Bachelor's Thesis

Bachelor's degree in Industrial Technologies and Economic Analysis

Offshore Wind Park Optimization

June 2024

Author: Carles Roca Reverter

Supervisor: Josep Fanals i Batllori

Tutor: Oriol Gomis Bellmunt

Call: Spring 2023-2024

ETSEIB

Escola Tècnica Superior
d'Enginyeria Industrial de Barcelona

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

ETSEIB

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

ETSEIB

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.

Códigos MSC: 90C11, 90C15, 90C29, 90C30, 90C59

Contents

ETSEIB

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

List of Figures

List of Tables

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 26

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.
- Implement a power flow solver with Python.
- Formulate the optimization problem to minimize all types of costs taking into account the technical constraints of the system.
- 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 design and reactive power compensation problem

When designing the transmission system of an OWPP, several factors must be considered to ensure optimal performance and efficiency. The system must be capable of transmitting the generated power from the wind turbines to the onshore grid while trying to be as energy and cost-efficient as possible. There are two main types of technologies that can bu used, HVDC and HVAC. In this thesis we will focus our study to the HVAC technology.

To put in context the relevance of this topic, the work and software developed in this thesis will be used as the breeding-ground of a parternship between eRoots and Acciona, a leading infrastructre company in Spain that has shown interest in developing a tool for the optimal design of OWPP's transmission systems.

One drawback of using HVAC cables is the high shunt capcitance they have, which is even larger in underground cables, which are the ones used for OWPP. The charging current of this capacitance limits the active power tranfer capacity of the line and increases power losses and voltage across the line due to the Ferranti effect[3]. This effect can be described by the votage difference between the sending and reciving end of transmission line under no-load conditions is:

$$\frac{V_o - V_i}{V_o} = \omega^2 CL\frac{l^2}{2} \tag{1}$$

where V_o and V_i are the receiving and sending end voltages respectively, ω is the frequency, C is the capacitance per unit length, L is the inductance per unit length and l is the length of the line. Note that the voltage difference is proportional to the square of the length of the line which leads to overvoltages for long transmission lines.

However, the possbility to include reactive power compensation elements helps reduce the reactive power generation. Figure 2 shows how including this compensation reduces power losses, especially when we approach the no-load condition, which is equavialent to not having any type of active power injection from the OWPP, i.e. the wind speed is very low.

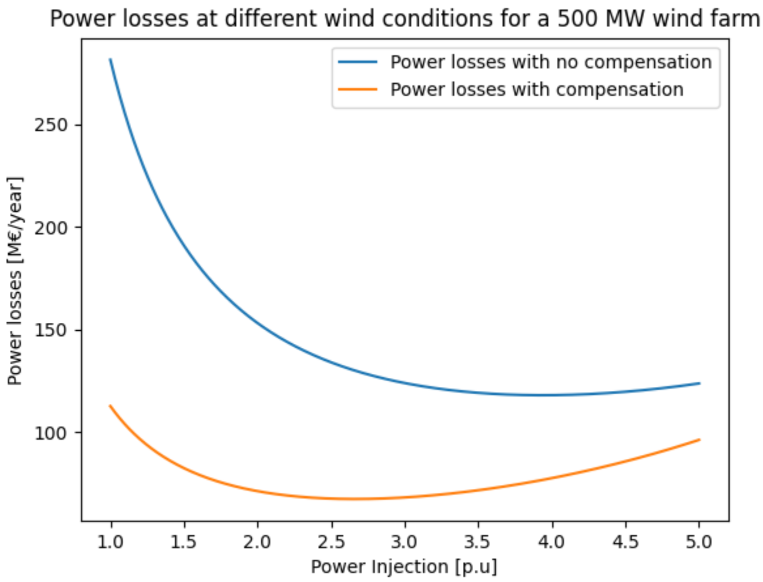

Figure 2: Power losses comparision when including reactive power compensation

The goal of the project is todetermine where this compensation has to be placed and how to size it. But this is only part of the design carachteristics we want to optimize. A full descrption of the optimitization variables will be presented in Chapter 4.

3.3 Grid elements

To be able to do a steady-state analysis of the transmission system we need to model all the elements contained in the model. This section models this elements and presents some important concepts to understand the grid.

