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Robust optimal power flow for AC/DC grids under multi-purpose interconnector setup

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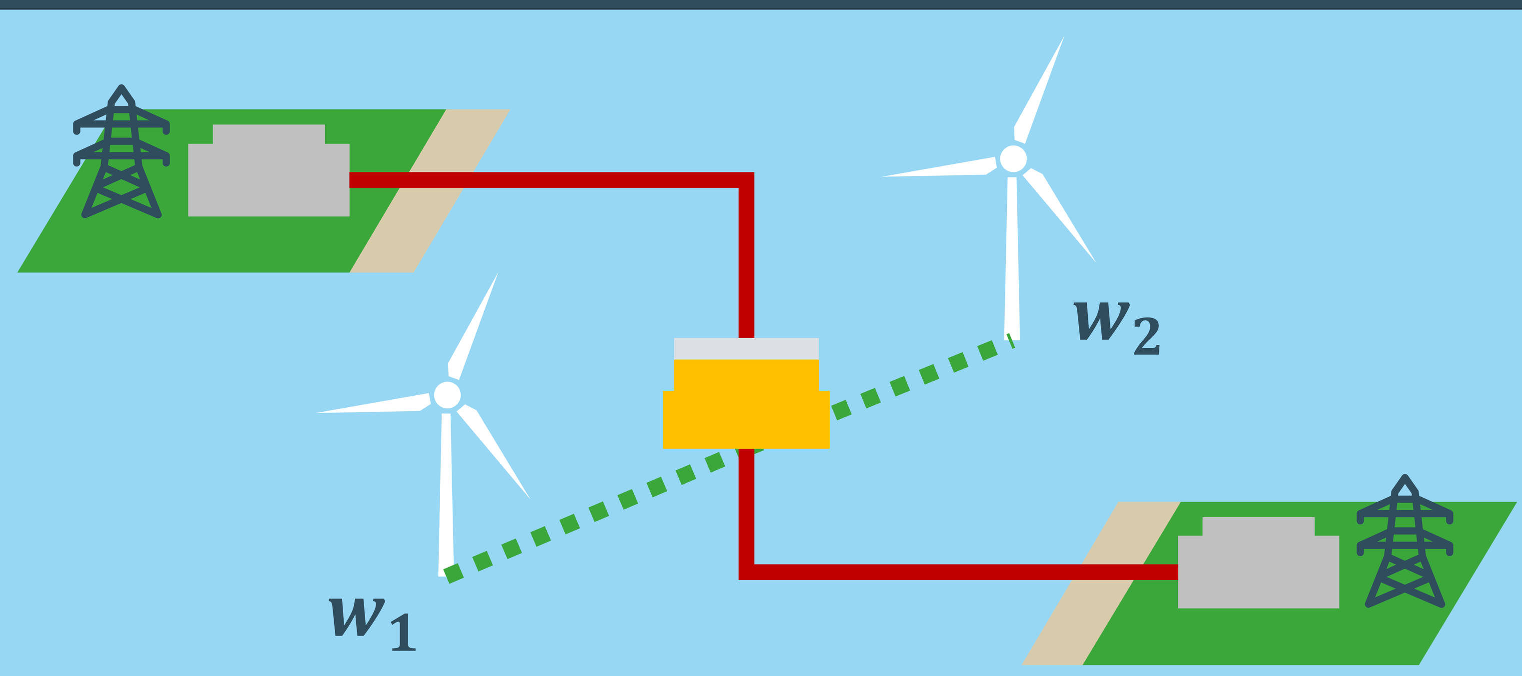
Multi-purpose interconnector

Offshore wind farm generation + **Cross-border flows**

Offshore wind farm generation	Cross-border flows
Limitedly predictable ↓ uncertainty	Critical infrastructure, capacity scarcity
Uncertainty is introduced to the interconnector capacity	Needs for efficient and robust operational decisions



Robust approach

Why robust approach?

