB: planning studies
  - BB: operational studies

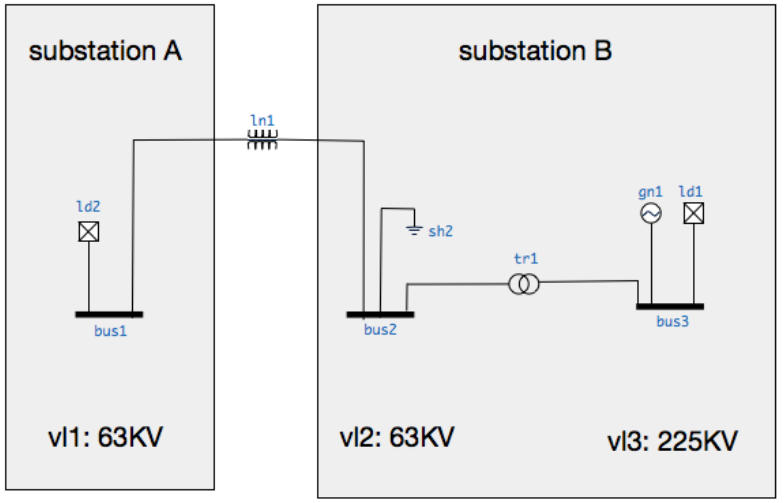
From GRG-ND to GRG-BB



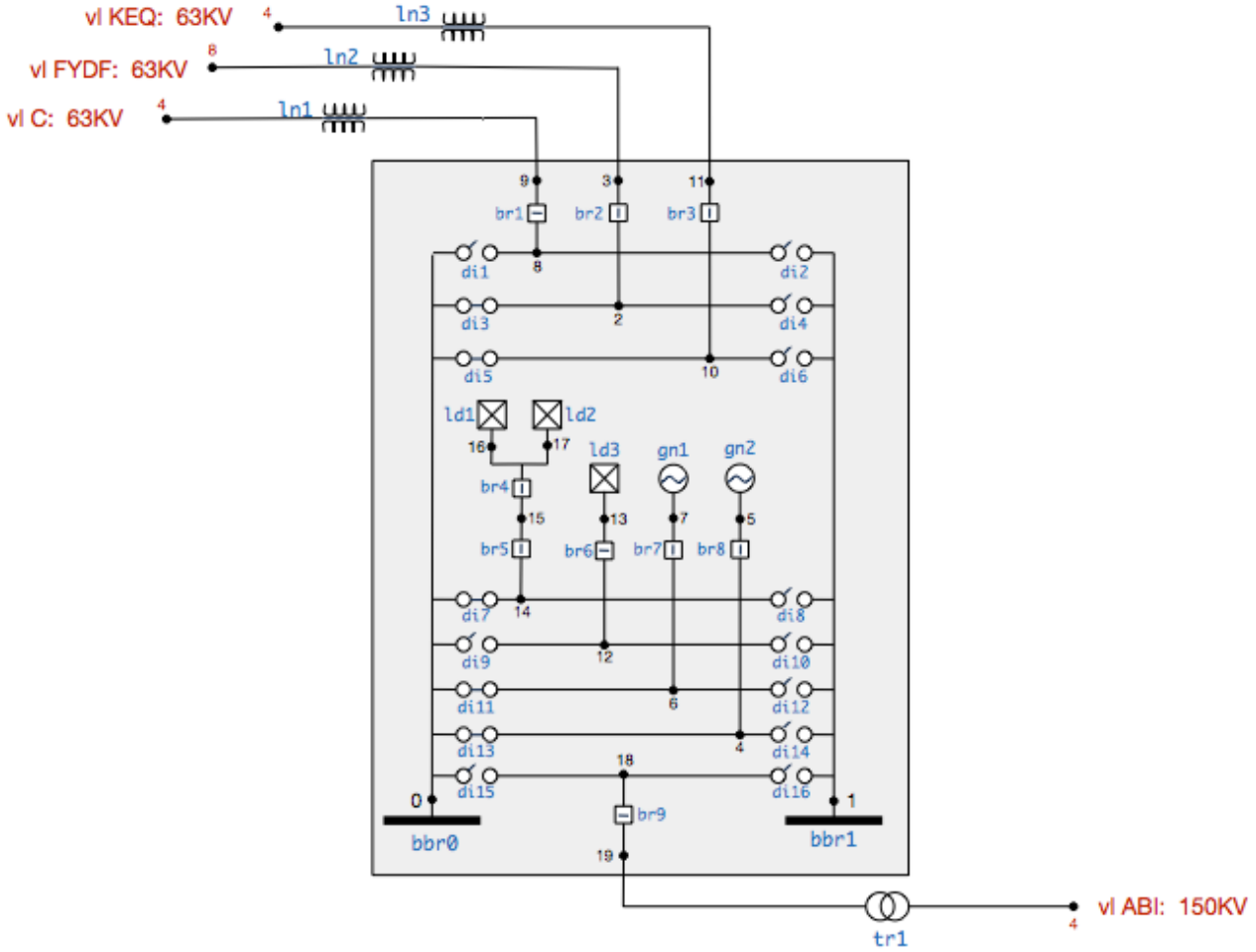


From GRG-BB to GRB-BBCH

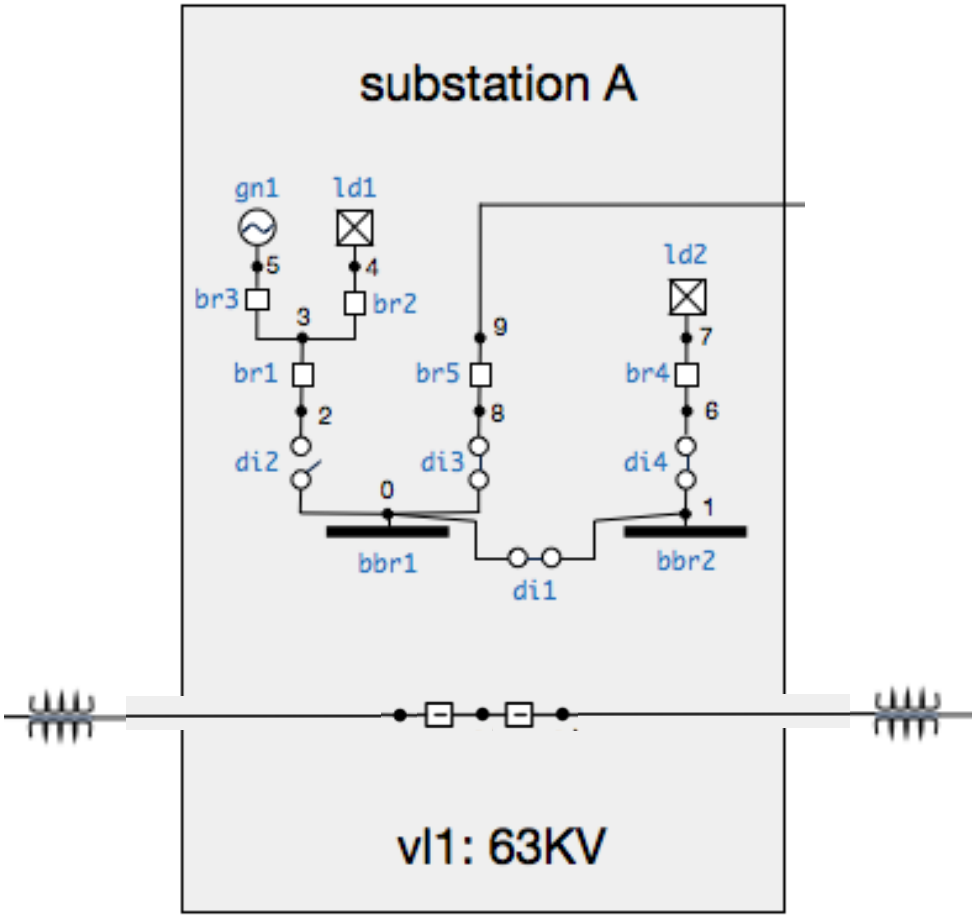




Real-Life Networks (at RTE)



Real-Life Networks (at RTE)



Overview

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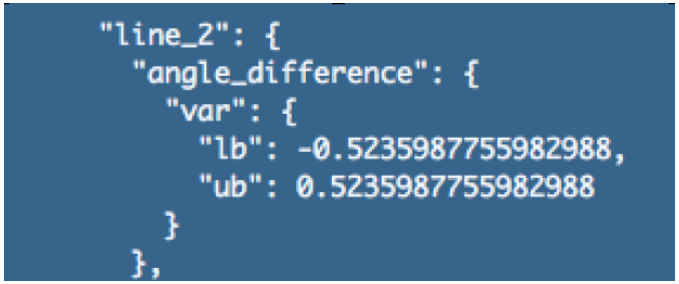
Key Concepts of the Format

- Electrical abstractions
  - e.g., admittance
- Component references
  - JSON pointers
- Explicit distinction between
  - parameters and decision variables
- Logical buses
  - abstraction of busbars in bus breaker representation
- Substations
  - with voltage levels

Variables versus Parameters

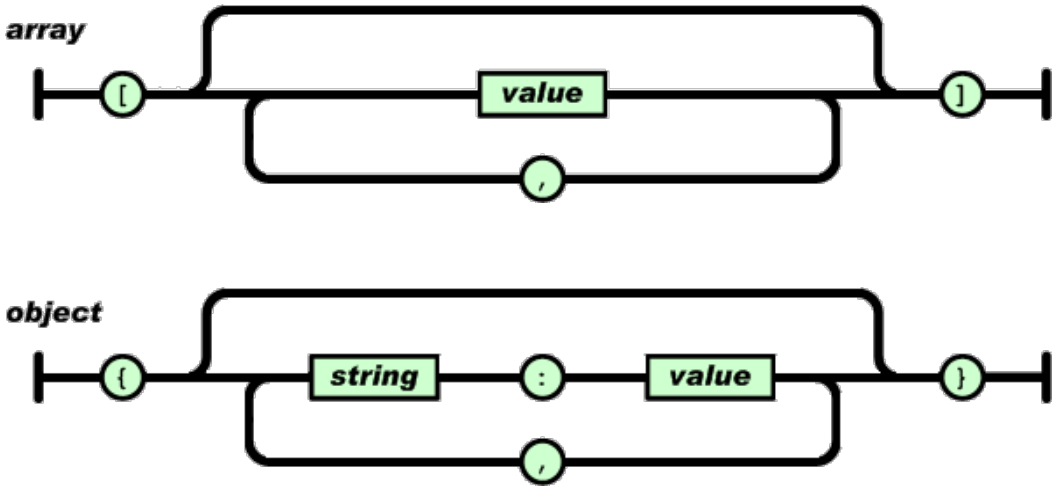
- Key motivation
  - one network description
  - multiple uses (opf, ots, ..)
- Assignments
  - specializes the networks
  - specific examples of transformations
- Basic philosophy
  - one physical network
  - separate sections describing configurations, setpoints, solutions, …



JSON 101

- **Primitive types**
  - string
  - number (int or float)
  - boolean (true, false)
  - null

Recursive Types



Key benefit: JSON can be parsed into a dictionary-like data structure in any language

