# Master Thesis

**Double MSc Degree in Industrial Engineering and Energy Engineering**

# Dynamic Simulation and Stability Analysis of Power Systems: Development of RMS and EMT Tools within VeraGrid at eRoots

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# Glossary

## Symbols

| | |
|---|---|
| $\boldsymbol{\theta}$ | Voltage angle vector |
| $\lambda$ | Eigenvalue |
| $\zeta$ | Damping ratio |
| $\boldsymbol{\omega}$ | Angular frequency vector |
| $\boldsymbol{A}$ | State matrix |
| $\boldsymbol{B}$ | Input matrix |
| $\boldsymbol{C}$ | Output matrix |
| $\boldsymbol{D}$ | Feedthrough matrix |
| $\boldsymbol{x}$ | State vector |
| $\boldsymbol{u}$ | Input vector |
| $\boldsymbol{y}$ | Output vector |

| | |
|---|---|
| $n_{m_p}$ | example |
| $n_{\tau}$ | example |

## Acronyms

| | |
|---|---|
| AC | Alternating Current |
| CIG | converter-interfaced generation |
| DAE | Differential Algebraic Equation |
| DC | Direct Current |
| EMT | Electro Magnetic Transient |
| ETSEIB | Escola Tècnica Superior d'Enginyeria Industrial de Barcelona |
| GUI | Guided User Interface |
| IGE | Induction Generator Effect |
| PF | Participation Factor |
| PSCAD | Power Systems Computer Aided Design |
| RMS | Root Mean Square |
| SSCI | Subsynchronous control interaction |
| SSR | Subsynchronous resonance |

## Preface

# 1 Introduction

## 1.1 Objectives

This thesis is part of the ongoing development of the dynamic simulation framework, with a focus on extending its capabilities to include small-signal stability analysis and foundational electromagnetic transient (EMT) modeling. The work is carried out within the Veragrid environment, where new modules and methodologies are being implemented. The main goal is to equip Veragrid with advanced tools for studying the dynamic behavior of power systems, integrating symbolic modeling, numerical routines, and graphical interfaces for analysis and visualization.

### General Objectives

To develop and validate advanced methodologies for dynamic simulation and stability analysis of power systems by incorporating small-signal stability techniques and foundational EMT modeling, fully integrated into the Veragrid environment.

### Specific Objectives

- To develop the small-signal analysis module for RMS models, including the formulation and linearization of differential-algebraic equations at the operating point, the computation of eigenvalues and participation factors from the Jacobian matrix, and its integration into Veragrid's graphical interface.

- To implement the foundational components for EMT simulation, modeling transmission lines and system elements in the abc domain, applying discretization techniques such as the Dommel algorithm and alternatives like the 2S-DIRK method, and validating the EMT solver using benchmark systems compared against commercial tools such as PSCAD.

- To extend symbolic system formulation to support custom models and control schemes, improving numerical routines, and ensuring consistent initialization of dynamic studies.

- To validate the developed methodologies through case studies, continuously comparing results with commercial tools to ensure model reliability and correctness.

## 1.2 Scope

This thesis is part of the ongoing development of Veragrid, a leading software platform for power system planning and simulation. The work focuses on improving dynamic simulation tools for modern grids, particularly in the context of small-signal stability and electromagnetic transient (EMT) modeling. Over a nine-month period—from September 2025 to May 2026—the project aims to build essential components that support symbolic formulation, numerical validation, and integration with existing simulation environments.

The first major area of focus is the implementation of small-signal stability analysis using RMS-based state-space models. This includes the computation of eigenvalues and participation factors, symbolic reduction of system equations, and integration of these routines into the VeraGrid graphical interface. The goal is to provide researchers and engineers with intuitive and accurate tools for identifying dominant modes and assessing system stability under varying conditions.

The second area involves the development of a foundational EMT solver in the abc domain. This includes modeling transmission lines and components, implementing discretization techniques such as the Dommel algorithm and two-stage diagonally implicit Runge-Kutta (2S-DIRK) methods, and benchmarking solver performance against commercial tools like PSCAD. Although the EMT module is not intended to be exhaustive, it serves as a proof of concept for future expansion and integration.

