# Bachelor's Thesis

**Bachelor's degree in Industrial Technologies and Economic Analysis**

# Offshore Wind Park Optimization

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UPC

## Abstract

Short and must include results.



**Keywords:** offshore wind power plant, power flow, renewable energy, HVAC, transmission system, optimization, mixed-integer programming, genetic algorithms.

**MSC codes:** 90C11, 90C15, 90C29, 90C30, 90C59


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## Resum

Short and must include results.

**Paraules clau:** parc eòlic marí, flux de potència, energia renovable, HVAC, sistema de transmissió, optimització, programació enter mixta, algoritmes genètics.

**Codis MSC:** 90C11, 90C15, 90C29, 90C30, 90C59

## Resumen

Short and must include results.

**Palabras clave:** parque eólico marino, flujo de potencia, energía renovable, HVAC, sistema de transmisión, optimización, programación entera mixta, algoritmos genéticos.

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## Nomenclature

The next list describes several abbreviations and symbols that will be later used within the body of the thesis.

AC Alternating Current

DC Direct Current

HVAC High Voltage Alternating Curent

HVDC High Voltage Direct Current

MVRSM Mixed-Variable ReLU-based Surrogate Modelling

N-R Newton-Raphson Method

OPF Optimal Power Flow

OSS Offshore Substation

OWF Offshore Wind Farm

OWPP Offshore Wind Power Plant

PF Power Flow

SCR Short Circuit Ratio

XLPE Cross-Linked Polyethylene

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# 1 Preface

Argurably, climate change is one of the most pressing challenges we are facing today as humanity. That's why I wanted to develop a project revolving around sustainable solutions for the energy system of the future. As an engineering student I wanted to explore how renewable energy sources can by integrated into the grid and what challenges it poses, that's why I contacted Oriol Gomis to explore thesis topics within this field.

He introduced me diverse research areas and also eRoots, a spin-off from the UPC-CITCEA that develops software solutions for modern grid modelling, analyis and optimization. Then Josep Fanals, my supervisor and eRoots CEO, presented to my various topics that they would be potenitially interested to develop a thesis on. This is when he introduced me to the topic of design, sizing and optimization of the transmission system of offshore wind power plants. The research group CITCEA-UPC has been working in this area [2] and further developement on this field was the breeding ground for this proposal. The topic inmediatly caught my attention and that is how I ended up as an intern at eRoots developing software solutions for the optimization of offshore wind power plants.

Figure 1: Una imatge del logo de l'ETSEIB

Per referir-se a la Fig.1. Per no repetir informació és millor referir-se a altres apartats 5.

I recorda, sempre és important citar a la bibliografia [2].
La bibliografia ha d'estar ordenada, en teniu un exemple a la pàgina 23

# 2 Introduction

## 2.1 Motivation

During the industrial engineering studies you get in touch with a wide range of topics that can be applied to different fields. During the last years to get introduced to electrical engineering fundamentals and its applications. I discovered a deep interests for those topics and realized is a key tool for ensuring a future towards energy systems that can inegrate renwable energy sources.

The main driving force behind choosing this topic is the need to develop a sustainable energy system that can ensure a future for the next generations. The energy system is a key player in the fight against climate change. Moreover, the last report on global sustainable development [1] highlights how *Goal 7: Affordable and clean energy* is failing to meet its targets. In fact, it actually notices a backward trend in the 2020-2023 period when it comes to this goal targets, which signals that it is an area where efforts have to be put in.

This thesis is my modest and passionate contribution to provide sustainable solutions for our future.

## 2.2 Scope

This work will limit its study to the optimal design of HVAC transmission systems, without considering the cost comparision with HVDC. Moreover, it will limit its study to the steady-state of balanced three phase load systems, without considering unbalanced or transient states.

## 2.3 Objectives

The main objectives of the thesis are the following:

- Model all the elements of the transmission system of an offshore wind power plant and find its equivalent circuit.
- Formulate the optimization problem to minimize all types of costs taking into account the technical constraints of the system.
- Implement a power flow solver with Python.
- Bencharmark different optimization algorithms thar find solutions faster than state of the art methods.
- Study some specific cases applicable to real offshore wind power plants.

## 2.4 Outline

The thesis is structured as follows:

- Chapter 3 introduces offshore wind power plants, the problem we want to tackle and models the elements that we find in a HVAC transmission system.
- Chapter 4 formulates the minimization problem, including objective functions and constraints. In this section we also build the power flow solver that deals with the equality contraints and the algorithm for computing objective function values.
- Chapter 5 explains state of the art methods to solve the problem, its limitations, and our new approaches involving surrogate models, genetic algorithms and optimal power flow.
- Chapter 6 showcases results for different OWPP's sizes and distance to shore and compare it with existing results in terms of validity and computational time.
- Chapter 7 collects the main outcomes of the thesis and proposes future lines of work.
- Chapter 8 presents the planning and viability studies for the project.