JSON Schema

- Specify the format formally
- Can we use to check whether a file is valid

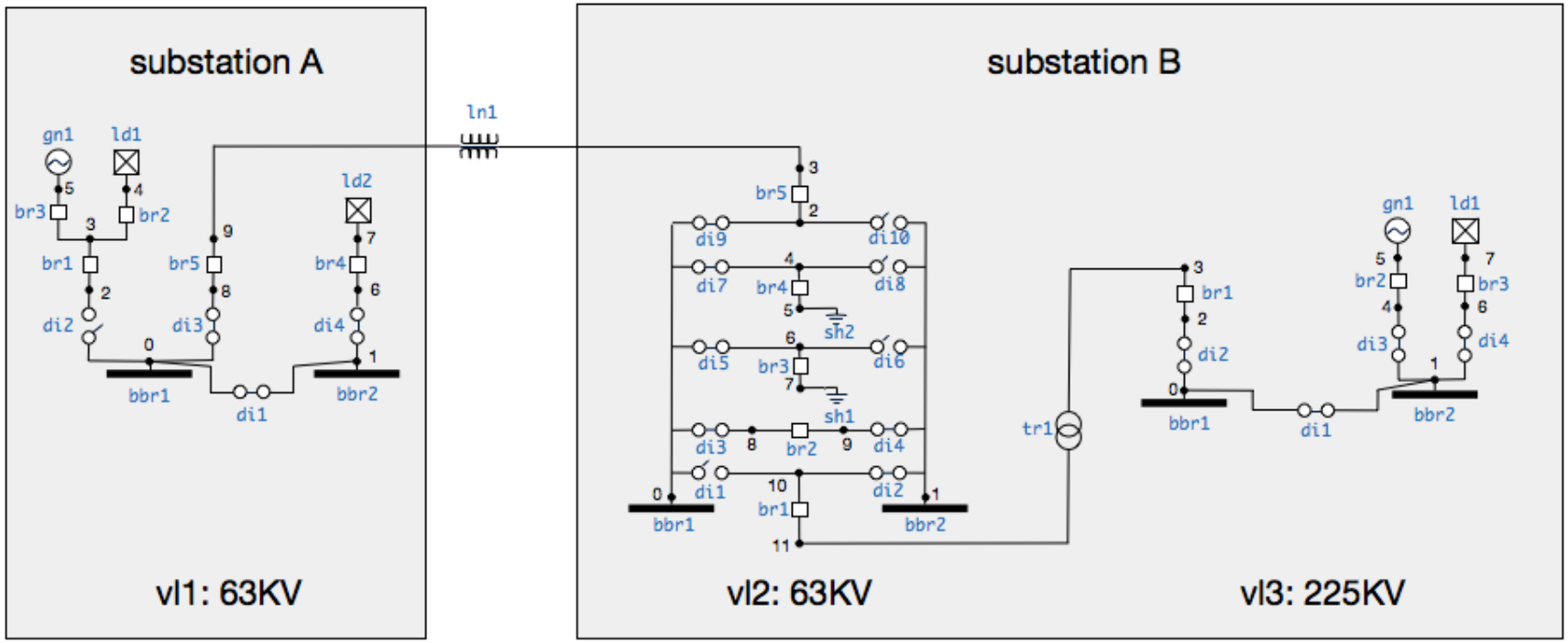
```
{“required": ["link", "demand"],
 "properties": {
  "type":{
   "type":"string",
   "pattern":"load"
  },
  "link":{"type":"string"},
  "demand":{"$ref": “#/…”}
}
```

GRG Network: Hierarchy

Network

A GRG network is organized as:

- A set of substations
- A set of transmission lines

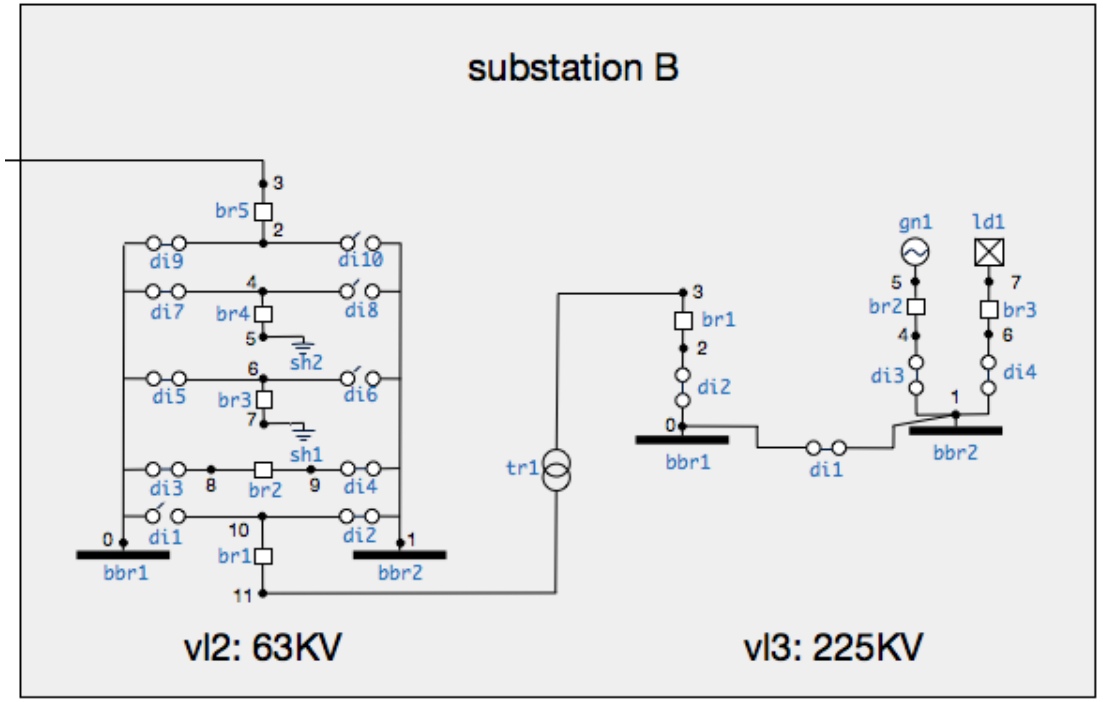


GRG Network: Hierarchy

Substation

A substation is a collection of:

- Voltage Levels
- Transformers

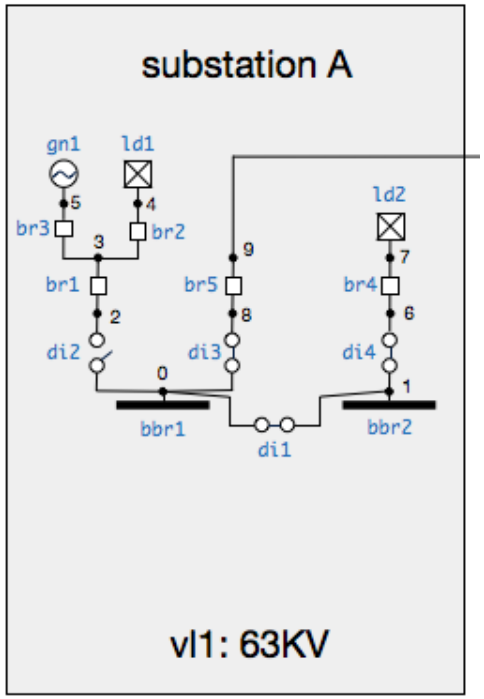


GRG Network: Hierarchy

Voltage Level

A voltage level is a collection of:

- Buses (busbars, logical buses, buses)
- Loads
- Synchronous Condensers
- Generators
- Switches
- Shunts



GRG Network: Hierarchy

```
{
  "grg-version": "1.0.0",
  "network": {
     –
     "components": {
        "substation_A": {
           –
           "voltage_level_C" : {
              "GN1": {
                   . . .
              },
        }
     },
  },
  "assignments": {
      –
  }
},
"mappings": {
      . . .
}
}
```

A GRG document is composed by:

- A "grg-version" field;
- A "network" object;
- A "mapping"object.

Electrical Values

Current Limits

```
"current_limits": {
  "type": "array",
  "items": {
  "type": "object",
  "properties": {
  "min": {"$ref": "#/values/extended_number"},
  "max": {"$ref": "#/values/extended_number"},
  "report": {
   "enum": ["off", "on"]
  },
  "duration": {"$ref": "#/values/extended_number"}
  }
  }
}
```

Amount of current: $[I^{min}, I^{max})$ the branch can safely carry for a duration d.

GRG name	Symbol	Unit
min	I^{min}	kiloAmpere (kA)
max	I^{max}	kiloAmpere (kA)
duration	d	Minutes (min)

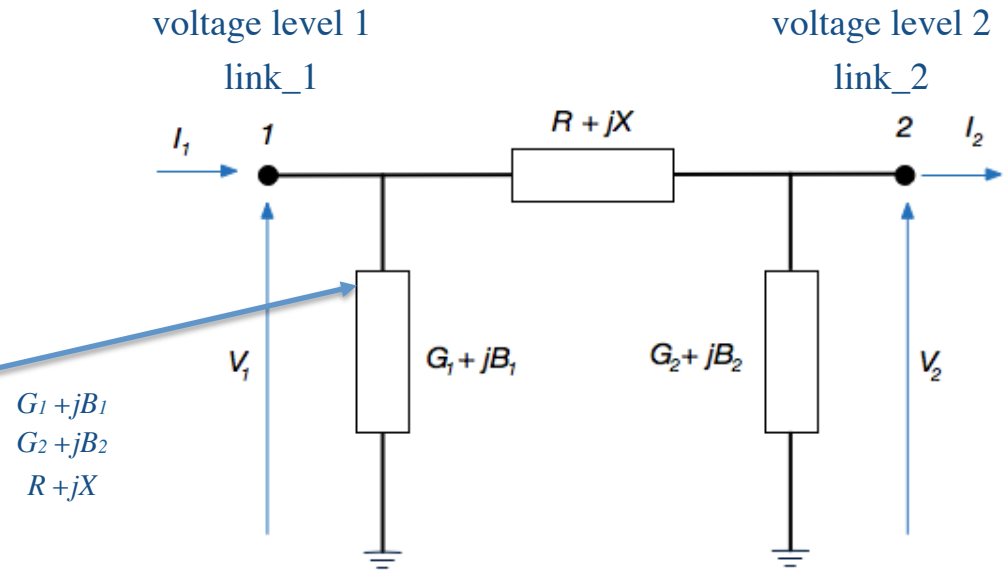
Example

```
"current_limits_1" : [
          { "duration" : “Inf", "max" : 563,   "min" : 0,   "report" : “off" },
          { "duration" : “Inf", "max" : 746,   "min" : 563, "report" : “on”},
          { "duration" : 6300,  "max" : “Inf", "min" : 746, "report" : “off”}
],
```

Network Components

AC Line

```
"AC_line": {
   "properties": {
  "type": {"enum": ["ac_line"]},
  "id": {"type": "string"},
  "description": {"type": "string"},
  "link_1": {"type": "string"},
  "link_2": {"type": "string"},
  "voltage_level_1_id": {"type": "string"},
  "voltage_level_2_id": {"type": "string"},
  "shunt_1": {"$ref": "#/admittance_rectangular"},
  "shunt_2": {"$ref": "#/admittance_rectangular"},
  "impedance": {"$ref": "#/impedance_rectangular"},
  "angle_difference": {"$ref": "#/abstract_value"},
  "current_limits_1": {"$ref": "#/current_limits"},
  "current_limits_2": {"$ref": "#/current_limits"}
  }
}
```



$$I_1 = Y_1 \cdot V_1 + \frac{1}{Z}(V_1 - V2)$$

$$I_2 = Y_2 \cdot V_2 + \frac{1}{Z}(V_1 - V2)$$

$$S_i = \bar{I}_i \cdot V_i \qquad (i \in \{1, 2\})$$

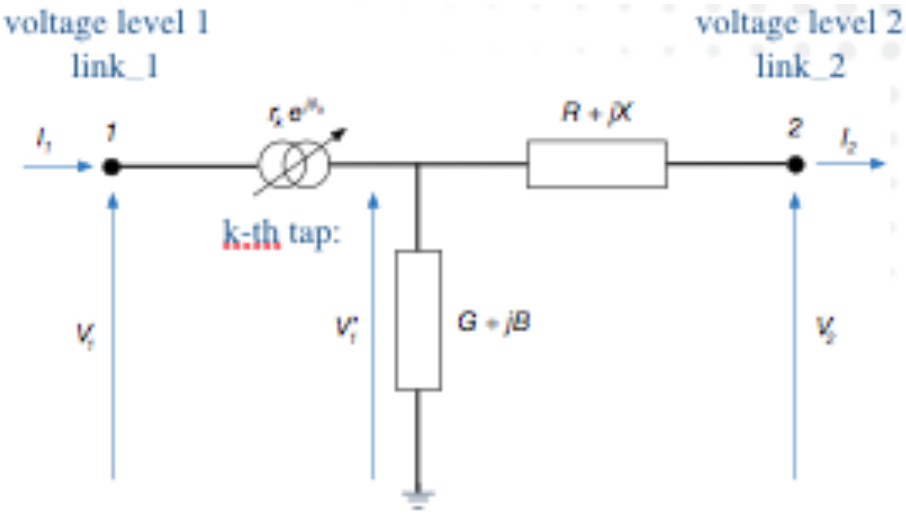
Network Components

Two Windings Transformer

```
"two_windings_transformer": {
    "type": {"enum": ["line"]},
    "id": {"type": "string"},
    "description": {"type": "string"},
    "link_1": {"type": "string"},
    "link_2": {"type": "string"},
    "voltage_level_1_id": {"type": "string"},
    "voltage_level_2_id": {"type": "string"},
    "shunt": {"$ref": "#/admittance"},
    "impedance": {"$ref": "#/impedance"},
    "angle_difference": {"$ref": "#/abstract_value"},
    "current_limits_1": {"$ref": "#/current_limits"},
    "current_limits_2": {"$ref": "#/current_limits"},
    "tap_changer": {
        "position": {"$ref": "#/abstract_value"},
        "OLTC": {
            "status": {"$ref": "#/status"},
            "regulating_side": {"enum": [1, 2]},
            "target_voltage": {"$ref": "#/values/abstract_value"}
        }
    },
    "steps": {
        "type": "array",
            "items": {
                "impedance": {"$ref": "#/impedance"},
                "shunt": {"$ref": "#/admittance"},
                "tap_ratio": {"$ref": "#/abstract_value"},
                "angle_shift": {"$ref": "#/abstract_value"}
            }
        }
    }
}
```