- To protect against the worst-case realization (suitable for critical infrastructures)
- Limited to no access to sufficient data to represent the uncertainty
- Adjustable level of conservativeness

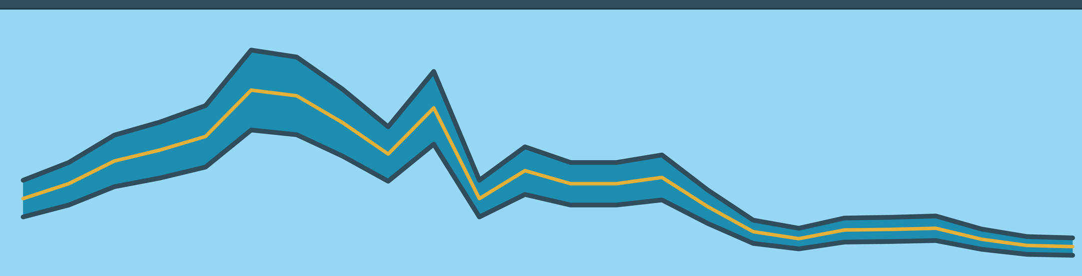
Optimization problem formulation

$$\max_{w} \min_{y} f(y, w)$$

y = decision variables
w = uncertainty variables

! Bilevel programming can be difficult to solve

Uncertainty representation



Robust sets

$$w_i^{ref} - w_i^{\Delta} \le w_i \le w_i^{ref} + w_i^{\Delta}, \quad \forall i$$

Uncertainty budget

$$\sum_{i=1}^{n} \frac{|w_i - w_i^{ref}|}{w_i^{\Delta}} \le \Gamma, \quad \forall i$$

Γ = level of uncertainty, $0 \le \Gamma \le 1$

Robust optimal power flow

Different optimal power flow formulations

Nonlinear AC formulation	Semidefinite programming (SDP)
Second-order cone programming (SOCP)	Linear AC approximation
DC approximation	Nonlinear AC formulation with convex restrictions

- Solving a linear robust optimal power flow problem is already a difficult task
- Trade off between having tractable problems and getting closer to AC feasible solutions

Robust optimal power flow formulation

$\max_{w} \min_{y}$

- Generation costs
- Generation curtailment costs
- Load curtailment costs

subject to

Uncertainty variables	Generator constraints
Power flow constraints	Branch constraints
Converter constraints (AC-DC grids)	Curtailment constraints

Scaling up optimal power flow problem

Scaling up optimal power flow problem by adding technical constraints or stages can give more meaningful results

Multi stages	Unit commitment constraints
Security constraints as uncertainty variables	Frequency stability constraints
Enhanced technical constraints (e.g., for HVDC links)	Voltage stability constraints

Two-stage robust security- and network- constrained unit commitment

Two-stage problem

$$\min_{x} \Big(\text{Day-ahead unit commitment costs} + \max_{w,k} \min_{y} \text{Real-time operational costs} \Big)$$

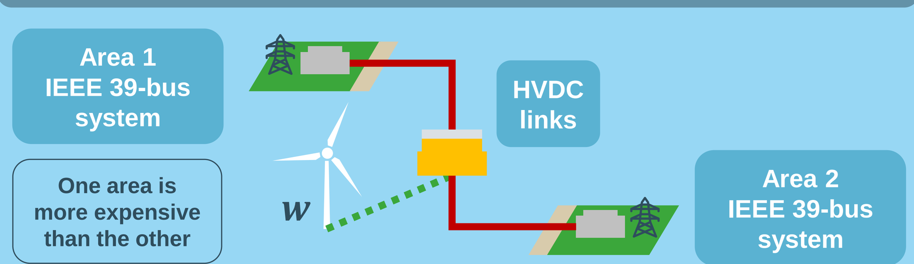
1st stage:
- The unit commitment variables are binary variables comprising start-up, shut-down, and on-and-off status of the generators
- The unit commitment constraints consist of minimum up and down times

2nd stage:
- The optimal power flow problem is formulated using linear DC approximation
- The contingency variable k is included in the 2nd stage problem as uncertainty variable

Observation

- Capacity utilization of the multi-purpose interconnector on the first and second stages
- Worst-case realization of w and k

Test system (two-area system)



Methodology

1. Decompose the two-stage problem into master problem (first-stage problem) and subproblem (second-stage problem)
2. Master problem (first-stage problem, MILP)
3. Subproblem (second-stage problem)
   - Reformulate the bilevel max-min problem to a single-level maximization problem by means of formulating a dual problem of the inner minimization problem
   - The problem becomes a MINLP due to bilinear terms formed by the uncertainty variables w, k and the dual variables associated with inner-problem constraints
   - Apply convex relaxations to the bilinear terms by applying the McCormick envelop method
4. Solve the master problem and the subproblem iteratively using column-and-constraint-generation (CCG) algorithm