Offshore Wind Park Optimization

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Contents

Motivation

- Increasing need and demand for renewable energy sources, such as wind power.
- Trade-off between investment costs and technical constraints when designing the transmission system of an Offshore Wind Power Plant (OWPP).
- Need for new optimization tools for multi-objective, mixed variable and non-linear optimization problems.
- Industry interest, such as Acciona, in developing software for this purpose.

Goals

- Model all the elements of the HVAC transmission system of an OWPP.
- Implement a Power Flow solver in Python.
- Formulate the optimization problem of the reactive power compensation and the transmission system design.
- Design and implement an optimization algorithm in Python that allows to find the Pareto Frontier of optimal solutions.

HVAC transmission system for an OWPP

What we want to design?

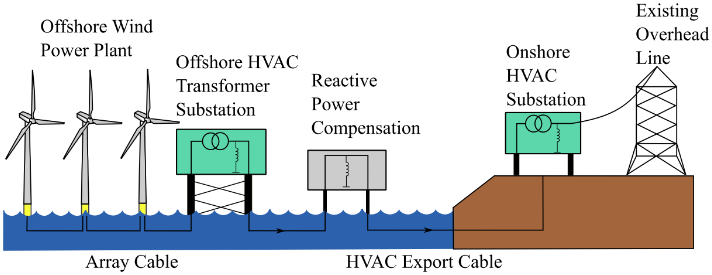

Figure 1: HVAC transmission system layout for an OWPP with reactive power compensation [*check memory for citation*] .

Reactive power compensation

Underground HVAC cables have high capacitance, reactive power generation becomes a problem.

	Overhead Lines	Underground Lines
Capacitance Per Unit Length (μF/km)	0.01 - 0.02	0.3 - 0.6

Table 1: Comparison of Capacitance Per Unit Length of Overhead and Underground Lines.

Reactive power compensation helps overcoming associated issues.

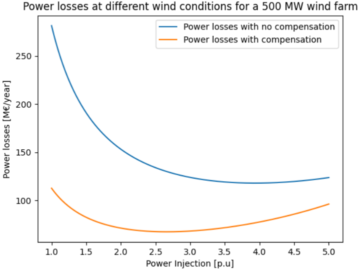

Figure 2: Effect of including reactive power compensation.

Shunt reactors

Reactive power compensated by a shunt reactor is $Q_l = Y_{sh} \cdot U_{AC-N}^2$.

$$Y_{sh} = \frac{1}{j\omega L} \tag{1}$$

where L is the inductance of the shunt reactor, ω the angular frequency and U_{AC-N}^2 the nominal transmission voltage.

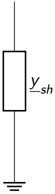

Figure 3: Shunt reactor model.

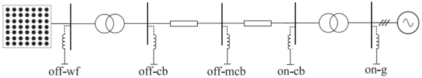

Figure 4: Possible locations for the shunt reactors [*check memory for citation*].

Transmission system design

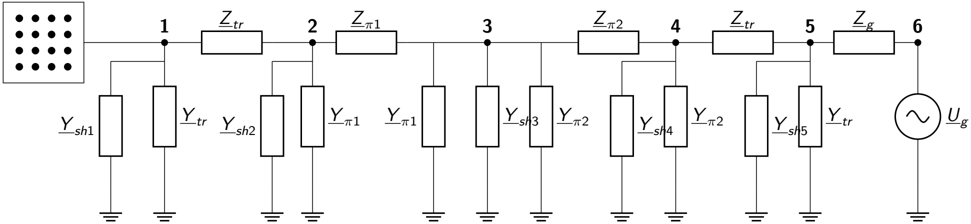

Figure 5: Transmission system model and buses.

Figure 6: Bus types.

Bus Number	Bus Type
1	PQ
2	PQ
3	PQ
4	PQ
5	PQ
6	Slack

Figure 7: Elements in the transmission system.

Elements
XPLE Cables
Transformers
Shunt reactors
Switchgears
Main Grid (given)
Substation (cost dependent on OWPP)

Solving the Power Flow will allow as to find the steady-state powers and voltages of the system.
The PF equations will become the equality constraints of the optimization problem ($\mathbf{H}(\mathbf{x}) = 0$) and its solution will determine the inequality contraints deviations and the active power losses:

$$P_{losses} = (P_{owf} - P_6) \cdot S_{base} \cdot 10^{-6} \quad \text{MW} \tag{2}$$

We will using the per-unit system:

$$\text{Per unit value} = \frac{\text{Actual value}}{\text{Base value}} \tag{3}$$

$$\begin{cases} I_{base} = S_{base} V_{base} \\ Y_{base} = \frac{S_{base}}{V_{base}^2} \end{cases} \tag{4}$$

where $S_{base} = 100$ MVA and $V_{base} =$ transmission voltage in kV.