$G + jB$
$R + jX$

$R_k + jX_k$
$G_k + jB_k$
r_k
θ_k



$$I_1' = \rho_k \cdot (Y_1 \cdot V_1' + 1/Z_K (V_1' - V_2))$$

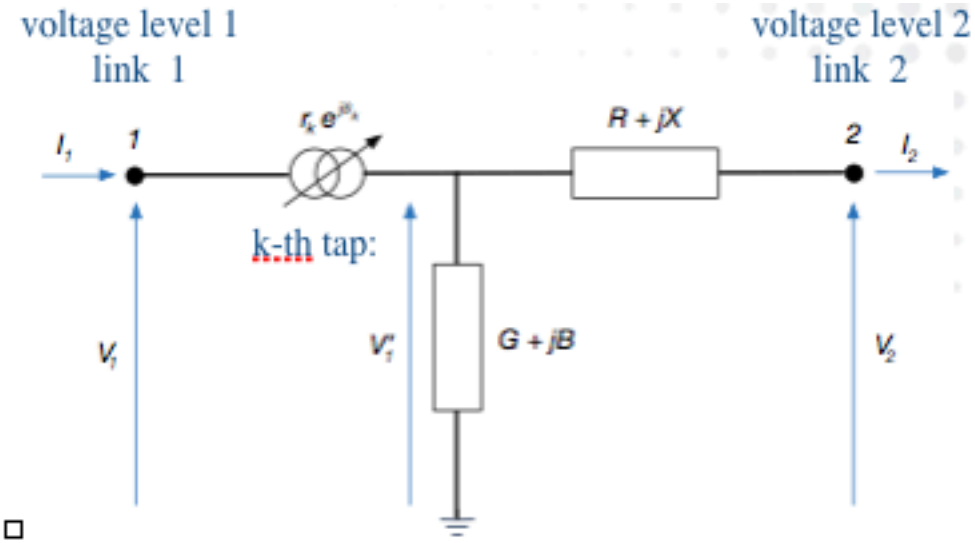
$$I_1' = 1/Z_K (V_2 - V_1')$$

$$V_1' = \rho_k \cdot V_1$$

$$S_i = \bar{I}_i \cdot V_i \qquad (i \in \{1, 2\})$$

Network Components

```
"two_windings_transformer_tr1" : {
    "type" : "two_windings_transformer",
    "id" : "tr1",
    "link_1" : "l1",
    "link_2" : "3",
    "voltage_level_1_id" : "vl2",
    "voltage_level_2_id" : "vl3",
    "angle_difference" : {"var": {"lb": -30.0, "ub": 30.0}},
    "current_limits_1" : [
        {"duration":"Inf", "max":1029, "min":0, "report":"off"},
        {"duration":1200, "max":1342, "min":1029, "report":"off"},
        {"duration":300, "max":1790, "min":1342, "report":"off"}
        {"duration":60, "max":"Inf", "min":1790, "report":"off"}
    ],
    "impedance": {"reactance": 60.1, "resistance": 1.512},
    "shunt": {"conductance":0, "susceptance": 0},
    "tap_changer" : {
        "OLTC" : {
            "regulating_side": 1,
            "status": {"var":["off", "on"]},
            "target_voltage": {"var":{"lb":"-Inf", "ub":"Inf"}}
        },
        "position": {"var": {"lb":0, "ub":2}},
        "steps":[{
            "impedance" : {"reactance" : 0, "resistance" : 0},
            "shunt" : {"conductance" : 0, "susceptance" : 0},
            "tap_ratio" : 1.011, "angle_shift": 0
            }, {
            "impedance" : {"reactance" : 0, "resistance" : 0},
            "shunt" : {"conductance" : 0, "susceptance" : 0},
            "tap_ratio" : 1.0, "angle_shift" : 0,
            },{
            "impedance" : {"reactance" : 0, "resistance" : 0},
            "shunt" : {"conductance" : 0, "susceptance" : 0},
            "tap_ratio" : 0.988, "angle_shift" : 0 }]
    }
}
```



$$I_1' = \rho_k \cdot (Y_1 \cdot V'_1 + 1/Z_K (V'_1 - V_2))$$

$$I_1' = 1/Z_K (V_2 - V'_1)$$

$$V_1' = \rho_k \cdot V_1$$

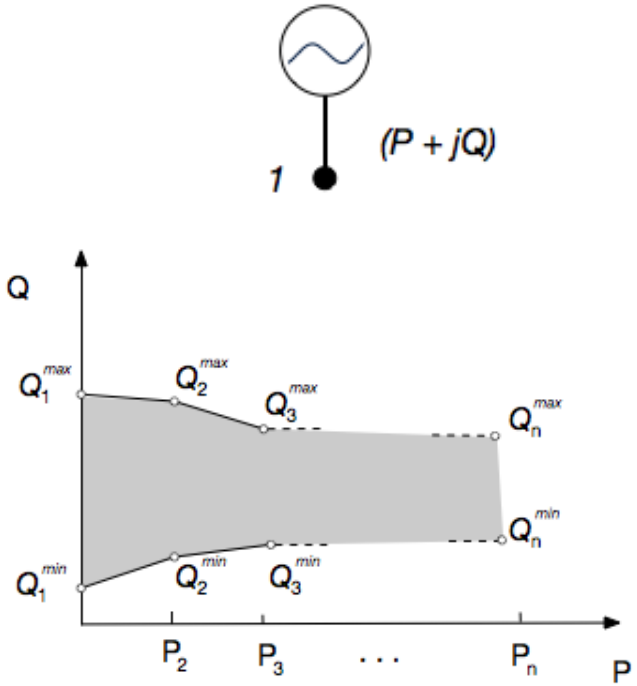
$$S_i = \bar{I}_i \cdot V_i \qquad (i \in \{1,2\})$$

Network Components

Generator

```
"generator": {
             "type": {"enum": [“generator"]},
             "subtype": {"enum": ["hydro", "wind", "thermal", "other", "nuclear", “solar"]},
             "id": {"type": “string"},
             "link": {"type": “string"},
             "voltage_regulation": {"$ref": “#/abstract_status"},
             "startup_cost": {"type": “number"},
             "shutdown_cost": {"type": “number"},
             "output": {"$ref": “#/power"},
             "PQ_curve": {
                          "type": “array", "items": {
                                       "activ^": {"type": “number"},
                                       "react P ": {
                                                    "upper_limit": {"type": “number"},
                                                    " Q^min _limit": {"type": “number”}}
                          }                         Q^max
             }
}
```

$P + jQ$



b.

```
"generator_vl1_gn1" : {
             "type" : “generator”,
             "subtype" : “solar",
             "id" : “gn1",
             "link" : “5",
             "voltage_regulation" : “off",
             "PQ_curve" : [
                          {"active":0, "reactive":{"lower_limit":0, "upper_limit":0}},
                {"active" : 20.7, "reactive":{"lower_limit":0, “upper_limit”:0}}],
             "output" : {
                          “active": {"var": {"lb":0, "ub": 20.7}},
                          "reactive": {"var": {"lb":0, "ub": 0.0 }}
  }
}
```

Assignments

```
{
  "grg-version": "1.0.0",
  "network": {
     _
     "components": {
        "substation_A": {
           _
           "voltage_level_C" : {

              "GN1": {
                   . . .
              },
        }
     },
  },
  "assignments": {
     _
  }
},
  "mappings": {
      . . .
  }
}
```

A GRG document is composed by:

- A "grg-version" field;
- A "network" object;
- A "mapping"object.

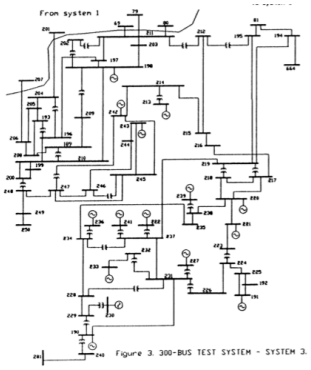
GRG Network: Assignment

Example

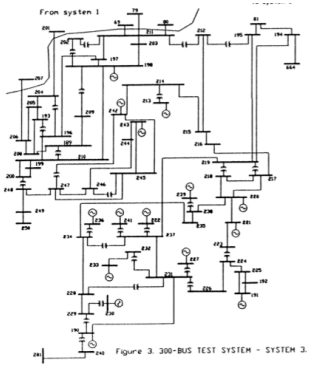
```
"assignment": {
  "switch_vl1_br1": {
      "status": "on"
   },
  "busbar_vl1_bbr1" : {
     "voltage" : {
         "angle" : 4.23,
         "magnitude" : 63.12
     }
  },
}
```

An “assignment” describes value assignments for network components’ objects.