All development is conducted in Python, with an emphasis on code quality, symbolic computation, and reproducibility. The thesis also includes continuous benchmarking and validation using real-world data, including industrial cases. Technical supervision is provided by the eRoots team, ensuring alignment with architectural standards and long-term project goals.

## 1.3 State of the art

sdfsfgsfd

## 1.4 Veragrid

dfdfgassa

## 1.5 Previous requirements

Before starting this thesis, it was necessary to have a solid understanding of power system dynamics, numerical methods for differential equations, and programming in Python.

### 1.5.1 Dynamic framework in Veragrid

dfdg

### 1.5.2 Symbolic formulation

ewstrw

### 1.5.3 DAE

dsffg

# 2 Small-signal stability analysis

## 2.1 Power system stability

Power system stability is defined as that property of a power system that enables it to remain in a state of operating equilibrium under normal conditions and to regain an acceptable state of equilibrium after being subjected to a disturbance [1]. Other definitions state not only the state of equilibrium must be acceptable but also most system variables must be bounded so that practically the entire system remains intact[2].

Although the primary concern is the behavior of the interconnected system as a whole, the stability of individual components such as generators, motor loads, or regional subsystems; can be equally significant, particularly when localized instability does not propagate to the broader network. The system's dynamic behavior is governed by nonlinear interactions among its elements, and its response to perturbations is influenced by both the prevailing operating conditions and the specific nature of the disturbance. Stability is understood around an equilibrium point and is subject to change under small or large disturbances.

Power system stability is commonly classified depending on the pysical nature of the instability, the size of the disturbance considered and the devices, processes and time span that must be considered to assess stability [2]. The combination of these factors influence the methodologies, tools and considerations used in the analysis. The main categories of power system stability are described in the following enumeration.

- *Rotor angle stability*: The ability the ability of the interconnected synchronous machines in a power system to remain in synchronism under normal operating conditions and to regain synchronism after being subjected to a small or large disturbance [1]. A synchronous machine stays in synchronism when the electromagnetic torque exactly balances the mechanical torque from the prime mover, producing zero net accelerating torque. Stability therefore depends on the machine and its controls restoring that torque balance after a disturbance; failure to do so causes rotor acceleration or deceleration and loss of synchronism.

- *Voltage stability*: The capacity of the network to maintain acceptable voltage magnitudes at all buses during normal operation and following disturbances, such that voltages do not decrease sustainedly. Loss of this capacity manifests as progressive voltage drops and, ultimately, voltage collapse, which may force extensive load disconnection or generalised service interruption.

- *Frequency stability*: The capability of the system to preserve a near-nominal frequency following a major imbalance between generation and demand, through inertial response and secondary/tertiary control actions. Inadequate frequency stability results in sustained under-frequency or over-frequency transients that can damage equipment, trigger protective disconnections, and precipitate broader system failure.

Due to the incrising penetration of power electronics into the grid, two new categories of stability have been considered [3].

- *Converter-driven stability*: Refers to oscillatory behaviour caused by control interactions in converter-interfaced generation (CIG). Fast-interaction instabilities arise from high-frequency dynamics (hundreds of Hz to kHz) involving inner control loops and grid components. Slow-interaction instabilities occur at low frequencies (<10 Hz), driven by PLL and outer-loop controls, especially in weak grids. Synchronization issues and power transfer limits further compromise stability. These phenomena differ from classical generator dynamics and require tailored mitigation strategies

- *Ressonance stability*: Refers to the system's ability to withstand oscillatory energy exchange without magnifying voltage, current, or torque beyond safe limits. It includes subsynchronous resonance (SSR), which arises from interactions between series compensation and either mechanical shaft modes or electrical generator characteristics. The mechanical form leads to torsional resonance, while the electrical form—9 (Induction Generator Effect (IGE)) can cause self-excitation. Converter controls in DFIGs can exacerbate these effects, leading to subsynchronous control interaction (SSCI). These phenomena pose risks to both mechanical integrity and electrical equipment.