Admittance matrix and equations

Inspecting the Kirchhoff's Current Law (KCL) we can observe how the admittance matrix is the fundamental relationship between voltages and currents :

$$\mathbf{I} = \mathbf{Y}_{bus}\mathbf{V} \tag{5}$$

We have built $\mathbf{Y}_{bus}$ by inspection applying KCL at each node. The expanded Power Flow equations become:

$$P_i = \sum_{k=1}^{n} |V_i||V_k|(G_{ik}cos(\theta_{ik}) + B_{ik}sin(\theta_{ik})) \quad i = 1, 2, ..., n \tag{6}$$

$$Q_i = \sum_{k=1}^{n} |V_i||V_k|(G_{ik}sin(\theta_{ik}) - B_{ik}cos(\theta_{ik})) \quad i = 1, 2, ..., n \tag{7}$$

where G_{ik} and B_{ik} are the real and imaginary parts of $\mathbf{Y}_{bus}$ respectively.

Newton-Raphson Method

We will use the Newton-Raphson method is an iterative method to solve the set of Power Flow non-linear equations:

Algorithm 1 Newton-Raphson Method

```
procedure RUN_PF
    Initialize V with ones and θ with zeros
    Set V[slack] to 1, θ[slack] to 0
    Set P, Q based on OWPP data
    Set iter = 0, tol and k = 0
    while iter < max_iter and ΔPQ > tol do
        Compute P_present, Q_present using V, θ, Y_bus
        Compute mismatch ΔPQ = [dP, dQ] as difference between calculated and given P, Q
        Compute the Jacobian matrix J.
        Solve the linear system J · Δx_k = −ΔPQ.
        Compute the updated x^{k+1} = x^k + Δx^k.
        Update V, θ using dP, dQ, Y_bus
        if max(ΔPQ) < tol then
            break
        end if
    end while
    return V, θ
    Compute P_slack, Q_slack
end procedure
```

Figure 8: Newton-Raphson method.

Optimization Problem Formulation

A multi-objective optimization problem in its more general form can be defined as:

$$\begin{aligned} \min \quad & \mathbf{f}(\mathbf{x}) = (f_1(x), f_2(x), ..., , f_k(x)) \\ \text{subject to} \quad & \mathbf{H}(\mathbf{x}) = 0 \\ & \mathbf{G}(\mathbf{x}) \leq 0 \end{aligned} \tag{8}$$

- $\mathbf{x} \in \mathbb{R}^n$: n-decision variables.
- $\mathbf{f}(\mathbf{x})$: k-objective functions.
- $\mathbf{H}(\mathbf{x})$: Equality constraints.
- $\mathbf{G}(\mathbf{x})$: Inequality constraints.

Decision Variables

We can get the **x** variables from the parameters on which the transmission system model ($\mathbf{Y}_{bus}$) depends on:

$$\mathbf{x} = \left[vol_{tr}, \quad n_{cables}, \quad react_{bi_1}, \quad , \dots \quad , react_{bi5} \quad , react_{cont1} \quad , \dots \quad , react_{cont5} \quad , react_{bi5} \quad , S_{trafo}\right] \tag{9}$$

- vol_{tr}: Transmission voltage level.
- n_{cables}: Number of transmission cables placed in parallel.
- $react_{bi_i} \quad \forall i = 1, \dots, 5$: Is a binary variable (i.e. either 0 or 1) that tells if we place or not a reactor at position i.
- $react_{cont_i} \quad \forall i = 1, \dots, 5$: Sizing of reactor at position i, therefore its Y_{sh_i} in p.u.
- S_{trafo}: Rated power of the transformer in VA.

Mixed-variable: Continous, binary and integer variables.