Networks

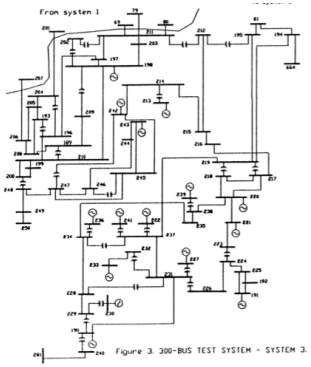


apply mapping



Assignment 1

apply mapping



Assignment 2

Overview

- Overview
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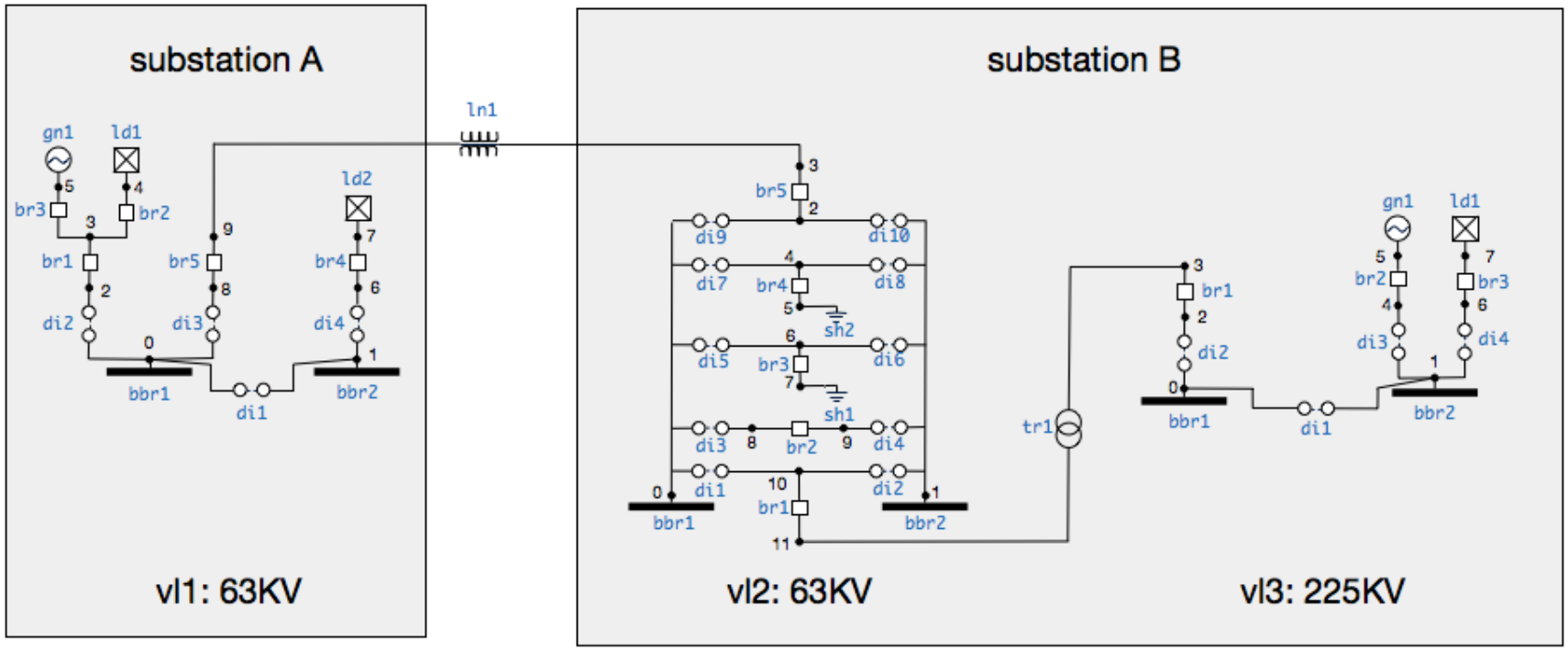
GRG Scripting Language

```
{
    "grid_version": "0.1.0a0",
    "script": {
        "scope": "/…/input_networks/",
        "network_filename": "demo_net",
        "steps": [
            {
                "name": "net_0",
                "type": "load",
                "status": "on"
            },
            {
                "name": "net_1",
                "type": "transform",
                "subtype": "assign",
                "status": "on",
                "apply_assignment": "disconnectors_assignment"
            },
            {
                "name": "net_2",
                "type": "transform",
                "subtype": "nodebreaker_to_busbreaker",
                "status": "on"
            },
            {
                "name": "net_3",
                "type": "transform",
                "subtype": "assign",
                "status": "on",
                "apply_assignment": "breakers_assignment"
            },
            {
                "name": "net_4",
                "type": "transform",
                "subtype": "busbreaker_to_busbranch",
                "status": "on"
            },
            {
                "name": "net_5",
                "type": "transform",
                "subtype": "per_unit",
                "nominal_power": 100.00,
                "status": "on"
            },
            {
                "name": "net_6",
                "type": "solve",
                "subtype": "ac_opf",
                "status": "on",
                "solver": "ipopt",
                "relaxation": "ACPOL",
                "starting_points": {"apply_assignment": "starting_"}
            },
            {
                "name": "net_7",
                "type": "rollback",
                "target": "net_0",
                "status": "on"
            },
            {
                "type": "output",
                "subtype": "network",
                "status": "on"
                "file_out": "/…/output_networks/demo_net"
            }
        ]
    }
}
```

Loading

```
{
    "grid_version": "0.1.0a0",
    "script": {
        "scope": "/../input_networks/",
        "network_filename": "demo_net",
        "steps": [
            {
                "name": "net_0",
                "type": "load",
                "status": "on"
            },
            {
                "name": "net_1",
                "type": "transform",
                "subtype": "assign",
                "status": "on",
                "apply_assignment": "disconnectors_assignment"
            },
            {
                "name": "net_2",
                "type": "transform",
                "subtype": "nodebreaker_to_busbreaker",
                "status": "on"
            },
            {
                "name": "net_3",
                "type": "transform",
                "subtype": "assign",
                "status": "on",
                "apply_assignment": "breakers_assignment"
            },
            {
                "name": "net_4",
                "type": "transform",
                "subtype": "busbreaker_to_busbranch",
                "status": "on"
            },
            {
                "name": "net_5",
                "type": "transform",
                "subtype": "per_unit",
                "nominal_power": 100.00,
                "status": "on"
            },
            {
                "name": "net_6",
                "type": "solve",
                "subtype": "ac_opf",
                "status": "on",
                "solver": "ipopt",
                "relaxation": "ACPOL",
                "starting_points": {"apply_assignment": "starting_"}
            },
            {
                "name": "net_7",
                "type": "rollback",
                "target": "net_0",
                "status": "on"
            },
            {
                "type": "output",
                "subtype": "network",
                "status": "on"
                "file_out": "/../output_networks/demo_net"
            }
        ]
    }
}
```

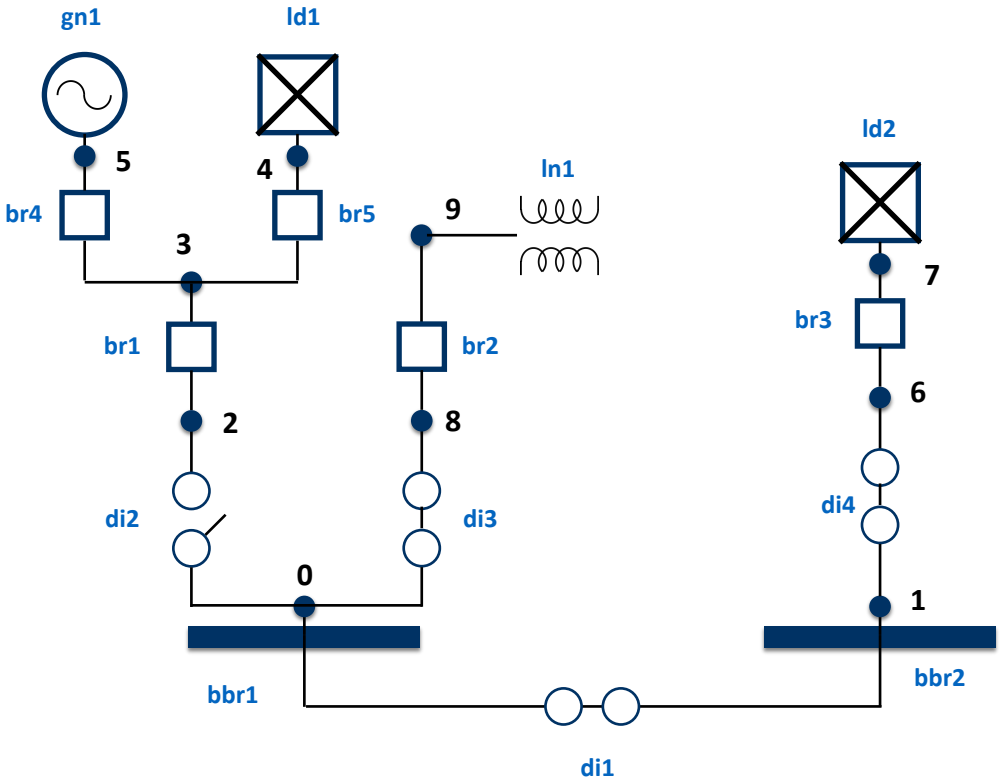
GRG Script: Load



Assignment of Disconnectors

```
{
    "grid_version": "0.1.0a0",
    "script": {
        "scope": "/../input_networks/",
        "network_filename": "demo_net",
        "steps": [
            {
                "name": "net_0",
                "type": "load",
                "status": "on"
            },
            {
                "name": "net_1",
                "type": "transform",
                "subtype": "assign",
                "status": "on",
                "apply_assignment": "disconnectors_assignment"
            },
            {
                "name": "net_2",
                "type": "transform",
                "subtype": "nodebreaker_to_busbreaker",
                "status": "on"
            },
            {
                "name": "net_3",
                "type": "transform",
                "subtype": "assign",
                "status": "on",
                "apply_assignment": "breakers_assignment"
            },
            {
                "name": "net_4",
                "type": "transform",
                "subtype": "busbreaker_to_busbranch",
                "status": "on"
            },
            {
                "name": "net_5",
                "type": "transform",
                "subtype": "per_unit",
                "nominal_power": 100.00,
                "status": "on"
            },
            {
                "name": "net_6",
                "type": "solve",
                "subtype": "ac_opf",
                "status": "on",
                "solver": "ipopt",
                "relaxation": "ACPOL",
                "starting_points": {"apply_assignment": "starting_"}
            },
            {
                "name": "net_7",
                "type": "rollback",
                "target": "net_0",
                "status": "on"
            },
            {
                "type": "output",
                "subtype": "network",
                "status": "on"
                "file_out": "/../output_networks/demo_net"
            }
        ]
    }
}
```

GRG Script: Assignment



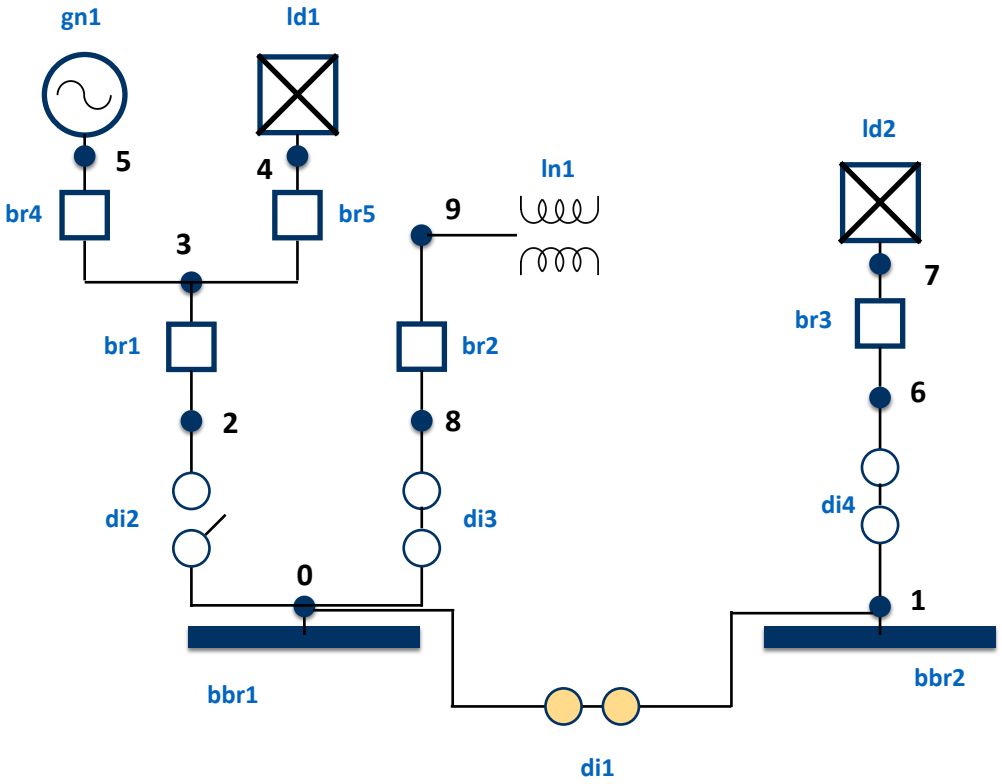

```
"voltage_level_vl1" :
{
  "id" : "vl1",
  "type" : "voltage_level",
  "voltage" : {
    "lower_limit" : 59.0,
    "nominal_value" : 63.0,
    "upper_limit" : 68.0
  },
  "voltage_level_components" :
  {
    “vl1_bbr1” : {“link”: 0, … },
    “vl1_bbr2” : {“link”: 1, … },
    "vl1_gn1" : {“link”: 5, …},
    "vl1_ld1" : {“link”: 4, …},
    "vl1_ld2" : {“link”: 7, …},
    "vl1_br1" : {“link_1”: 3, “link_2”: 2, …},
    "vl1_br2" : {“link_1”: 9, “link_2”: 8, …},
    "vl1_br3" : {“link_1”: 7, “link_2”: 6, …},
    "vl1_br4" : {“link_1”: 5, “link_2”: 3, …},
    "vl1_br5" : {“link_1”: 4, “link_2”: 3, …},
    "vl1_di1" : {“link_1”: 0, “link_2”: 1, …},
    "vl1_di2" : {“link_1”: 2, “link_2”: 0, …},
    "vl1_di3" : {“link_1”: 8, “link_2”: 0, …},
    "vl1_di4" : {“link_1”: 6, “link_2”: 1, …},
  }
},

assignments: {
..“voltage_level_vl1”: {
   “voltage_level_components”:
                {
    "vl1_di1": { status = “on”},
    "vl1_di2": { status = “off”},
    "vl1_di3": { status = “on”},
    "vl1_di4": { status = “on"}
                }
  }
}
```