3.3.1 Cables

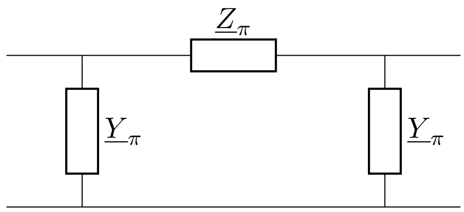

Figure 3: Pi model transmission line

3.3.2 Transformers

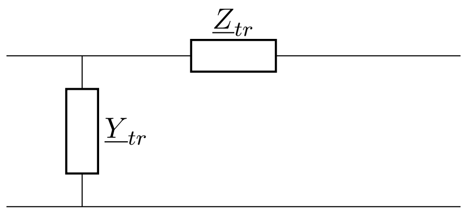

Figure 4: Transformer model

3.3.3 Shunt reactor: reactive power compensation

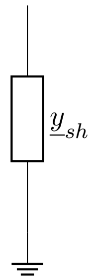

Figure 5: Shunt reactor model

3.3.4 Main grid

It will be the slack bus.

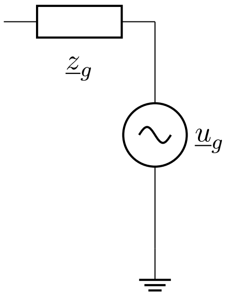

Figure 6: Main grid model

3.3.5 Power plant

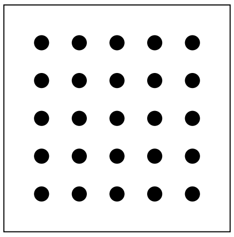

Figure 7: Power plant

3.4 Costs modelling

3.4.1 Cables

3.4.2 Transformers

3.4.3 Shunt reactor

3.4.4 Switchgears

3.4.5 Substation platform

3.5 Full transmission sytem modelling

Types of buses

3.5.1 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.

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

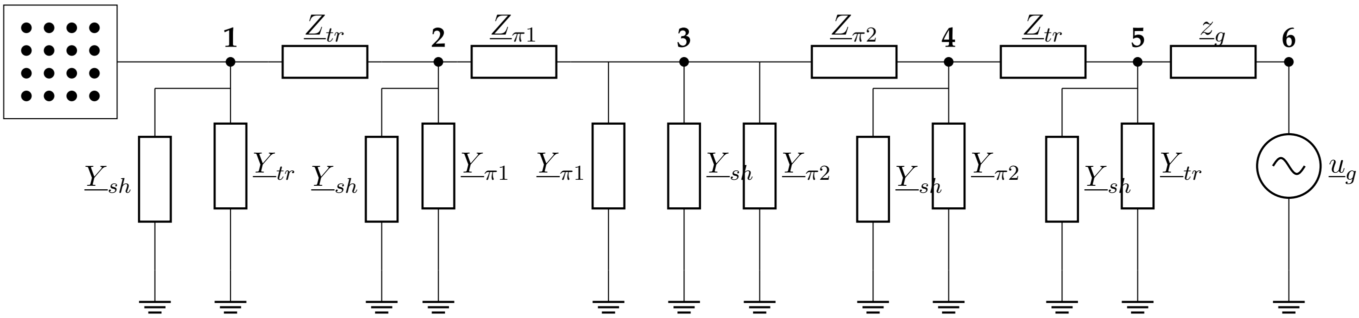

Figure 8: Transmission system model

3.5.2 Power flow equations

4 Optimization problem formulation

Explicar pq separem en multiobjective, ventages respsecvte solució tradicional, etc

$$\mathbf{x} = \Big[vol_{tr}, \quad n_{cables}, \quad react_{bi_1}, \quad ,\ldots \quad ,react_{bi5} \quad ,react_{cont1} \quad ,\ldots \quad ,react_{cont5} \quad ,react_{bi5} \quad ,S_{trafo}\Big] \tag{3}$$

In equation 3 we define the vector of unknowns that we want to find the optimal values for. The vector includes the voltage of the transformer, the number of cables ...

4.1 Objective function: multiobjective and mixed-integer

4.2 Constraints

4.2.1 Equality: Power Flow

Now we define de equality constraints as seen in Eq. 4

$$\mathbf{h_m}(\mathbf{x}) = \mathbf{0} \tag{4}$$

$$\mathbf{S_i} = \mathbf{V_i}(\sum_{\mathbf{j=1}}^{\mathbf{N_{nodes}}} \mathbf{Y_{ij}V_j})^* \tag{5}$$