Equality Constraints: Power Flow

The equality constraints $\mathbf{H}(\mathbf{x}) = 0$ in the optimization problem are the imposed by the power flow equations. In fact, the power mismatch vector takes the desired form:

$$\mathbf{H}(\mathbf{x}) = \begin{bmatrix} \mathbf{\Delta P}(\mathbf{x}) \\ \mathbf{\Delta Q}(\mathbf{x}) \end{bmatrix} = \begin{bmatrix} P_1(\mathbf{x}) - P_1 \\ \vdots \\ P_{n-1}(\mathbf{x}) - P_{n-1} \\ Q_1(\mathbf{x}) - Q_1 \\ \vdots \\ Q_{n-1}(\mathbf{x}) - Q_{n-1} \end{bmatrix} = \mathbf{0} \tag{10}$$

Inequality Constraints: Technical requirements

Bus voltage limits: We set the nodal bus-i voltage, V_i, limits as:

$$\begin{aligned} L_i^{Vu} &= V_i - V_{max} \leq 0, \quad i \in N \quad \text{is the upper limit} \\ L_i^{Vl} &= V_{min} - V_i \leq 0, \quad i \in N \quad \text{is the lower limit} \end{aligned} \tag{11}$$

We have taken V_{max} and V_{min} to be ± 0.1 p.u. of the nominal voltage respectively.
Maximum current limits for the lines:

$$L_i^{I} = I_i - I_{max} \leq 0, \quad i \in N_{lines} \tag{12}$$

where $I_{max} = 1.1$ p.u. of I_{rated}.
Reactive power delivered to the grid:

$$\begin{aligned} L_6^{Qu} &= Q_6 - Q_{max} \leq 0 \\ L_6^{Ql} &= Q_{min} - Q_6 \leq 0 \end{aligned} \tag{13}$$

where we have taken $Q_{max} = Q_{min} = 0$, but they can be set by grid code requirements.

Objective Function I

We want to get insight on the trade-off between conflicting objectives, therefore we will use a multi-objective optimization approach. We will define the objective functions as:

$$\mathbf{f}(\mathbf{x}) = (f_{invest}(\mathbf{x}), f_{tech}(\mathbf{x})) \tag{14}$$

where:

$$\begin{aligned} f_{invest}(\mathbf{x}) &= C_{cables}(\mathbf{x}) + C_{tr}(\mathbf{x}) + C_{sh}(\mathbf{x}) + C_{gis-AC}(\mathbf{x}) + C_{ss-AC}(\mathbf{x}) \\ f_{tech}(\mathbf{x}) &= C_{loss-AC}(\mathbf{x}) + c \cdot \mathbf{p}(\mathbf{x}) \end{aligned} \tag{15}$$

c is the penalty factor and $\mathbf{p}(\mathbf{x})$ is the penalty function:

$$\mathbf{p}(\mathbf{x}) = \sum_{L_i^X \in G(x)} \max(0, \mathbf{L_i}(\mathbf{x})) \tag{16}$$

Objective Function II

With this approach we expect to get a set of Pareto optimal solutions, i.e. a set of solutions where we cannot improve one objective without worsening another:

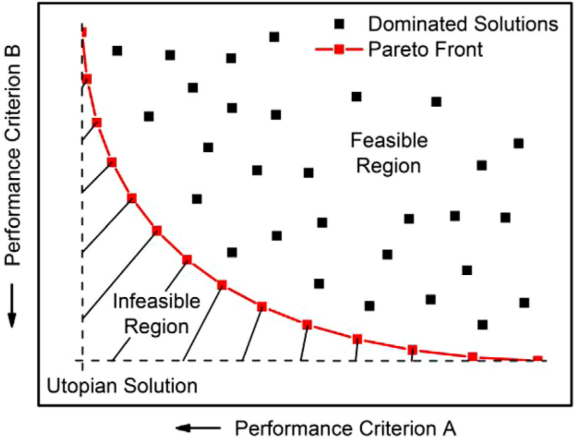

Figure 9: Explanation of domination [*check memory for citation*] .

What we need?

We need an optimization method that:

- Can handle mixed-variable problems.
- Can handle multi-objective problems.
- Can handle non-linear optimization problems.
- Can handle find a set of Pareto optimal solutions, i.e. works with a population of solutions.

PROPOSAL: **NSGA-II: Non-dominated Sorting Genetic Algorithm II**.

NSGA-II Genetic Algorithm

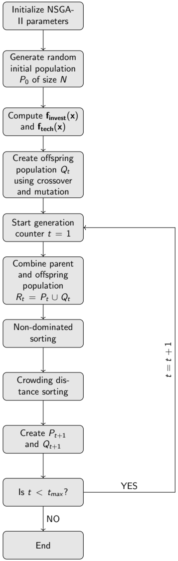

Figure 10: NSGA-II algorithm.

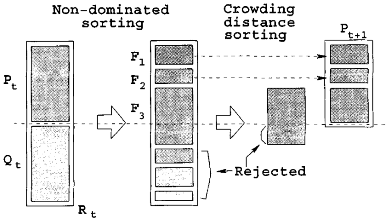

Figure 11: Sorting and Crowding process [*check memory for citation*].