# 3 Technical background: grid to study

## 3.1 Offshore wind power plants

As global energy demands surge and the pressing need for sustainable development becomes ever more urgent, the quest for renewable energy sources has intensified. Among these, wind power has emerged as a frontrunner due to its potential to generate substantial amounts of clean electricity. While onshore wind farms have been widely implemented, their offshore counterparts are gaining increasing attention for their ability to harness the stronger and more consistent winds found over the oceans.

Offshore wind power, defined as the use of wind turbines located in bodies of water to generate electricity, presents several advantages over onshore installations. The primary benefit lies in the higher wind speeds and lower turbulence experienced offshore, which contribute to greater energy yields. Additionally, offshore wind farms can be situated closer to urban centers located along coastlines, thereby reducing transmission losses and enhancing energy efficiency. The development of offshore wind technology has seen rapid advancements in recent years. From the deployment of the first offshore wind farm in Denmark in 1991 to the establishment of massive installations such as the Hornsea Project in the UK, the scale and capacity of these projects have grown significantly. Technological innovations, including larger turbines, floating foundations, and improved grid integration techniques, have further propelled the industry forward.

## 3.2 Transmission systems and reactive power compensation problem

## 3.3 Grid modelling

### 3.3.1 Cables

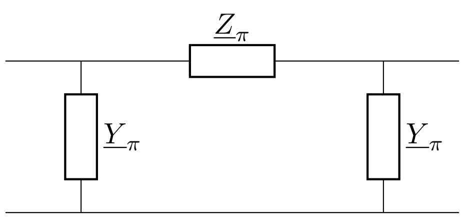


Figure 2: Pi model transmission line

### 3.3.2 Transformers

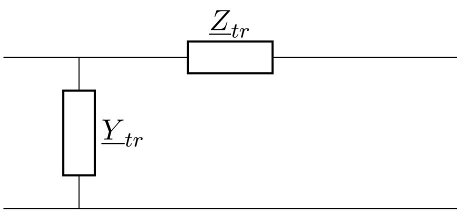


Figure 3: Transformer model

### 3.3.3 Shunt reactor: reactive power compensation

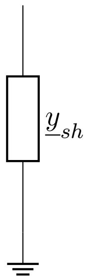


Figure 4: Shunt reactor model

### 3.3.4 Main grid

It will be the slack bus.

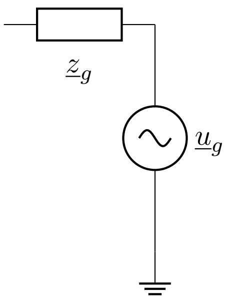


Figure 5: Main grid model

### 3.3.5 Power plant

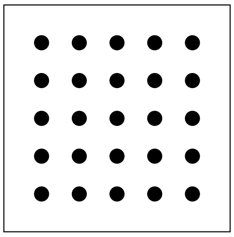

Figure 6: Power plant

### 3.3.6 Admittance matrix

Now we can build the full HVAC trasnsmission system model and fins its admittance matrix $\underline{Y}_{bus}$, which will be essential for the power flow solver.

$$\mathbf{Y_{bus}} = \begin{bmatrix} (2\underline{y}_{tr} + \underline{y}_{sh}) & -\underline{y}_{tr} & 0 & 0 & 0 & 0 \\ -\underline{y}_{tr} & (2\underline{y}_{\pi 1} + \underline{y}_{sh} + \underline{y}_{tr}) & -\underline{y}_{\pi 1} & 0 & 0 & 0 \\ 0 & -\underline{y}_{\pi 1} & (2\underline{y}_{\pi 1} + 2\underline{y}_{\pi 2} + \underline{y}_{sh}) & -\underline{y}_{\pi 2} & 0 & 0 \\ 0 & 0 & -\underline{y}_{\pi 2} & (2\underline{y}_{\pi 2} + \underline{y}_{sh} + \underline{y}_{tr}) & -\underline{y}_{tr} & 0 \\ 0 & 0 & 0 & -\underline{y}_{tr} & (2\underline{y}_{tr} + \underline{y}_{sh} + \underline{y}_{g}) & -\underline{y}_{g} \\ 0 & 0 & 0 & 0 & -\underline{y}_{g} & \underline{y}_{g} \end{bmatrix} \tag{1}$$

# 4 Minimization problem formulation

## 4.1 Objective function: multiobjective and mixed-integer

## 4.2 Costs modelling

### 4.2.1 Cables

### 4.2.2 Transformers

### 4.2.3 Shunt reactor

### 4.2.4 Switchgears

### 4.2.5 Substation platform

## 4.3 Constraints

### 4.3.1 Equality: Power Flow

Now we define de equality constraints as seen in Eq. 2

$$\mathbf{h_m}(\mathbf{x}) = \mathbf{0} \tag{2}$$

$$\mathbf{S_i} = \mathbf{V_i}(\sum_{\mathbf{j=1}}^{\mathbf{N_{nodes}}} \mathbf{Y_{ij}} \mathbf{V_j})^* \tag{3}$$