$$\begin{aligned}
\underline{s}_1 - (p_{owf} + jq_{owf}) = 0, \\
\underline{s}_1 - \underline{u}_1[(2\underline{y}_{tr} + \underline{y}_l)\underline{u}_1 - (\underline{y}_{tr})\underline{u}_2]^* = 0, \\
\underline{s}_2 - \underline{u}_2[-(\underline{y}_{tr})\underline{u}_1 + (2\underline{y}_{\pi 1} + \underline{y}_l + \underline{y}_{tr})\underline{u}_2 - (\underline{y}_{\pi 1})\underline{u}_3]^* = 0, \\
\underline{s}_3 - \underline{u}_3[-(\underline{y}_{\pi 1})\underline{u}_2 + (2\underline{y}_{\pi 1} + 2\underline{y}_{\pi 2} + \underline{y}_l)\underline{u}_3 - (\underline{y}_{\pi 2})\underline{u}_4]^* = 0, \\
\underline{s}_4 - \underline{u}_4[-(\underline{y}_{\pi 2})\underline{u}_3 + (2\underline{y}_{\pi 2} + \underline{y}_l + \underline{y}_{tr})\underline{u}_4 - (\underline{y}_{tr})\underline{u}_5]^* = 0, \\
\underline{s}_5 - \underline{u}_5[-(\underline{y}_{tr})\underline{u}_4 + (2\underline{y}_{tr} + \underline{y}_l + \underline{y}_g)\underline{u}_5]^* = 0
\end{aligned} \tag{6}$$

The power flow solver is described in Algorithm 1.

Algorithm 1 Newton Raphson Solver

procedure RUN_PF
  Initialize V with ones and θ with zeros
  Set $V[slack]$ to 1, $\theta[slack]$ to 0
  Set P, Q based on OWPP data
  Set $iter = 0$, tol and $k = 0$
  while $iter < max\_iter$ and $\Delta PQ > tol$ **do**
    Compute $P\_present$, $Q\_present$ using V, θ, 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 $J \cdot \Delta x_k = -\Delta PQ$.
    Compute the updated $x_{k+1} = x_k + \Delta x_k$.
    Update V, θ using dP, dQ, Y_bus
    if $\max(\Delta PQ) < tol$ **then**
      break
    end if
  end while
  return V, θ
end procedure

4.2.2 Inequality: Technical constraints

$$\mathbf{g_n}(\mathbf{x}) \leq \mathbf{0} \tag{7}$$

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

$$U_{min} - U_{kj} \leq 0 \tag{9}$$

$$I_{kj} - I_{max} \leq 0 \tag{10}$$

$$Q_{min} - Q_{gj} \leq 0 \tag{11}$$

$$Q_{gj} - Q_{max} \leq 0 \tag{12}$$

$$Y_{l-ij} - Y_{l-i}^{max} \leq 0 \tag{13}$$

$$N_{react} - N_{react}^{max} \leq 0 \tag{14}$$

$$\tag{15}$$

4.3 Algorithm overview

H

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

6.1 500 MW OWPP

6.2 1000 MW OWPP

h

7 Conclusions

7.1 Outcome

7.2 Future work

h

8 Planning and viability studies

8.1 Time Planning

Figure 9 shows the time distribution for the tasks carried out in the thesis.