Algorithm overview

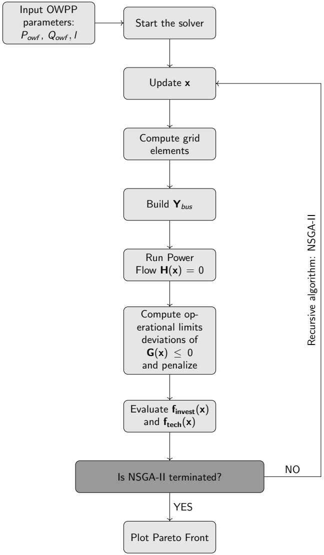

Figure 12: Proposed optimization algorithm.

OPF for reactor sizing validation

We modify the traditional AC-OPF objective function of minimizing cost of generating active power, P_G, for minimizing C_{sh}, reactive power compensation cost, while satisfying the constraints:

$$\min_{Q_{sh}} \quad \mathbf{c}_{\mathbf{sh}}^{\mathbf{T}} \mathbf{Q}_{\mathbf{sh}} \quad \text{where} \quad \mathbf{c}_{\mathbf{sh}} = \begin{bmatrix} K \\ P \\ 0 \end{bmatrix} \tag{17}$$

where K and P come from the cost function of the shunt reactors:

$$C_{sh} = K \cdot Q_{sh} + P = K \cdot Y_{sh} \cdot U_{AC-N}^2 + P \quad [\text{M€}] \tag{18}$$

Location	K	P
Onshore	0.01049	0.8312
Offshore	0.01576	1.244
Mid-cable	0.01576	12.44

Table 2: K and P for different positions of the shunt reactors [*check memory for citation*].

Random search vs NSGA-II

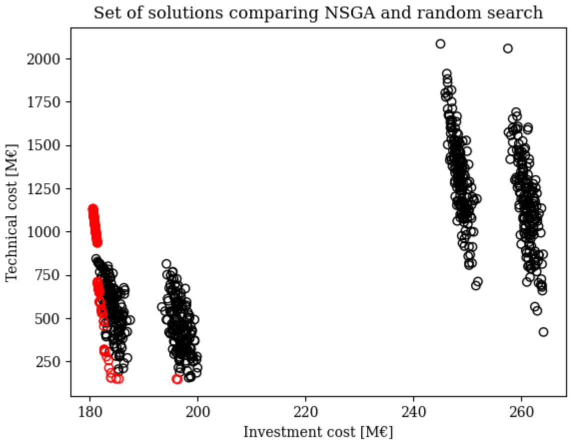

Figure 13: Random search (black) compared to NSGA-II (red).

Zoom on Pareto Front

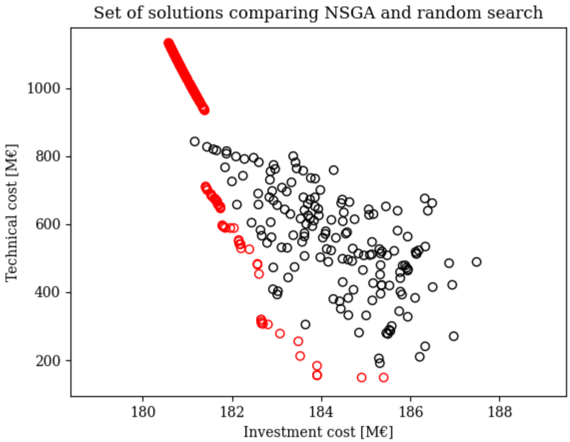

Figure 14: Zoom on Pareto Front, random search (black) compared to NSGA-II (red).

OPF validation: Convergence

It takes OPF about 1.5 s to converge, x25 slower than he traditional PF.

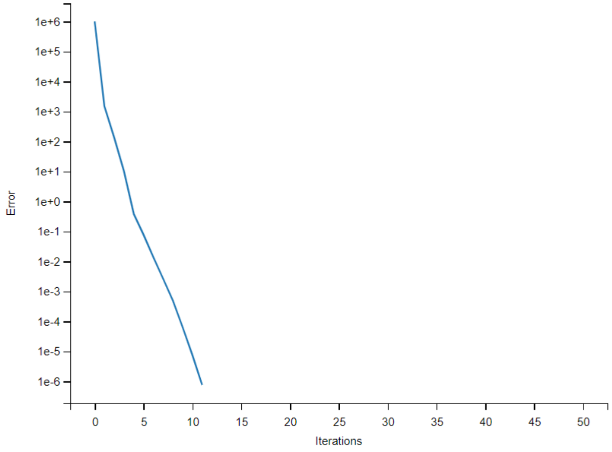

Figure 15: Convergence of the OPF algorithm.