Rotor angle stability is inherent of classical power systems with synchronous machines. Modern power grids, with the increasing penetration of power electronics, have introduced new dynamics and interactions that can affect rotor angle stability. Converters decrease the inertia of the system and have an effect on the electromechanical modes. However, the fundamental principles of rotor angle stability remain intact and still takes a crucial role on stability analysis of power systems.

Therefore, understanding and analyzing rotor-angle stability remains essential for ensuring the overall reliability of power systems. Insufficient or negative synchronizing torque produces aperiodic, non-oscillatory transient instability that drives large rotor-angle deviations and is typically studied with time-domain numerical integration. In contrast, the absence of adequate damping torque gives rise to small-disturbance oscillatory instability.

In the context of this thesis, the focus is on rotor angle stability, particularly small-signal stability, its eigenvaule-based characterization, modal properties, and analysis methods. The following sections describe the theoretical background and methodologies used for small-signal stability analysis in power systems.

## 2.2 Stability of a dynamic system

A dynamic system is considered stable if, when subjected to a disturbance, it returns to its original state or to a new equilibrium state without exhibiting unbounded behavior. The equilibrium points are those states where all the derivatives $\dot{x}$ are zero, meaning the system is at rest or in a steady state.

Linearity affects on the stability of a system. The stability of a liner system is independent of the input and the initial conditions. However, for a non-linear system, stability depends on the magnitude of the input and initial conditions. Depending on the region of the state-space, stability is classified into the following categories:

- *Local stability*: the system is locally stable around an equilibrium point if when a small perturbation is applied, it remains around the equilibrium point. If as time increases it returns to the equilibrium point, it is locally asymptotically stable[1].
- *Finite stability*: the system is finitely stable if when a perturbation of finite size is applied, it remains bounded and does not diverge to infinity.
- *Global stability*: the system is globally stable if it returns to an equilibrium point for any initial condition in the whole state-space.

Therefore, linearizing a non-linear system around an equilibrium point allows to study its local stability as if it was a linear system.

## 2.3 Small-Signal stability

Small-signal stability refers to the ability of a power system to maintain synchronism when subjected to small disturbances [1], such as minor load changes or small faults. These small disturbances (typically within 1%)occur frequently in power systems and allow the linearization of non-linear system equations around a specific operating point in order to perform analysis. The resulting linear representation enables the use of standard control engineering tools to assess system stability and dynamic performance [4].

The resulting instability due to those small perturbations can have two forms: Non-oscillatory unstability defined as an increase in rotor angle due to insufficient synchronizing torque and oscillatory unstability, oscillations of increasing magnitude due to insufficient damping torque [1]. In practice, most of the instabilities come from insufficient damping torque. The following list summarizes the main oscillatory modes to consider:

- *Local modes*: Oscillations involving individual generators or small groups of units swinging against the rest of the system, typically localized near a generating station.

- *Inter area modes*: Low-frequency oscillations between large groups of generators in different regions, often linked by weak transmission corridors.
- *Control modes*: Oscillations arising from interactions between poorly tuned control systems—such as exciters, speed governors, HVDC converters, or static var compensators.
- *Torsional modes*: Oscillations associated with the mechanical shaft system of turbine-generators, which may become unstable due to interactions with control systems or series-compensated transmission lines.

Although small-signal analysis only applies to small variations around a fixed operating point, it remains a practical and widely used method for studying power system dynamics. By linearizing the system, it allows to apply control theory tools like eigenvalue analysis and state-space modeling. This helps identify poorly damped modes and assess how the system responds to small disturbances. Despite its limitations, it is a reliable approach for early detection of potential instabilities and for designing stabilizing controls.

## 2.4 State-space representation

Small-signal stability assessment methods are generally categorized into two main groups: state-space techniques and frequency-domain techniques. State-space techniques allow one to represent the system using a set of first order differential equations written in the following form:

$$\dot{x} = f(x, u, t) \tag{2.1}$$

Where $x$ is the state column vector that stores the state variables, $u$ is the input column vector that stores external signals that influence the system performance and $t$ is time. The system can also not depend on time, that system is called time-invariant. It is also important to notw that state variables are the minimum amount of variables needed to represent the system and be able to compute its future behaviour.

