SCOPF: challenges and methods

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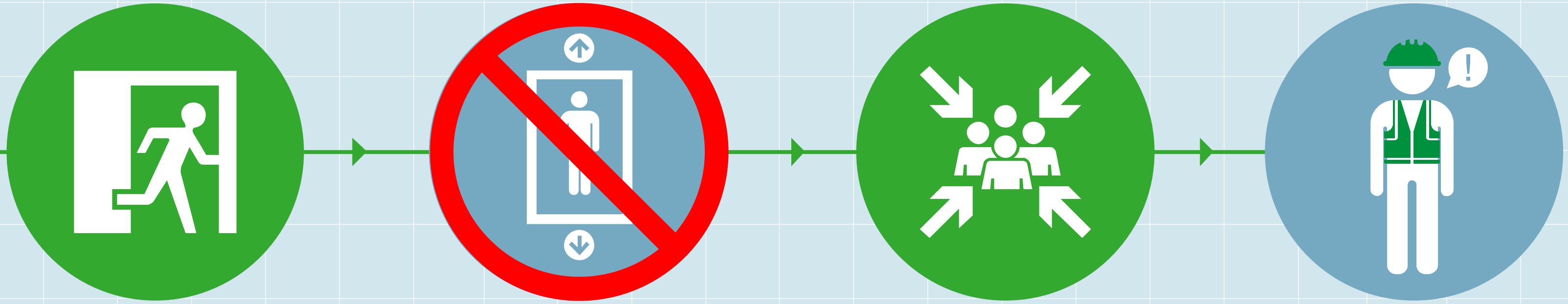
A moment for safety

Together we provide a safe working environment. We learn from mistakes and sharing ideas, concerns and asking questions are a matter of course.

We also draw attention to the following safety measures in case of evacuation of the premises