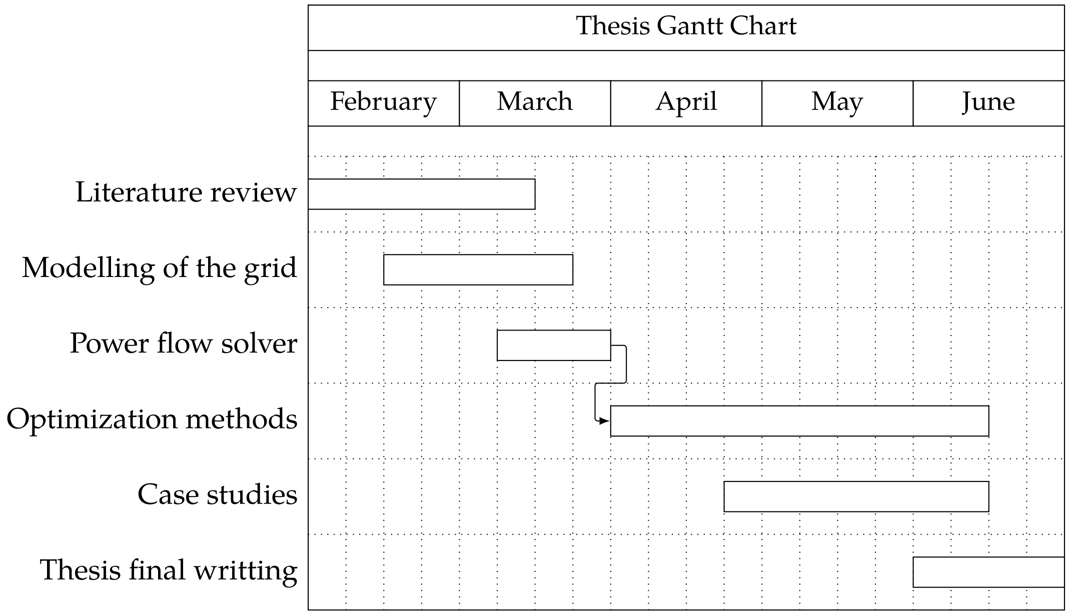

Figure 9: Thesis Gantt Chart

8.2 Economic assessment

Concept	Cost
Computer	\$XXX
Working hours	\$XXX
Tutor supervision	\$XXX

Table 1: Thesis Costs

8.3 Environmental assessment

This environmental assessment evaluates the energy costs incurred during the development of a thesis over five months, using a computer as the primary tool. The primary energy consumption arises from the computer's usage, which includes writing, research, data analysis, and communication.

Assuming an average laptop with a power consumption of 60 watts, used for approximately 6 hours daily, the total energy consumption over five months is around 54 kWh. This consumption translates to roughly 30 kg of CO2 emissions, assuming the average emission factor for electricity generation.

To reduce these energy costs and associated environmental impacts in future thesis projects, several strategies can be employed. Utilizing energy-efficient computers, enabling power-saving modes, and limiting usage time can significantly lower consumption. Additionally, adopting renewable energy sources, such as solar panels for charging devices, further reduces the carbon footprint, contributing to a more sustainable academic practice.

8.4 Social and gender equality assessment

This assessment evaluates the social and gender equality aspects of a bachelor's thesis focused on developing a tool for optimizing renewable energy system design, authored by a 22-year-old white engineering student. While the thesis itself addresses a critical area in sustainable development, examining its social dimensions is essential to ensure inclusivity and equality.

The demographic profile of the author reflects broader trends in STEM fields, where women and minority groups remain underrepresented. This lack of diversity can influence the perspectives and priorities embedded in the research. Ensuring diverse representation in such projects is crucial for incorporating a wide range of insights and addressing the needs of various communities.

To promote social and gender equality, the research should consider the differential impacts of renewable energy systems on diverse populations. Inclusive design processes involve consulting with and incorporating feedback from women, marginalized communities, and other underrepresented groups. This approach ensures that the developed tools and technologies are accessible and beneficial to all segments of society.

Moreover, educational institutions should encourage and support participation from diverse backgrounds in engineering and renewable energy fields. Mentorship programs, scholarships, and targeted recruitment can help bridge the gender and social gap, fostering an environment where innovative solutions for renewable energy are developed through diverse and inclusive contributions.

Acknowledgements

Primer de tot vull agraïr profundament el suport constant del Josep, el meu tutor, que m'ha donat suport, consell i ajuda quan l'he necessitat cada dia des de que vaig entrar a eRoots. Per extensió, agraïr la rebuda i suport de tot l'equip d'eRoots durant aquests mesos, especialment a l'Oriol Gomis que ha proporcionat noves idees i enfocs al desenvolupament de la tesi.

Aquest TFG tanca un capítol de quatre anys de la meva vida que han sigut molt feliços gràcies als meus amics del grau; gràcies a tots nou. Finalment, agraïr a la meva família i a la Mire el seu suport incondicional cada dia i a ensenyar-me a estimar.

Bibliography

[1] *Global Sustainable Development Report (GSDR) 2023*, United nations, 2023. [Online]. Available: Global Sustainable Development Report (GSDR) 2023

[2] J. Dakic, M. Cheah-Mane, O. Gomis-Bellmunt, and E. Prieto-Araujo, *"HVAC Transmission System for Offshore Wind Power Plants Including Mid-cable Reactive Power Compensation: Optimal Design and Comparison to VSC-HVDC transmission"*, *IEEE Trans. Power Del.*, vol. 36, no. 5, pp. 2814–2824, Oct. 2021.

[3] W. Wiechowski and P. B. Eriksen, *"Selected studies on offshore wind farm cable connections - challenges and experience of the Danish TSO"*, *Proc. IEEE Power Energy Soc. General Meet.: Convers. Del. Elect. Energy the 21st Century*, PES, 2008, pp. 1–8.