Often the purpose of the state-space representation is to look at a set of the system variables, called outputs $y$. Then, a new expression is added to the state-space representation:

$$y = g(x, u, t) \tag{2.2}$$

Where $y$ is the output column vector that stores the output variables.

A dynamic system can be described in many different ways depending on which variables are chosen as states, inputs, and outputs. These choices shape how the system behaves mathematically and how easily can it be analyzed. For example, using electrical quantities like voltage and current might be more practical for converter models, while mechanical variables such as rotor angle and speed are better suited for synchronous machines. The flexibility in selecting these variables allows to adapt the model to the specific goals of the study while still ensuring that the essencial dynamics of the system are captured.

State-space models are commonly represented in their matrix formulation as follows:

$$\dot{x} = Ax + Bu \tag{2.3}$$

$$y = Cx + Du \tag{2.4}$$

Where:

- $x$ : state variables vector
- $u$ : system inputs vector
- $y$ : outputs vector
- $A$ : state matrix
- $B$ : input matrix
- $C$ : output matrix
- $D$ : direct transmission matrix

### 2.4.1 Linearization of state-space models

In order to linearize a non-linear state-space model, a small perturbation is applied around the operationg point (equilibrium point).

$$\mathcal{X} \triangleq x - x^* \tag{2.5}$$

$$\mathcal{Y} \triangleq y - y^* \tag{2.6}$$

$$\mathcal{U} \triangleq u - u^* \tag{2.7}$$

Where $x^*$, $y^*$ and $u^*$ are the state, output and input vectors at the equilibrium point respectively. The new linearized state-space model is given by:

$$\dot{\mathcal{X}} = A\mathcal{X} + B\mathcal{U} \tag{2.8}$$

$$\mathcal{Y} = C\mathcal{X} + D\mathcal{U} \tag{2.9}$$

Where the new matrices are computed as the Jacobian matrices of the non linear system evaluated at the equilibrium point:

$$A = \begin{bmatrix} \frac{\partial f_1}{\partial x_1} & \cdots & \frac{\partial f_1}{\partial x_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial f_n}{\partial x_1} & \cdots & \frac{\partial f_n}{\partial x_n} \end{bmatrix} \tag{2.10}$$

$$B = \begin{bmatrix} \frac{\partial f_1}{\partial u_1} & \cdots & \frac{\partial f_1}{\partial u_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial f_n}{\partial u_1} & \cdots & \frac{\partial f_n}{\partial u_n} \end{bmatrix} \tag{2.11}$$

$$C = \begin{bmatrix} \frac{\partial g_1}{\partial x_1} & \cdots & \frac{\partial g_1}{\partial x_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial g_n}{\partial x_1} & \cdots & \frac{\partial g_n}{\partial x_n} \end{bmatrix} \tag{2.12}$$

$$D = \begin{bmatrix} \frac{\partial g_1}{\partial u_1} & \cdots & \frac{\partial g_1}{\partial u_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial g_n}{\partial u_1} & \cdots & \frac{\partial g_n}{\partial u_n} \end{bmatrix} \tag{2.13}$$

For simplicity, the perturbation notation is often omitted, and the linearized state-space model is expressed as:

$$\Delta\dot{x} = A\Delta x + B\Delta u \tag{2.14}$$

$$\Delta y = C\Delta x + D\Delta u \tag{2.15}$$

### 2.4.2 DAE to state-space representation

In power systems, the dynamic behaviour is mathematically represented by a set of Differential-Algebraic Equations (DAEs) that capture the interaction between dynamic components and network constraints. This formulation naturally arises because power systems combine elements with both dynamic and instantaneous responses.

- *Differential equations*: describe the time-dependent evolution of state variables associated with components that possess energy storage or control dynamics. These include synchronous generators (rotor angle and speed dynamics), excitation systems, governors, power electronic converters, and various control loops such as voltage and frequency regulators.

- *Algebraic equations*: represent the instantaneous electrical relationships and constraints imposed by the network. They stem primarily from Kirchhoff's laws, ensuring power balance and voltage-current consistency at each bus, as well as from static components like loads, transmission lines, and transformers, which are assumed to reach steady-state conditions instantaneously.