Follow the escape route as indicated

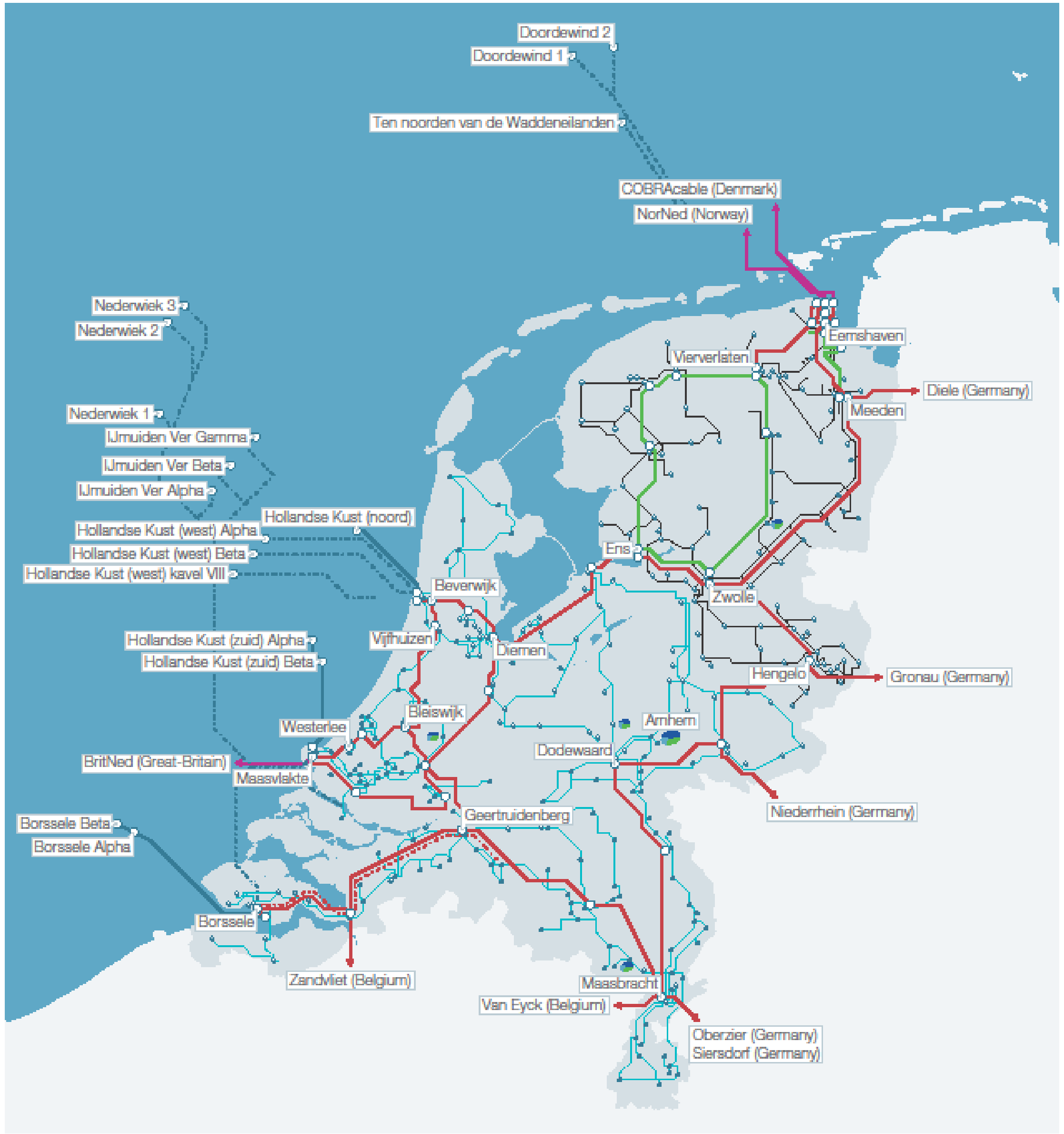
Use the stairs instead of the lift

Go to the assembly point

Follow the instructions of the in-company emergency responder

Introduction: TenneT

- Dutch Transmission system operator
- Transmission grid
  - Building
  - Maintaining
  - Operating
- Optimal Power Flow:
  - Making optimal use of the grid in operation



Example: reactive power dispatch

- Situation: high supply of reactive power → rising voltages
- Goal: keep voltages within safety limits
- Possible actions:
  - Control transformer tap ratio set-points
  - Control shunt set-points
  - Control voltage magnitude set-points of some generators
- Consideration: setting voltage set-points has a cost
- How to do this optimally?

Content

- Power Flow
- Security Constrained Optimal Power Flow
- Challenges and existing methods
- Proposed research steps

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- **Power Flow**
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A Mathematical Model

- The grid as a graph
- Nodes: points of interest
  - Generators and loads inject current
- Edges: connections between nodes
  - Power Lines or Cables
  - Transformers
  - Admittance
- Admittance matrix Y
  - Component $Y_{k,l}$ is admittance of edge (k, l)
  - Diagonal elements contain shunt admittances
  - Admittance of transformers is dependent on tap ratio

Electrical Quantities at Nodes

- Four quantities:
  - (Net) injected active power P_i
  - (Net) injected reactive power Q_i
  - Voltage magnitude $|V_i|$
  - Voltage angle δ_i
- Complex notation
  - $S_i = P_i + jQ_i$
  - $V_i = |V_i|e^{j\delta_i}$
- At each node: 2 known, 2 unknown
- Depends on the components attached to the bus

Bus type	Known variables	Unknown variables
PQ bus	P_i, Q_i	$\lvert V_i\rvert, \delta_i$
PV bus	$\lvert V_i\rvert, P_i$	δ_i, Q_i
Slack bus	$\lvert V_i\rvert, \delta_i$	P_i, Q_i

Power Flow Problem

- Relates four quantities P_i, Q_i, $|V_i|$, δ_i at all nodes
- Kirchhoff's circuit laws and Ohm’s law
- Power flow equations:

$$S_k = V_k \left(\sum_{l \in \mathcal{N}} Y_{kl} V_l \right)^* \qquad \text{For all nodes } k$$

- Power flow problem: solve these equations for the $2N$ unknowns
- Result: whole state of the system is known

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Optimal Power Flow

- Optimally control components in the grid
- Nonlinear (non-convex) Optimization (NLP) problem
- Standard form:
- Objective function
- Decision variables, state variables, fixed variables
- Constraints

$$\begin{aligned} \underset{\mathbf{u},\mathbf{x}}{\text{minimize}} \quad & \mathbf{f}(\mathbf{u},\mathbf{x},\mathbf{z}) \\ \text{subject to} \quad & \mathbf{g}(\mathbf{u},\mathbf{x},\mathbf{z}) = 0, \\ & \mathbf{h}(\mathbf{u},\mathbf{x},\mathbf{z}) \leq 0. \end{aligned}$$