GRG Script: Node-breaker To Bus-breaker

```
{
    "grid_version": "0.1.0a0",
    "script": {
        "scope": "/…/input_networks/",
        "network_filename": "demo_net",
        "steps": [
            {
                "name": "net_0",
                "type": "load",
                "status": "on"
            },
            {
                "name": "net_1",
                "type": "transform",
                "subtype": "assign",
                "status": "on",
                "apply_assignment": "disconnectors_assignment"
            },
            {
                "name": "net_2",
                "type": "transform",
                "subtype": "nodebreaker_to_busbreaker",
                "status": "on"
            },
            {
                "name": "net_3",
                "type": "transform",
                "subtype": "assign",
                "status": "on",
                "apply_assignment": "breakers_assignment"
            },
            {
                "name": "net_4",
                "type": "transform",
                "subtype": "busbreaker_to_busbranch",
                "status": "on"
            },
            {
                "name": "net_5",
                "type": "transform",
                "subtype": "per_unit",
                "nominal_power": 100.00,
                "status": "on"
            },
            {
                "name": "net_6",
                "type": "solve",
                "subtype": "ac_opf",
                "status": "on",
                "solver": "ipopt",
                "relaxation": "ACPOL",
                "starting_points": {"apply_assignment": "starting_"}
            },
            {
                "name": "net_7",
                "type": "rollback",
                "target": "net_0",
                "status": "on"
            },
            {
                "type": "output",
                "subtype": "network",
                "status": "on"
                "file_out": "/…/output_networks/demo_net"
            }
        ]
    }
}
```

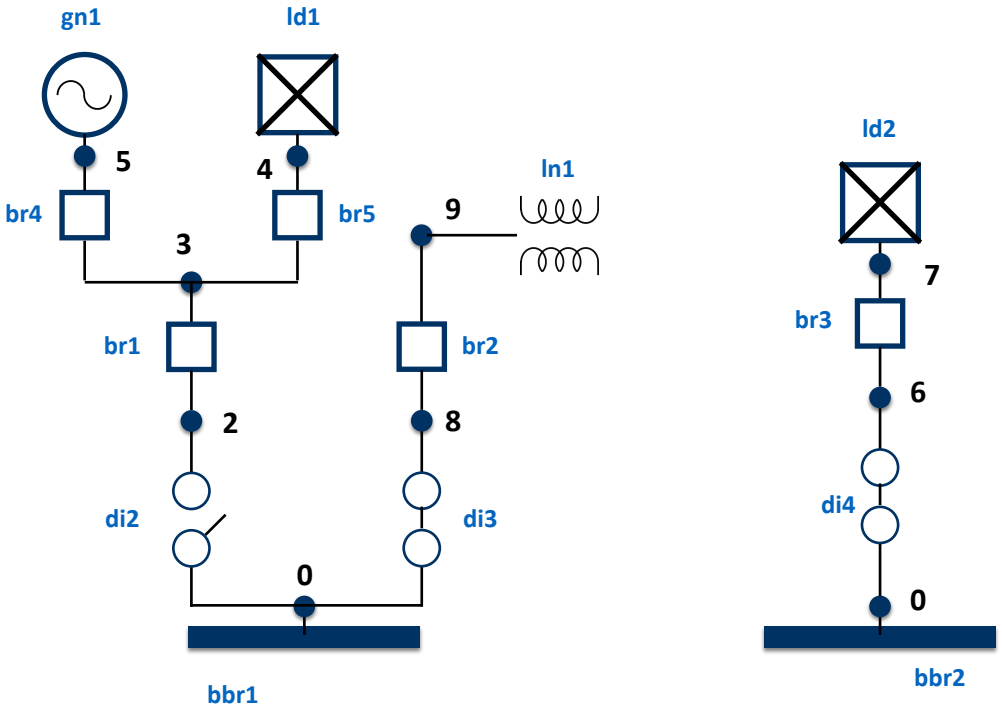
GRG Script: Node-breaker To Bus-breaker




```
"voltage_level_vl1" :
{
  "id" : "vl1",
  "type" : "voltage_level",
  "voltage" : {
    "lower_limit" : 59.0,
    "nominal_value" : 63.0,
    "upper_limit" : 68.0
  },
  "voltage_level_components" :
  {
    “vl1_bbr1” : {“link”: 0, … },
    “vl1_bbr2” : {“link”: 1, … },
    "vl1_gn1" : {“link”: 5, …},
    "vl1_ld1" : {“link”: 4, …},
    "vl1_ld2" : {“link”: 7, …},
    "vl1_br1" : {“link_1”: 3, “link_2”: 2, …},
    "vl1_br2" : {“link_1”: 9, “link_2”: 8, …},
    "vl1_br3" : {“link_1”: 7, “link_2”: 6, …},
    "vl1_br4" : {“link_1”: 5, “link_2”: 3, …},
    "vl1_br5" : {“link_1”: 4, “link_2”: 3, …},
    "vl1_di1" : {“link_1”: 0, “link_2”: 1, …},
    "vl1_di2" : {“link_1”: 2, “link_2”: 0, …},
    "vl1_di3" : {“link_1”: 8, “link_2”: 0, …},
    "vl1_di4" : {“link_1”: 6, “link_2”: 1, …},
  }
},

assignments: {
..“voltage_level_vl1”: {
   “voltage_level_components”:
                {
    "vl1_di1": { status = “on”},
    "vl1_di2": { status = “off”},
    "vl1_di3": { status = “on”},
    "vl1_di4": { status = “on"}
                }
  }
}
```

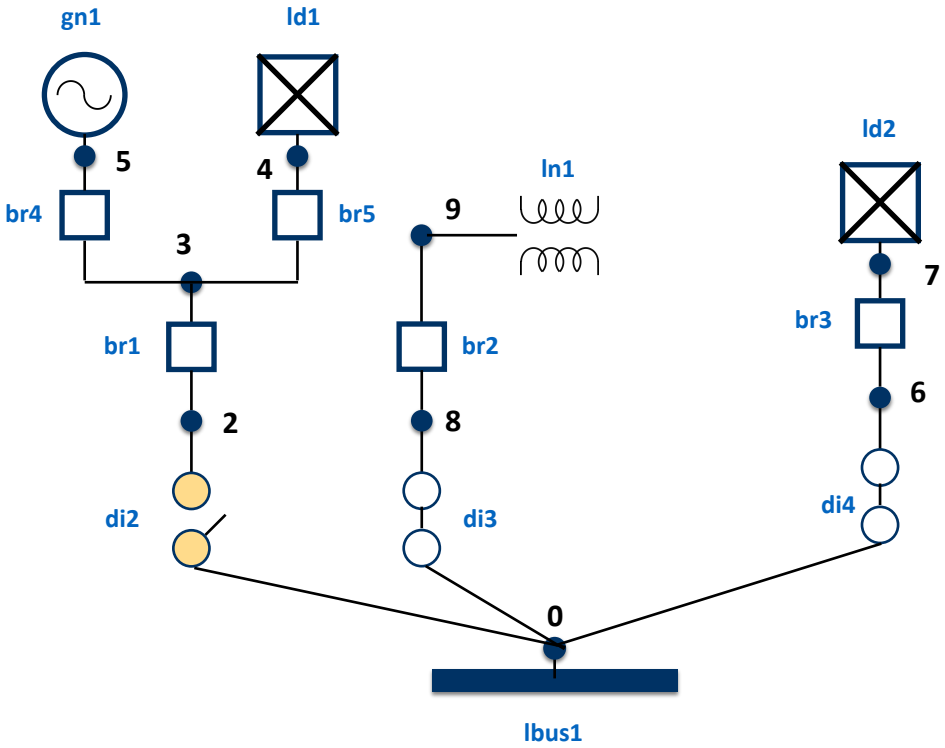
GRG Script: Node-breaker To Bus-breaker




```
"voltage_level_vl1" :
{
  "id" : "vl1",
  "type" : "voltage_level",
  "voltage" : {
    "lower_limit" : 59.0,
    "nominal_value" : 63.0,
    "upper_limit" : 68.0
  },
  "voltage_level_components" :
  {
    “vl1_bbr1” : {“link”: 0, … },
    “vl1_bbr2” : {“link”: 0, … },
    "vl1_gn1" : {“link”: 5, …},
    "vl1_ld1" : {“link”: 4, …},
    "vl1_ld2" : {“link”: 7, …},
    "vl1_br1" : {“link_1”: 3, “link_2”: 2, …},
    "vl1_br2" : {“link_1”: 9, “link_2”: 8, …},
    "vl1_br3" : {“link_1”: 7, “link_2”: 6, …},
    "vl1_br4" : {“link_1”: 5, “link_2”: 3, …},
    "vl1_br5" : {“link_1”: 4, “link_2”: 3, …},
    "vl1_di2" : {“link_1”: 2, “link_2”: 0, …},
    "vl1_di3" : {“link_1”: 8, “link_2”: 0, …},
    "vl1_di4" : {“link_1”: 6, “link_2”: 0, …},
  }
},

assignments: {
..“voltage_level_vl1”: {
    “voltage_level_components”:
                {
    "vl1_di2": { status = “off”},
    "vl1_di3": { status = “on”},
    "vl1_di4": { status = “on"}
                }
  }
}
```

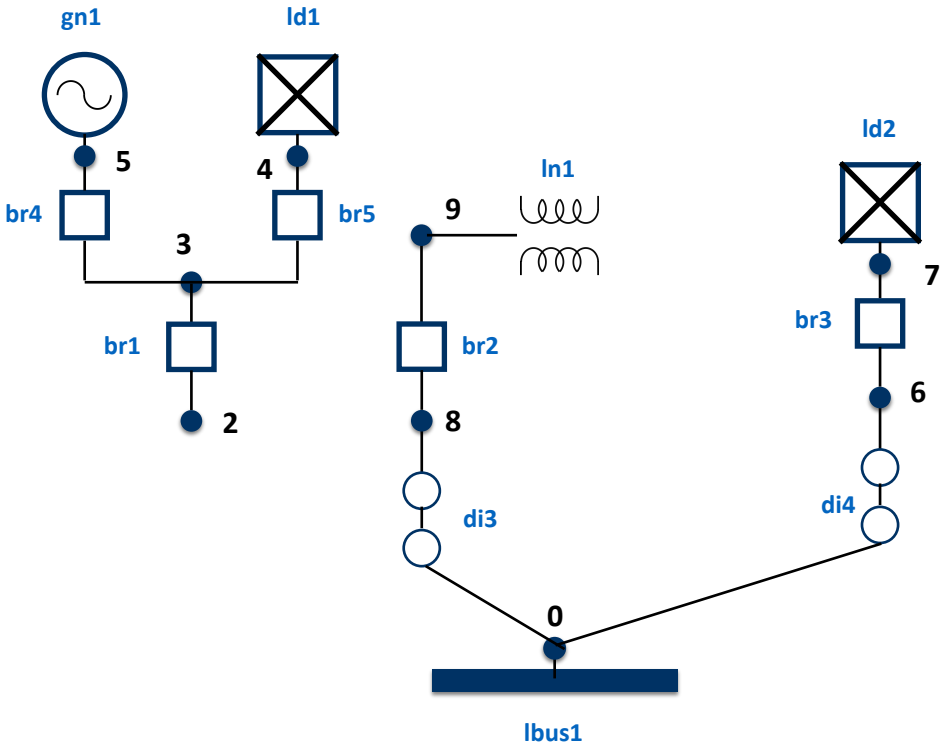
GRG Script: Node-breaker To Bus-breaker




```
"voltage_level_vl1" :
{
  "id" : "vl1",
  "type" : "voltage_level",
  "voltage" : {
    "lower_limit" : 59.0,
    "nominal_value" : 63.0,
    "upper_limit" : 68.0
  },
  "voltage_level_components" :
  {
    "vl1_lbus1" : {"link": 0, … },
    "vl1_gn1" : {"link": 5, …},
    "vl1_ld1" : {"link": 4, …},
    "vl1_ld2" : {"link": 7, …},
    "vl1_br1" : {"link_1": 3, "link_2": 2, …},
    "vl1_br2" : {"link_1": 9, "link_2": 8, …},
    "vl1_br3" : {"link_1": 7, "link_2": 6, …},
    "vl1_br4" : {"link_1": 5, "link_2": 3, …},
    "vl1_br5" : {"link_1": 4, "link_2": 3, …},
    "vl1_di2" : {"link_1": 2, "link_2": 0, …},
    "vl1_di3" : {"link_1": 8, "link_2": 0, …},
    "vl1_di4" : {"link_1": 6, "link_2": 0, …},
  }
},

assignments: {
..“voltage_level_vl1”: {
   “voltage_level_components”:
              {
    "vl1_di2": { status = “off”},
    "vl1_di3": { status = “on”},
    "vl1_di4": { status = “on"}
              }
  }
}
```