The explicit formulation of the DAE system is given by:

$$T\dot{x} = f(x, y) \tag{2.16}$$

$$0 = g(x, y) \tag{2.17}$$

Which is linearized around an equilibrium point as follows:

$$T\Delta\dot{x} = \frac{\delta f}{\delta x}\Delta x + \frac{\delta f}{\delta y}\Delta y \tag{2.18}$$

$$0 = \frac{\delta g}{\delta x}\Delta x + \frac{\delta g}{\delta y}\Delta y \tag{2.19}$$

From the second equation, $\Delta y$ can be expressed in terms of $\Delta x$:

$$g_y\Delta y = -g_x\Delta x \rightarrow \Delta y = -g_y^{-1}g_x\Delta x \tag{2.20}$$

And then substituted into the first equation:

$$T\Delta\dot{x} = f_x\Delta x + f_y(-g_y^{-1}g_x\Delta x) \tag{2.21}$$

Rearranging the equation gives the linearized state-space representation and the expression for the state matrix $A$:

$$\Delta\dot{x} = T^{-1}(f_x - f_y g_y^{-1}g_x)\Delta x \rightarrow A = T^{-1}(f_x - f_y g_y^{-1}g_x) \tag{2.22}$$

The A matrix encapsulates the dynamic interactions between the system's state variables, accounting for both the intrinsic dynamics of the components and the constraints imposed by the network. From the state matrix the stability assessment can be performed as explained in the next section.

## 2.5 Stability assessment: Liapunov's first method

The stability of a system can be studied in large-signal and small-signal therms. Stability *in the large* needs to study the whole non-linear system. This method is complex and requires a high computational effort. On the other hand, stability *in the small* studies the system behaviour around an equilibrium point. This method is simpler and less computationally intensive, but it only provides information about the local stability of the system. Computing the eigenvalues of the state matrix $A$ allows to determine the small-signal stability of the system.

Eigenvalue analysis and participation factors (PF) are key tools for identifying dominant modes and evaluating system stability. These methods are well established in conventional power systems and are increasingly being applied to power-electronics-based systems, where dynamic behavior is often more complex and sensitive to operating conditions.

The eigenvalues $\lambda$ of the state matrix A, commonly referred to as the system's modes, characterize its small-signal stability according to the following criteria:

- All modes satisfy $Re(\lambda) < 0$: the system is asymptotically stable
- All modes satisfy $Re(\lambda) \leq 0$ : the system is marginally stable
- At least one mode satisfies $Re(\lambda) > 0$: the system is unstable

When a linearized system has complex conjugate modes, they represent oscillatory modes in the dynamic response:

- The real part determines damping:
  - $Re(\lambda) < 0$: exponential decay
  - $Re(\lambda) = 0$: oscillations persist indefinitely
  - $Re(\lambda) > 0$: exponential growth
- The imaginary part determines the oscillation frequency defined as: $f = \frac{Im(\lambda)}{2\pi}$

An other way to look at the damping of a mode is through the damping ratio $\zeta$. The damping ratio is a dimensionless measure that describes how oscillations in a system decay after a disturbance. It is defined as the ratio of actual damping to critical damping. The critical damping is the minimum amount of damping that prevents oscillations. The damping ratio is given by:

$$\zeta = -\frac{Re(\lambda)}{\sqrt{Re(\lambda)^2 + Im(\lambda)^2}} \tag{2.23}$$

Where $Re(\lambda)$ is the real part of the eigenvalue and $Im(\lambda)$ is the imaginary part of the eigenvalue. The interpretation of the damping ratio is described below.

- $\zeta < 0$: *Unstable oscillations.* The system exhibits modes that grow exponentially with time, caused by eigenvalues located in the right half of the complex plane.
- $\zeta = 0$: *Marginal stability.* The system produces undamped, sustained oscillations since the eigenvalues lie exactly on the imaginary axis.

- $0 < \zeta < 1$: *Stable oscillatory response.* The system returns to its equilibrium point through oscillations that gradually decay over time. In practical terms, a damping ratio of about $\zeta = 0.05$ is generally considered sufficient for well-damped behaviour.

- $\zeta = 1$: *Critical damping.* The system returns to equilibrium without oscillations, reaching the steady state in the shortest possible time without overshoot.