OPF validation: Reactors sizing

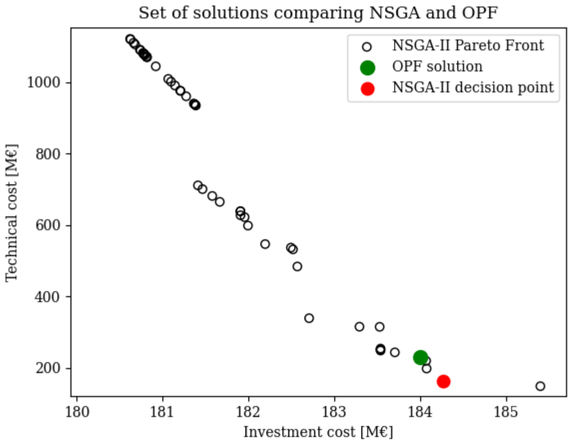

Figure 16: NSGA-II vs OPF for reactors sizing

Costs comparision

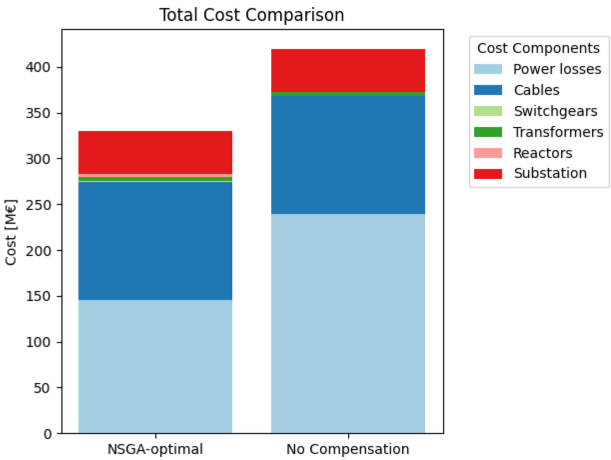

Figure 17: NSGA-II optimal solutions and no-compensation total cost comparision.

Variable Power Injection: Power losses

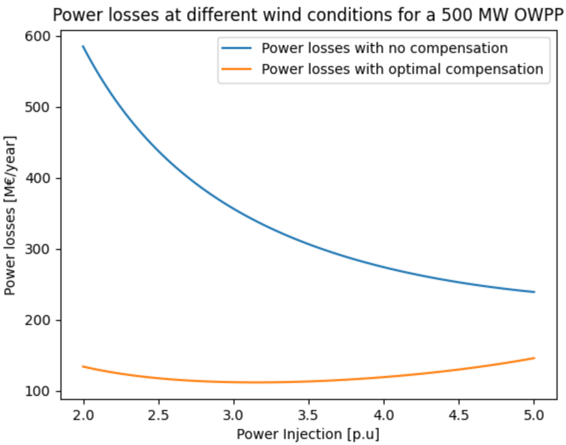

Figure 18: Power losses evolution with variable P_{owf}.

Variable Power Injection: Overvoltages

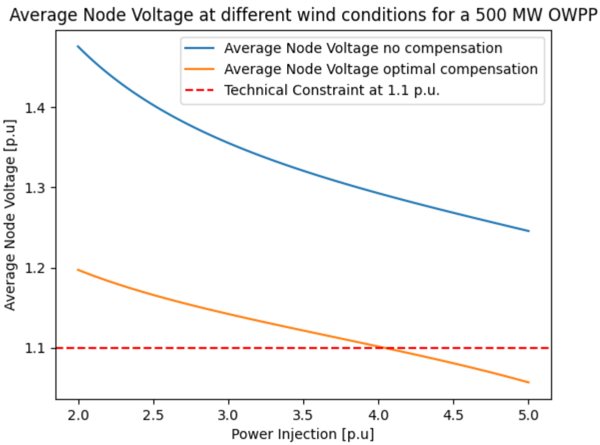

Figure 19: Average Node voltage evolution with variable P_{owf}.

Outcome

✓ To develop a multi-objective approach for the optimization problem.
✓ To include a Power Flow solver in Python.
✓ To implement a genetic algorithm for the optimization problem.
✓ To study a specific case study of an OWPP and validating the results using OPF approach.

Future work

- Consider wind speed distribution, i.e. variable power injection.
- Consider HVDC trasmission system comparision.
- Electrical collection system layout optimization.
- Further development of the costs functions.
- Integration into existing software, i.e. GridCal.

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