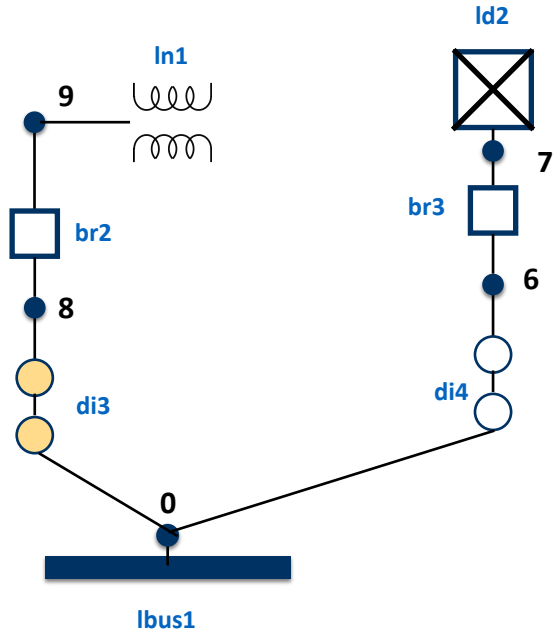
GRG Script: Node-breaker To Bus-breaker




```
"voltage_level_vl1" :
{
  "id" : "vl1",
  "type" : "voltage_level",
  "voltage" : {
    "lower_limit" : 59.0,
    "nominal_value" : 63.0,
    "upper_limit" : 68.0
  },
  "voltage_level_components" :
  {
    “vl1_lbus1” : {“link”: 0, … },
    "vl1_gn1" : {“link”: 5, …},
    "vl1_ld1" : {“link”: 4, …},
    "vl1_ld2" : {“link”: 7, …},
    "vl1_br1" : {“link_1”: 3, “link_2”: 2, …},
    "vl1_br2" : {“link_1”: 9, “link_2”: 8, …},
    "vl1_br3" : {“link_1”: 7, “link_2”: 6, …},
    "vl1_br4" : {“link_1”: 5, “link_2”: 3, …},
    "vl1_br5" : {“link_1”: 4, “link_2”: 3, …},
    "vl1_di3" : {“link_1”: 8, “link_2”: 0, …},
    "vl1_di4" : {“link_1”: 6, “link_2”: 0, …},
  }
},

assignments: {
..“voltage_level_vl1”: {
   “voltage_level_components”:
                {
    "vl1_di3": { status = “on”},
    "vl1_di4": { status = “on"}
                }
  }
}
```

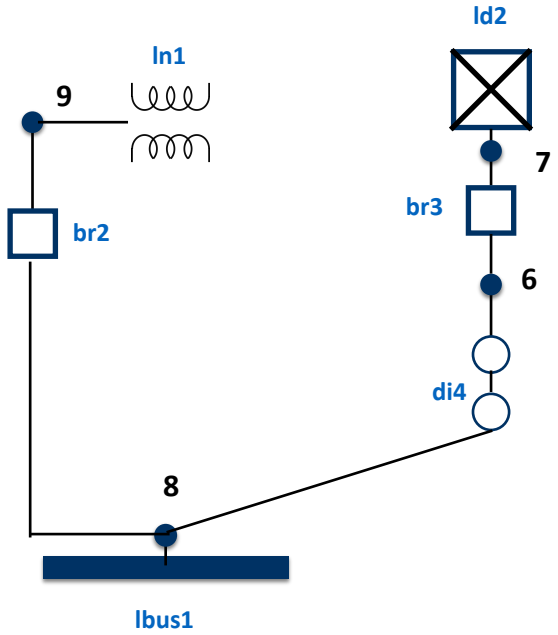
GRG Script: Node-breaker To Bus-breaker




```
"voltage_level_vl1" :
{
  "id" : "vl1",
  "type" : "voltage_level",
  "voltage" : {
    "lower_limit" : 59.0,
    "nominal_value" : 63.0,
    "upper_limit" : 68.0
  },
  "voltage_level_components" :
  {
    “vl1_lbus1” : {“link”: 0, … },
    "vl1_ld2" : {“link”: 7, …},
    "vl1_br2" : {“link_1”: 9, “link_2”: 8, …},
    "vl1_br3" : {“link_1”: 7, “link_2”: 6, …},
    "vl1_di3" : {“link_1”: 8, “link_2”: 0, …},
    "vl1_di4" : {“link_1”: 6, “link_2”: 0, …},
  }
},

assignments: {
..“voltage_level_vl1”: {
   “voltage_level_components”:
                {
    "vl1_di3": { status = “on”},
    "vl1_di4": { status = “on"}
                }
 }
}
```

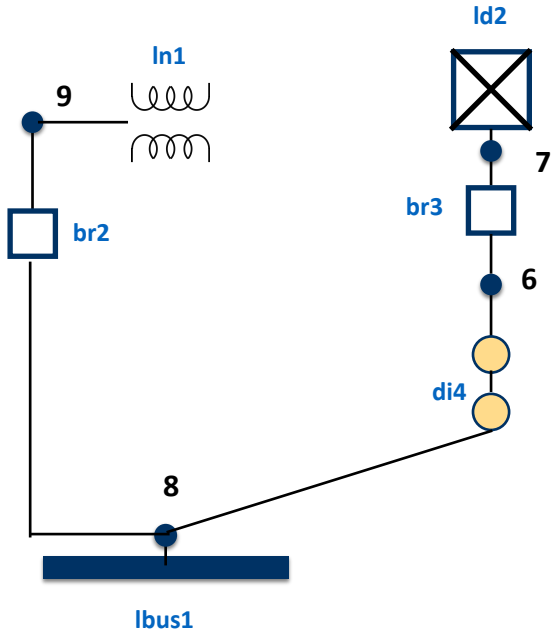
GRG Script: Node-breaker To Bus-breaker




```
"voltage_level_vl1" :
{
  "id" : "vl1",
  "type" : "voltage_level",
  "voltage" : {
    "lower_limit" : 59.0,
    "nominal_value" : 63.0,
    "upper_limit" : 68.0
  },
  "voltage_level_components" :
  {
    “vl1_lbus1” : {“link”: 8, … },
    "vl1_ld2" : {“link”: 7, …},
    "vl1_br2" : {“link_1”: 9, “link_2”: 8, …},
    "vl1_br3" : {“link_1”: 7, “link_2”: 6, …},
    "vl1_di4" : {“link_1”: 6, “link_2”: 8, …},
  }
},

assignments: {
..“voltage_level_vl1”: {
   “voltage_level_components”:
                {
   "vl1_di4": { status = “on"}
                }
 }
}
```

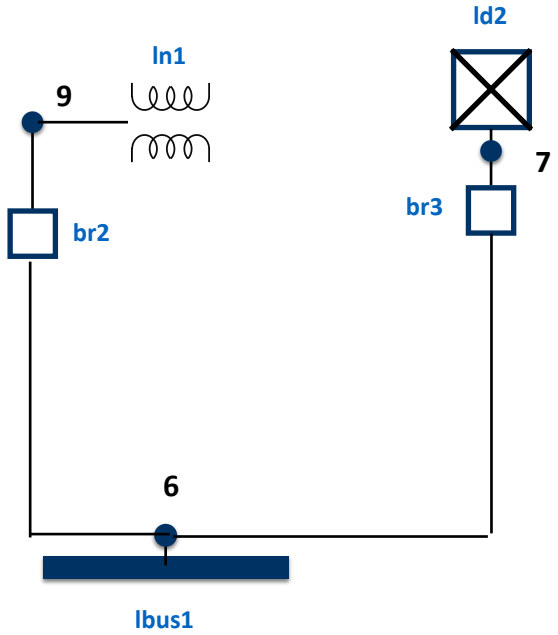
GRG Script: Node-breaker To Bus-breaker




```
"voltage_level_vl1" :
{
  "id" : "vl1",
  "type" : "voltage_level",
  "voltage" : {
    "lower_limit" : 59.0,
    "nominal_value" : 63.0,
    "upper_limit" : 68.0
  },
  "voltage_level_components" :
  {
    "vl1_lbus1" : {"link": 8, … },
    "vl1_ld2" : {"link": 7, …},
    "vl1_br2" : {"link_1": 9, "link_2": 8, …},
    "vl1_br3" : {"link_1": 7, "link_2": 6, …},
    "vl1_di4" : {"link_1": 6, "link_2": 8, …},
  }
},

assignments: {
..“voltage_level_vl1”: {
   “voltage_level_components”:
                {
   "vl1_di4": { status = “on"}
                }
 }
}
```

GRG Script: Node-breaker To Bus-breaker




```
"voltage_level_vl1" :
{
  "id" : "vl1",
  "type" : "voltage_level",
  "voltage" : {
    "lower_limit" : 59.0,
    "nominal_value" : 63.0,
    "upper_limit" : 68.0
  },
  "voltage_level_components" :
  {
    "vl1_lbus1" : {"link": 6, … },
    "vl1_ld2" : {"link": 7, …},
    "vl1_br2" : {"link_1": 9, "link_2": 6, …},
    "vl1_br3" : {"link_1": 7, "link_2": 6, …},
  }
},

assignments: {
.."voltage_level_vl1": {
   "voltage_level_components":
              {
              }
 }
}
```

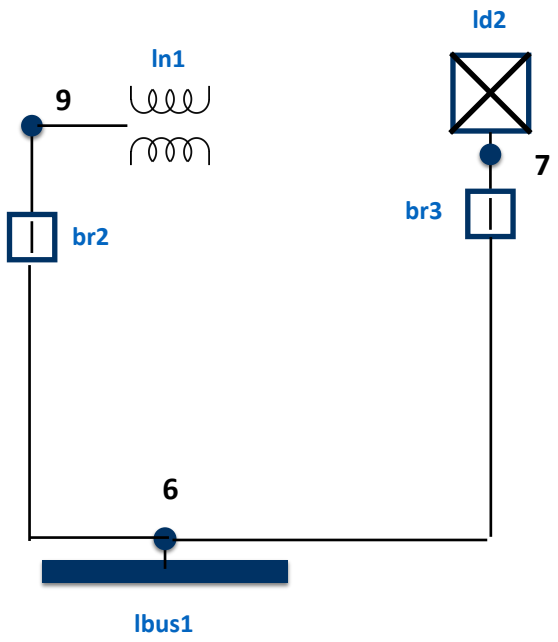
GRG Script: Assignments of Breakers

```
{
    "grid_version": "0.1.0a0",
    "script": {
        "scope": "/…/input_networks/",
        "network_filename": "demo_net",
        "steps": [
            {
                "name": "net_0",
                "type": "load",
                "status": "on"
            },
            {
                "name": "net_1",
                "type": "transform",
                "subtype": "assign",
                "status": "on",
                "apply_assignment": "disconnectors_assignment"
            },
            {
                "name": "net_2",
                "type": "transform",
                "subtype": "nodebreaker_to_busbreaker",
                "status": "on"
            },
            {
                "name": "net_3",
                "type": "transform",
                "subtype": "assign",
                "status": "on",
                "apply_assignment": "breakers_assignment"
            },
            {
                "name": "net_4",
                "type": "transform",
                "subtype": "busbreaker_to_busbranch",
                "status": "on"
            },
            {
                "name": "net_5",
                "type": "transform",
                "subtype": "per_unit",
                "nominal_power": 100.00,
                "status": "on"
            },
            {
                "name": "net_6",
                "type": "solve",
                "subtype": "ac_opf",
                "status": "on",
                "solver": "ipopt",
                "relaxation": "ACPOL",
                "starting_points": {"apply_assignment": "starting_"}
            },
            {
                "name": "net_7",
                "type": "rollback",
                "target": "net_0",
                "status": "on"
            },
            {
                "type": "output",
                "subtype": "network",
                "status": "on"
                "file_out": "/…/output_networks/demo_net"
            }
        ]
    }
}
```