Finally, participation factors quantify the relative influence of each state variable on the different dynamic modes of the system. In essence, they indicate how much a given state contributes to a specific mode and, conversely, how strongly that mode affects the state. This dual interpretation makes participation factors a valuable tool for understanding the internal structure of system dynamics.

In the context of power systems, participation factors play a key role in identifying the physical origin of oscillations and instabilities. By analysing these factors, it is possible to determine which components—such as generators, controllers, or converter units—are most involved in poorly damped or unstable modes. This information supports targeted actions for control tuning, model validation, and stability improvement. Participation factors are calculated as follows:

$$PF_{i,k} = W_{i,k} \cdot V_{i,k} \tag{2.24}$$

Where:

- $PF_{i,k}$ is the participation factor of the $k$-th state variable to the $i$-th mode.

- $W_{i,k}$ is the left eigenvector of the $k$-th state variable to the $i$-th mode of matrix $A$. It satisifies $w^T A = \lambda w^T$.

- $V_{i,k}$ is the right eigenvector of the $k$-th state variable to the $i$-th mode of matrix $A$. It satisifies $Av = \lambda v$.

The graphical representation of the eigenvalues in the complex plane, provides a visual tool for assessing system stability. Then, it is possible to identify the stability of the system and the oscillation of the modes at a glance. An example of an eigenvalue plot is shown in Figure 2.1.

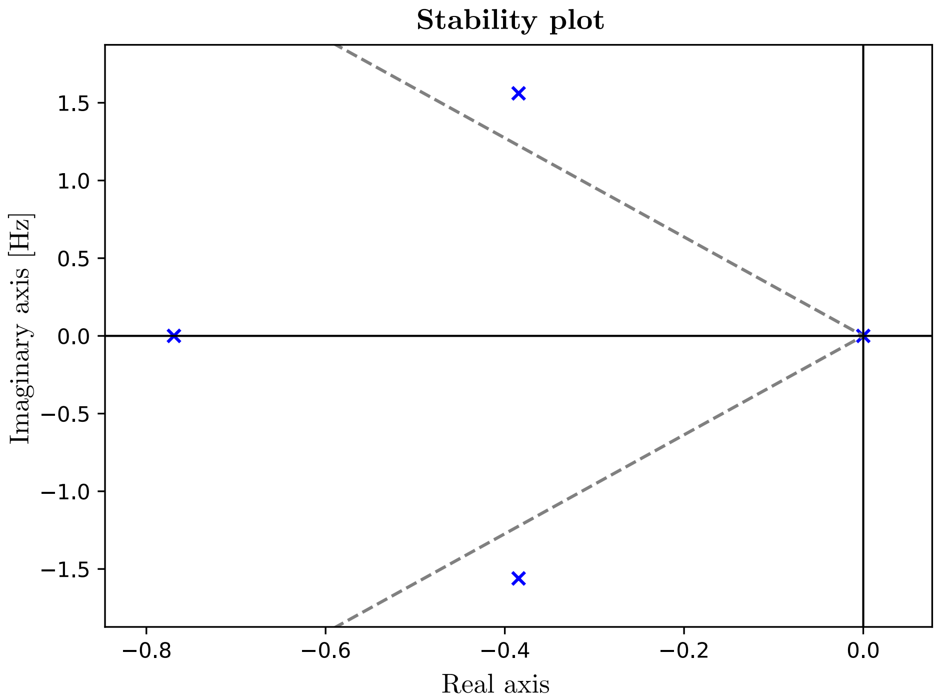


Figure 2.1: Eigenvalue plot example.

The imaginary axis divide the stable part (negative real part) from the unstable part (positive real part). Therefore, all the eigenvalues represented in the Figure are stable except for one which is in the origin, therefore the system is marginally stable. Moreover, modes outside the real axis represent oscillatory modes. In this case, one can see that there are two complex conjugate eigenvalues are represented, which means that the system has an oscillatory mode. the mode in the real axis is a non-oscillatory mode. Since it is the one with the highest real part, it is the dominant mode of the system.

# 3 Environmental, Social, and Gender Impact

The present chapter considers the impact that this project has in the society.