Three types of variables

- Decision variables $\boldsymbol{u}$: variables that can be controlled
  - Can be discrete (transformer tap ratio, shunt activation)
- Fixed variables $\boldsymbol{z}$
- State variables $\boldsymbol{x}$: unknown variables
- Type of variable depends on specific problem
  - Example: reactive power injection
  - Load: fixed
  - PQ generator: decision
  - PV generator: state

Objective function

- Function f
- Function of decision variables and state variables
- Examples
  - Minimize cost (reactive power dispatch example)
  - Minimize power losses
  - Minimize deviation of voltages from 1 pu

Example: reactive power dispatch

- Active power injections are fixed
- Some voltage set-points of generators can be controlled
- Shunt and transformer tap ratio set-points can be controlled
- Voltages and currents have safety constraints
- Set-points can also have upper and lower bounds
- Controlling generators has a cost, shunts and transformers not
- Objective: minimize cost

Equality constraints

- Function $\boldsymbol{g}$
- Power flow equations
- Makes sure that system is “valid”
- Determines state variables

Inequality Constraints

- Function $\boldsymbol{h}$
- Bounds on control variables and state variables
- Examples:
  - Voltage magnitude between 0.9 and 1.1 pu

$$0.9 \leq |V_i| \leq 1.1$$

  - Maximum current flowing through line

$$|Y_{kl}(V_l - V_k)| \leq I_{kl}^{\max}$$

Security Constrained Optimal Power Flow

- Additionally: constraints must be satisfied in case of contingency
- Failure of a line, cable or transformer
- Each contingency c has its own power flow equations $\boldsymbol{g}_c$, inequality constraints $\boldsymbol{h}_c$ and state $\boldsymbol{x}_c$
- Control variables remain the same

$$
\begin{aligned}
\underset{\mathbf{u}_0;\mathbf{x}_0,\ldots,\mathbf{x}_C}{\text{minimize}} \quad & \mathbf{f}(\mathbf{u}_0;\mathbf{x}_0,\ldots,\mathbf{x}_C) \\
\text{subject to} \quad & \mathbf{g}_0(\mathbf{u}_0,\mathbf{x}_0) = 0, \\
& \mathbf{h}_0(\mathbf{u}_0,\mathbf{x}_0) \leq 0, \\
& \mathbf{g}_c(\mathbf{u}_0,\mathbf{x}_c) = 0 \quad \text{for } c \in C, \\
& \mathbf{h}_c(\mathbf{u}_0,\mathbf{x}_c) \leq 0 \quad \text{for } c \in C.
\end{aligned}
$$

- Number of constraints and variables grows quickly!
- Also possible: allow control variables to change after contingency

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Existing software

- pandapower
  - Open source
  - OPF capabilities limited
    - No control over transformers and shunts
    - Limited options for constraints and objectives
    - Not capable of SCOPF
- PowerFactory
  - Commercial software, licensed by DIgSILENT
  - More capabilities, but still limited
    - Allows control over shunts and transformers
    - More possible types of objective functions
    - Capable of SCOPF, only with DC-approximation
  - Big downside: closed-source
  - Too slow for some applications

Scientific literature

- Quite some literature on (SC)OPF
- Area of active research
- Challenges:
  - Dealing with discrete variables
  - Computational complexity of SCOPF
  - Solving NLP problems

Dealing with discrete variables

- Also relevant for OPF
- Variables are only allowed to take integer values
- Little success with discrete solvers, due to problem size
  - First experiment: 0.2 seconds vs. 35 minutes
- Continuous relaxation: same problem, but discrete variables are treated as continuous variables
- Two common types of methods:
  - Rounding methods
    - Round discrete values to closest integer
  - Objective penalty methods
    - Add penalty to objective function, that “pushes” variables towards integer value

Handling discrete values: comparison

- Discrete solvers
  - most optimal solutions
  - very slow
- Rounding methods
  - Fast
  - less robust
  - less optimal
- Objective penalty methods
  - solutions more optimal than rounding
  - More robust than rounding
  - Slightly slower than rounding, but much faster than discrete solvers