GRG Script: Bus-breaker to Bus-branch

```
{
    "grid_version": "0.1.0a0",
    "script": {
        "scope": "/…/input_networks/",
        "network_filename": "demo_net",
        "steps": [
            {
                "name": "net_0",
                "type": "load",
                "status": "on"
            },
            {
                "name": "net_1",
                "type": "transform",
                "subtype": "assign",
                "status": "on",
                "apply_assignment": "disconnectors_assignment"
            },
            {
                "name": "net_2",
                "type": "transform",
                "subtype": "nodebreaker_to_busbreaker",
                "status": "on"
            },
            {
                "name": "net_3",
                "type": "transform",
                "subtype": "assign",
                "status": "on",
                "apply_assignment": "breakers_assignment"
            },
            {
                "name": "net_4",
                "type": "transform",
                "subtype": "busbreaker_to_busbranch",
                "status": "on"
            },
            {
                "name": "net_5",
                "type": "transform",
                "subtype": "per_unit",
                "nominal_power": 100.00,
                "status": "on"
            },
            {
                "name": "net_6",
                "type": "solve",
                "subtype": "ac_opf",
                "status": "on",
                "solver": "ipopt",
                "relaxation": "ACPOL",
                "starting_points": {"apply_assignment": "starting_"}
            },
            {
                "name": "net_7",
                "type": "rollback",
                "target": "net_0",
                "status": "on"
            },
            {
                "type": "output",
                "subtype": "network",
                "status": "on"
                "file_out": "/…/output_networks/demo_net"
            }
        ]
    }
}
```

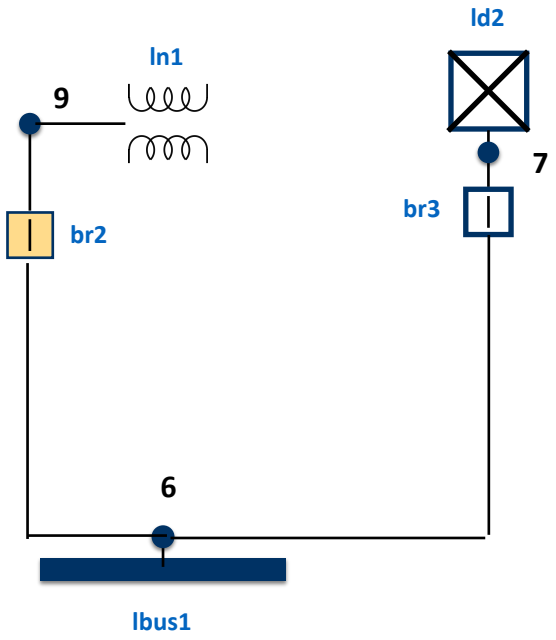
GRG Script: Bus-breaker to Bus-branch




```
"voltage_level_vl1" :
{
  "id" : "vl1",
  "type" : "voltage_level",
  "voltage" : {
    "lower_limit" : 59.0,
    "nominal_value" : 63.0,
    "upper_limit" : 68.0
  },
  "voltage_level_components" :
  {
    “vl1_lbus1” : {“link”: 6, … },
    "vl1_ld2" : {“link”: 7, …},
    "vl1_br2" : {“link_1”: 9, “link_2”: 6, …},
    "vl1_br3" : {“link_1”: 7, “link_2”: 6, …},
  }
}
“ln1”: {“link1”: “9”, “link2”: 3, …}

assignments: {
..“voltage_level_vl1”: {
   “voltage_level_components”:
                  {
      “vl1_br2”: {“status”: “on”},
      “vl1_br3”: {“status”: “on”}
             }
 }
}
```

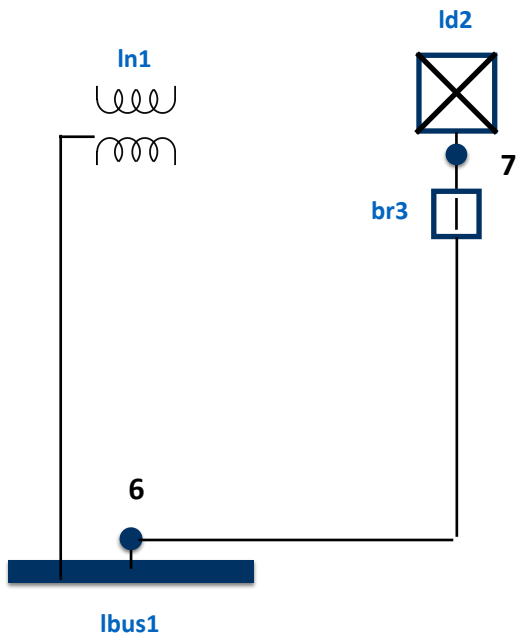
GRG Script: Bus-breaker to Bus-branch




```
"voltage_level_vl1" :
{
  "id" : "vl1",
  "type" : "voltage_level",
  "voltage" : {
    "lower_limit" : 59.0,
    "nominal_value" : 63.0,
    "upper_limit" : 68.0
  },
  "voltage_level_components" :
  {
    "vl1_lbus1" : {"link": 6, … },
    "vl1_ld2" : {"link": 7, …},
    "vl1_br2" : {"link_1": 9, "link_2": 6, …},
    "vl1_br3" : {"link_1": 7, "link_2": 6, …},
  }
}
"ln1": {"link1": "9", "link2": 3, …}

assignments: {
..“voltage_level_vl1”: {
   “voltage_level_components”:
                {
      “vl1_br2”: {“status”: “on”},
      “vl1_br3”: {“status”: “on”}
             }
 }
}
```

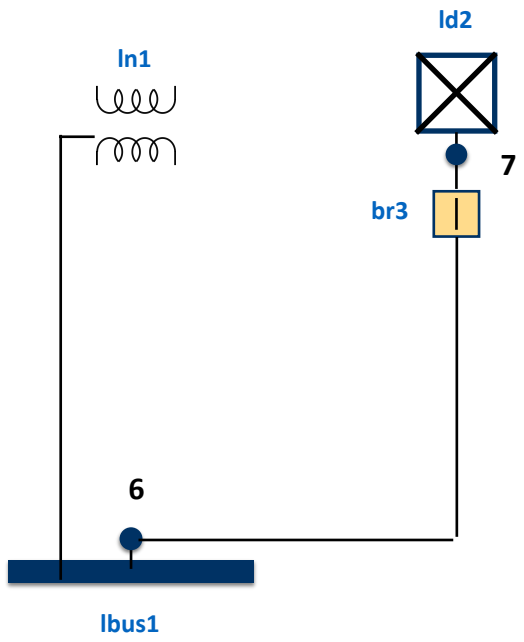
GRG Script: Bus-breaker to Bus-branch




```
"voltage_level_vl1" :
{
  "id" : "vl1",
  "type" : "voltage_level",
  "voltage" : {
    "lower_limit" : 59.0,
    "nominal_value" : 63.0,
    "upper_limit" : 68.0
  },
  "voltage_level_components" :
  {
    "vl1_lbus1" : {"link": 6, … },
    "vl1_ld2" : {"link": 7, …},
    "vl1_br3" : {"link_1": 7, "link_2": 6, …},
  }
}
"ln1": {"link1": "lbus1", "link2": 3, …}

assignments: {
..“voltage_level_vl1”: {
   “voltage_level_components”:
                {
      “vl1_br3”: {“status”: “on”}
                }
 }
}
```

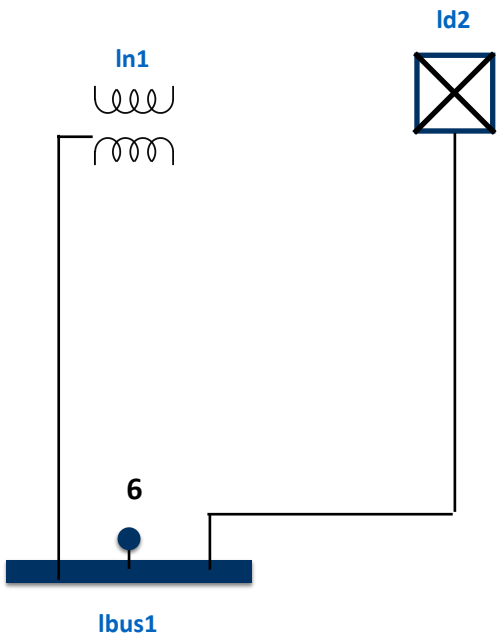
GRG Script: Bus-breaker to Bus-branch




```
"voltage_level_vl1" :
{
  "id" : "vl1",
  "type" : "voltage_level",
  "voltage" : {
    "lower_limit" : 59.0,
    "nominal_value" : 63.0,
    "upper_limit" : 68.0
  },
  "voltage_level_components" :
  {
    "vl1_lbus1" : {"link": 6, … },
    "vl1_ld2" : {"link": 7, …},
    "vl1_br3" : {"link_1": 7, "link_2": 6, …},
  }
}
"ln1": {"link1": "lbus1", "link2": 3, …}

assignments: {
.."voltage_level_vl1": {
   "voltage_level_components":
                {
      "vl1_br3": {"status": "on"}
                }
 }
}
```

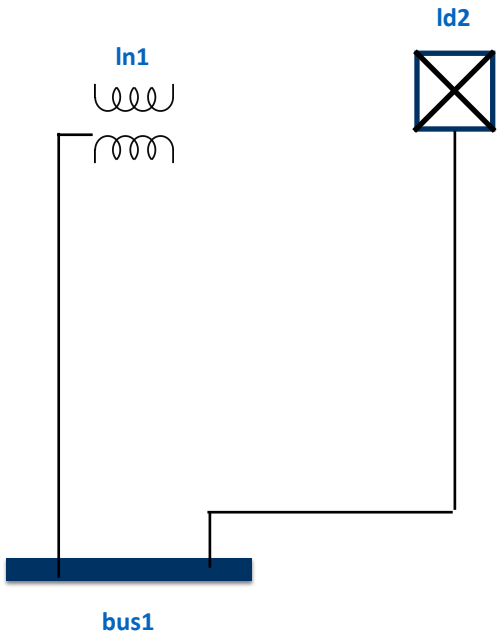
GRG Script: Bus-breaker to Bus-branch




```
"voltage_level_vl1" :
{
  "id" : "vl1",
  "type" : "voltage_level",
  "voltage" : {
    "lower_limit" : 59.0,
    "nominal_value" : 63.0,
    "upper_limit" : 68.0
  },
  "voltage_level_components" :
  {
    “vl1_lbus1” : {“link”: 6, … },
    "vl1_ld2" : {“link”: “lbus1”, …},
  }
}
“ln1”: {“link1”: “lbus1”, “link2”: 3, …}

assignments: {
..“voltage_level_vl1”: {
   “voltage_level_components”:
                {
                }
 }
}
```

GRG Script: Bus-breaker to Bus-branch




```
"voltage_level_vl1" :
{
  "id" : "vl1",
  "type" : "voltage_level",
  "voltage" : {
    "lower_limit" : 59.0,
    "nominal_value" : 63.0,
    "upper_limit" : 68.0
  },
  "voltage_level_components" :
  {
    "vl1_lbus1" : {… },
    "vl1_ld2" : {"link": "bus1", …},
  }
}
"ln1": {"link1": "bus1", "link2": 3, …}

assignments: {
..."voltage_level_vl1": {
   "voltage_level_components":
              {
              }
 }
}
```