$$\begin{aligned}
\underline{s}_1 - (p_{owf} + jq_{owf}) = 0,\\
\underline{s}_1 - \underline{u}_1[(2\underline{y}_{tr} + \underline{y}_l)\underline{u}_1 - (\underline{y}_{tr})\underline{u}_2]^* = 0,\\
\underline{s}_2 - \underline{u}_2[-(\underline{y}_{tr})\underline{u}_1 + (2\underline{y}_{\pi 1} + \underline{y}_l + \underline{y}_{tr})\underline{u}_2 - (\underline{y}_{\pi 1})\underline{u}_3]^* = 0,\\
\underline{s}_3 - \underline{u}_3[-(\underline{y}_{\pi 1})\underline{u}_2 + (2\underline{y}_{\pi 1} + 2\underline{y}_{\pi 2} + \underline{y}_l)\underline{u}_3 - (\underline{y}_{\pi 2})\underline{u}_4]^* = 0,\\
\underline{s}_4 - \underline{u}_4[-(\underline{y}_{\pi 2})\underline{u}_3 + (2\underline{y}_{\pi 2} + \underline{y}_l + \underline{y}_{tr})\underline{u}_4 - (\underline{y}_{tr})\underline{u}_5]^* = 0,\\
\underline{s}_5 - \underline{u}_5[-(\underline{y}_{tr})\underline{u}_4 + (2\underline{y}_{tr} + \underline{y}_l + \underline{y}_g)\underline{u}_5]^* = 0
\end{aligned} \tag{4}$$

The power flow solver is described in Algorithm 1.

**Algorithm 1** Power Flow Solver

**procedure** RUN_PF
  Initialize $V$ with ones and $\theta$ with zeros
  Set $V[slack]$ to 1, $\theta[slack]$ to 0
  Set $P$, $Q$ based on OWPP data
  Set $iter = 0$ and $tol$
  **while** $iter < max\_iter$ and $\Delta PQ > tol$ **do**
    Compute $P\_present$, $Q\_present$ using $V$, $\theta$, $Y_{bus}$
    Compute mismatch $\Delta PQ = [dP, dQ]$ as difference between calculated and given $P$, $Q$
    Compute the Jacobian matrix $J$.
    Solve the linear system $J \cdot \Delta x = -\Delta PQ$.
    Compute the updated $x = x_{old} + \Delta x$.
    Update $V$, $\theta$ using $dP$, $dQ$, $Y\_bus$
    **if** $\max(\Delta PQ) < tol$ **then**
      **break**
    **end if**
  **end while**
  **return** $V$, $\theta$
**end procedure**

#### 4.3.2 Inequality: Technical constraints

$$\mathbf{g_n}(\mathbf{x}) \leq \mathbf{0} \tag{5}$$

$$U_{kj} - U_{max} \leq 0 \tag{6}$$

$$U_{min} - U_{kj} \leq 0 \tag{7}$$

$$I_{kj} - I_{max} \leq 0 \tag{8}$$

$$Q_{min} - Q_{gj} \leq 0 \tag{9}$$

$$Q_{gj} - Q_{max} \leq 0 \tag{10}$$

$$Y_{l-ij} - Y_{l-i}^{max} \leq 0 \tag{11}$$

$$N_{react} - N_{react}^{max} \leq 0 \tag{12}$$

$$\tag{13}$$

### 4.4 Algorithm overview

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# 5 Optimization methods

## 5.1 State of the art: interior point method

## 5.2 NSGA-II: Genetic algorithm

## 5.3 Optimal Power Flow approach for compensation sizing

h

# 6 Case studies

## 6.1 200 MW OWPP

### 6.1.1 50km

### 6.1.2 100km

### 6.1.3 150km

## 6.2 1000 MW OWPP

### 6.2.1 50km

### 6.2.2 100km

### 6.2.3 150km

h

# 7 Conclusions

## 7.1 Outcome

## 7.2 Future work

h

# 8 Planning and viability studies

## 8.1 Time Planning

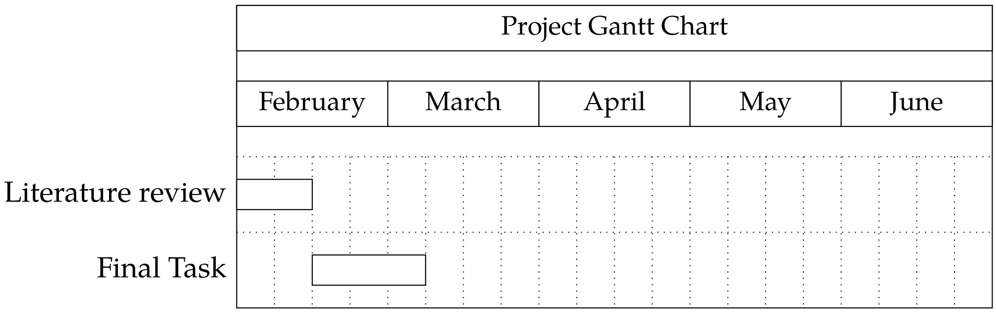


Figure 7: Project Gantt Chart

## 8.2 Economic assessment

## 8.3 Environmental assessment

## 8.4 Social and gender equality assessment

h

## Acknowledgements

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