Computational complexity of SCOPF

- Computational complexity grows quickly with number of contingencies
- Full problem only doable for small problems or very few contingencies
- Some solutions:
  - Contingency filtering
    - Only consider contingencies with “worst” violation of constraints
  - Network compression
    - Consider only part of network for contingency states
  - Problem decomposition
    - Decompose problem with Benders decomposition
  - DC-OPF
    - Linearize system, like DC power flow

Comparison of methods

- Contingency selection
  - Relatively easy to implement
  - Speed up not always sufficient
  - Often used in combination with other methods
- Network compression
  - Harder to implement
  - Promising results in literature
- Problem decomposition
  - Harder to implement
  - Very well parallelizable
  - Mixed results in literature
- DC-OPF
  - Easy to implement, good results
  - Based on approximations, not well suited for reactive power optimization

Optimization algorithms and solvers

- Most use existing implementations of primal-dual interior point methods
- Ipopt
  - Free, open-source
  - commonly used
- Knitro
  - Paid license
- Bonmin
  - Discrete solver
  - Free, open-source

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Proposed steps

1. OPF method with P_i, Q_i, $|V_i|$, δ_i as possible decision variables
2. Add transformer taps and shunt decision variables
3. Implement method of handling discrete variables
4. Implement full SCOPF
5. Decrease computational complexity of SCOPF

- Possible intermediate/extra steps
  - Implement unit dispatch
  - Elaborate comparison of rounding methods
  - Elaborate comparison of solvers
  - Testing with different decision variables and objectives
- Each step: focus on speed and robustness

Speed and robustness

- Robustness
  - Most important: always obtaining feasible solutions
  - Optimality also important, however…
  - (Proven) globally optimal solutions not required
- Speed
  - Speed should be sufficient for real-time calculations, or bulk calculations
  - OPF calculation with rounding on the order of 1 min
  - SCOPF calculation on the order of 30 min

Proposed tools

- Implement as part of ODINA toolbox
- Use Pyomo optimization framework
  - Python library
  - Model general optimization problems
  - Compatible with many solvers
- Start with Ipopt solver

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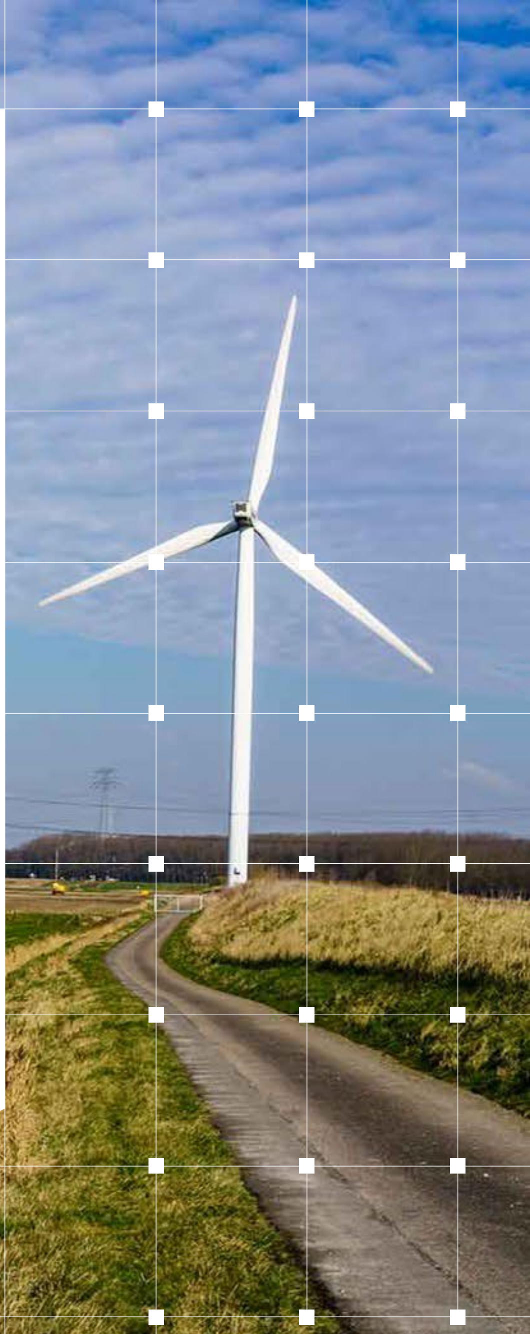
Lighting the way ahead together



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