GRG Script: Per-unit transform

```
{
    "grid_version": "0.1.0a0",
    "script": {
        "scope": "/…/input_networks/",
        "network_filename": "demo_net",
        "steps": [
            {
                "name": "net_0",
                "type": "load",
                "status": "on"
            },
            {
                "name": "net_1",
                "type": "transform",
                "subtype": "assign",
                "status": "on",
                "apply_assignment": "disconnectors_assignment"
            },
            {
                "name": "net_2",
                "type": "transform",
                "subtype": "nodebreaker_to_busbreaker",
                "status": "on"
            },
            {
                "name": "net_3",
                "type": "transform",
                "subtype": "assign",
                "status": "on",
                "apply_assignment": "breakers_assignment"
            },
            {
                "name": "net_4",
                "type": "transform",
                "subtype": "busbreaker_to_busbranch",
                "status": "on"
            },
            {
                "name": "net_5",
                "type": "transform",
                "subtype": "per_unit",
                "nominal_power": 100.00,
                "status": "on"
            },
            {
                "name": "net_6",
                "type": "solve",
                "subtype": "ac_opf",
                "status": "on",
                "solver": "ipopt",
                "relaxation": "ACPOL",
                "starting_points": {"apply_assignment": "starting_"}
            },
            {
                "name": "net_7",
                "type": "rollback",
                "target": "net_0",
                "status": "on"
            },
            {
                "type": "output",
                "subtype": "network",
                "status": "on"
                "file_out": "/…/output_networks/demo_net"
            }
        ]
    }
}
```

GRG Script: Per-unit transform

input

```
// Component
{
   "subtype" : "solar",
   "type" : "generator",
   "voltage_regulation" : "off"
   "link" : 5,
   "output" : {
  "active" : {
   "var" : {"lb" : 0, "ub" : 20.7 }
  },
  "reactive" : {
   "var" : {"lb" : 0, "ub" : 0.0 }
      }
   },
  "PQ_curve" : [
  { "active" : 0,
  "reactive" : {"lower_limit" : 0, "upper_limit" : 0}
  },
   {"active" : 20.699999999999999,
  "reactive" : {"lower_limit" : 0, "upper_limit" : 0}
   }
   ]
}

// Assignments
{ }

// Mappings
target_points: {
   "output" : {
  "active" : 0, "reactive" : 0, "voltage" : 65.744705}
   },
starting_points: {
   "output" : {
  "active" : 0, "reactive" : 0}
   }
}
```

output

```
// Component
{ . . . }

// Assignments
{
   "output" : {
  "active" : {
   "var" : {"lb" : 0, "ub" : 0.207}
  },
  "reactive" : {
   "var" : {"lb" : 0, "ub" : 0.0 }
      }
   },
  "PQ_curve" : [
  { "active" : 0,
  "reactive" : {"lower_limit" : 0, "upper_limit" : 0}
  },
   {"active" : 0.207,
  "reactive" : {"lower_limit" : 0, "upper_limit" : 0}
   }
   ]
}

// Mappings
target_points: {
   "output" : {
  "active" : 0, "reactive" : 0, "voltage" : 1.0435667}
   },
starting_points: {
   "output" : {
  "active" : 0, "reactive" : 0}
   }
}
```

GRG Script: Solve

```
{
    "grid_version": "0.1.0a0",
    "script": {
        "scope": "/…/input_networks/",
        "network_filename": "demo_net",
        "steps": [
            {
                "name": "net_0",
                "type": "load",
                "status": "on"
            },
            {
                "name": "net_1",
                "type": "transform",
                "subtype": "assign",
                "status": "on",
                "apply_assignment": "disconnectors_assignment"
            },
            {
                "name": "net_2",
                "type": "transform",
                "subtype": "nodebreaker_to_busbreaker",
                "status": "on"
            },
            {
                "name": "net_3",
                "type": "transform",
                "subtype": "assign",
                "status": "on",
                "apply_assignment": "breakers_assignment"
            },
            {
                "name": "net_4",
                "type": "transform",
                "subtype": "busbreaker_to_busbranch",
                "status": "on"
            },
            {
                "name": "net_5",
                "type": "transform",
                "subtype": "per_unit",
                "nominal_power": 100.00,
                "status": "on"
            },
            {
                "name": "net_6",
                "type": "solve",
                "subtype": "ac_opf",
                "status": "on",
                "solver": "ipopt",
                "relaxation": "ACPOL",
                "starting_points": {"apply_assignment": "starting_"}
            },
            {
                "name": "net_7",
                "type": "rollback",
                "target": "net_0",
                "status": "on"
            },
            {
                "type": "output",
                "subtype": "network",
                "status": "on"
                "file_out": "/…/output_networks/demo_net"
            }
        ]
    }
}
```

GRG Script: Rollback

```
{
    "grid_version": "0.1.0a0",
    "script": {
        "scope": "/…/input_networks/",
        "network_filename": "demo_net",
        "steps": [
            {
                "name": "net_0",
                "type": "load",
                "status": "on"
            },
            {
                "name": "net_1",
                "type": "transform",
                "subtype": "assign",
                "status": "on",
                "apply_assignment": "disconnectors_assignment"
            },
            {
                "name": "net_2",
                "type": "transform",
                "subtype": "nodebreaker_to_busbreaker",
                "status": "on"
            },
            {
                "name": "net_3",
                "type": "transform",
                "subtype": "assign",
                "status": "on",
                "apply_assignment": "breakers_assignment"
            },
            {
                "name": "net_4",
                "type": "transform",
                "subtype": "busbreaker_to_busbranch",
                "status": "on"
            },
            {
                "name": "net_5",
                "type": "transform",
                "subtype": "per_unit",
                "nominal_power": 100.00,
                "status": "on"
            },
            {
                "name": "net_6",
                "type": "solve",
                "subtype": "ac_opf",
                "status": "on",
                "solver": "ipopt",
                "relaxation": "ACPOL",
                "starting_points": {"apply_assignment": "starting_"}
            },
            {
                "name": "net_7",
                "type": "rollback",
                "target": "net_0",
                "status": "on"
            },
            {
                "type": "output",
                "subtype": "network",
                "status": "on"
                "file_out": "/…/output_networks/demo_net"
            }
        ]
    }
}
```

Overview

- Overview
- Desired Fidelity
- GRG Format
- Transformations
- Case Studies

Four Networks

Network Components Summary

		Marseille	France EHV	Lyon	France
Substations		74	1174	2376	4749
Voltage Levels		100	1523	2951	5742
Busbars		196	3305	5842	11644
Lines		112	1968	3775	7662
Transformers		43	558	937	1688
Generators		53	692	1202	2197
	Hydro	22	433	645	792
	Nuclear	0	59	59	59
	Solar	31	90	269	643
	Thermal	0	65	74	112
	Wind	0	43	152	587
Loads		142	2184	3750	6993
Shunt		15	196	214	381
Switches		1396	24818	41050	76461
	Breakers	553	8733	15003	28889
	Disconnectors	840	15832	25380	46404

Validation

- Validation of every component model
  - unit tests from load flow results
  - accuracy around 10^{-3}
  - validation is not performed in the per-unit system
    - load flow results are in nominal values
    - may be an interesting thing to add

Four Networks

Network Components Summary

		Marseille	France EHV	Lyon	France
Substations		74	1174	2376	4749
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Generators		53	692	1202	2197
	Hydro	22	433	645	792
	Nuclear	0	59	59	59
	Solar	31	90	269	643
	Thermal	0	65	74	112
	Wind	0	43	152	587
Loads		142	2184	3750	6993
Shunt		15	196	214	381
Switches		1396	24818	41050	76461
	Breakers	553	8733	15003	28889
	Disconnectors	840	15832	25380	46404

Metrics (Marseille Sous Realtor)

Network Components Summary

Substations	285
Voltage Levels	365
Busbar	4781
Lines	452
Transformers	122
Synchronous Condensers	0
Loads	594
Shunt	42

Generator Summary

Total	177
Solar	76
Wind	5
Thermal	15
Nuclear/Hydro	81
Other	0

Switch Summary

Total	9223
Breaker	2142
Disconnector	7057

Metrics (Marseille Sous Realtor)

Line Impedance

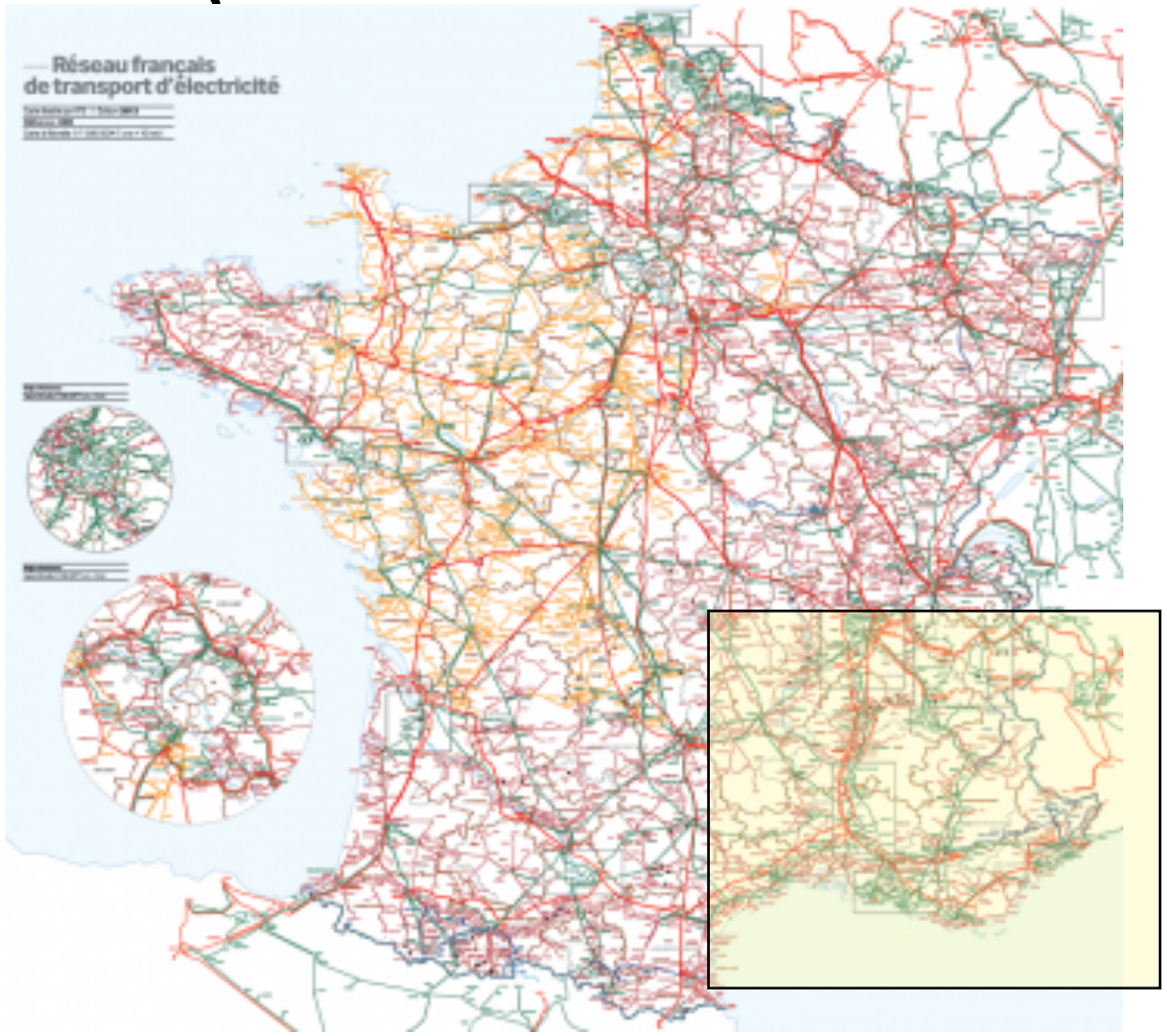
Impedance (Ohms)		
Reactance	avg	3.12
	min	0.00
	max	31.93
	sd	3.57
	median	2.23
Resistance	avg	0.89
	min	0.00
	max	6.98
	sd	0.94
	median	0.64

Network distances

Load to Generator		
Distance	avg	3.17
	min	1
	max	9
	sd	1.96
	median	3

Metrics (Marseille Sous Realtor)

Metrics (Marseille Sous Realtor)



Conclusions

- High fidelity modeling
  - network, models
  - targeted to the needs of industry
- Novel flexible and extensive format
  - JSON + suite of tools
- Real test cases
  - unit validation
  - Load flow
  - Optimal power flow
- Working on stressing the networks
  - creating interesting challenging test cases