# 4 Budget

The costs associated to the project are those that have to bee counted for the contract with Redeia, which considering it is an open-source implementation, only consider the consultancy workforce of the employees working on the project. In this case, there has been one full-time development engineer and one part-time supervisor (10-hour week). From Figure 5.1 we can see that the project has lasted 32 weeks, although only 26 of them can be considered as working weeks of the project since the documentation work is outside of the contract. The complete costs are detailed in Table 4.1.

Table 4.1: Total Costs.

| **Concept** | **Unit cost (€/h)** | **Quantity (h)** | **Total (€)** |
|---|---|---|---|
| Development engineer | 25.00 | 1,040 | 26,000.00 |
| Supervisor | 30.00 | 260 | 7,800.00 |
| **Total** | | | 33,800.00 |

# 5 Time Planning

Figure 5.1 shows the temporal evolution of the various tasks that have constituted the project.

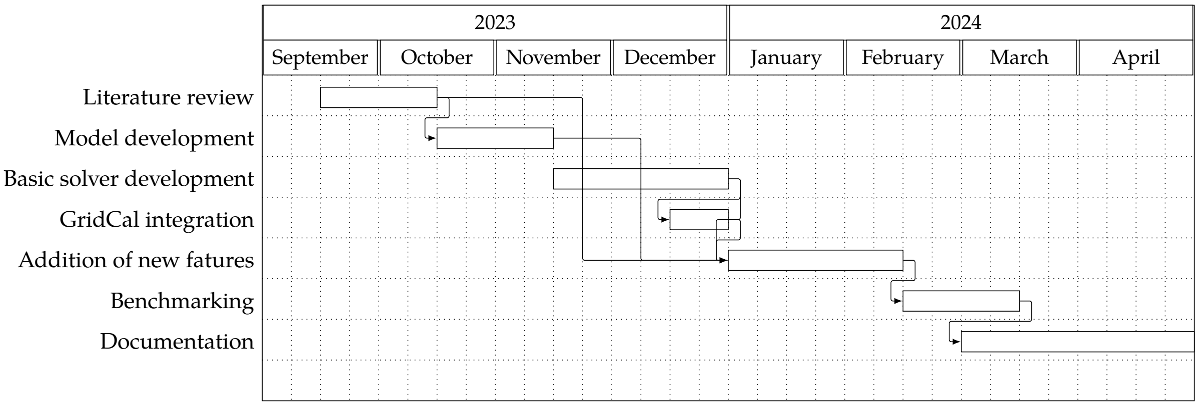


Figure 5.1: Gantt Chart of the project.

# 6 Conclusion

The work developed in this thesis has been focused on the implementation of an AC-OPF solver in GridCal. The results shown in Chapter **??** demonstrate the solver's capabilities and the impact of the features implemented in addition to the preexisting works in the topic.

The standard AC-OPF problem as implemented in Matpower has been successfully replicated, incorporating the option to start from a solution of the power flow with the effect of reducing the necessary iterations to reach convergence in some cases.

The addition of transformer setpoints optimization has also been tested, showing that adding these tap variables in the optimization problem yields a working point that lowers the costs of that found without considering them.

DC links have been added in a simplistic form in the model as a tool to perform quick analysis between islands connected through a DC line.

Reactive power limitations have also been added to the model as a simple relation to also have the possibility to consider such constraints in the optimization problem.

Overall, the implementation of this solver in the GridCal environment can be considered a success. As a tool tailored for Redeia's needs, the whole GridCal package is expected to be used for the future planning of the Spanish electrical grid, which involves the usage of the solver developed in this project, and due to the open-source nature of the package, other TSOs or DSOs could also benefit from it.

## 6.1 Further Work

The solver holds a lot of potential for enhancement, with many possible improvements of the existing features as well as future additions of new functionalities. Some of the future works that are being discussed are the following:

- Related to raw performance, some intermediate calculations for the gradients and Hessians could be optimized to reduce the time needed to solve the problem. This involves using the sparse structures used in the process of creating the Jacobian and Hessian matrices, although it is not a trivial task and requires a deep understanding of the data structure involved.

- The constraints related to reactive power limitations and DC links have been added in a primitive way, since they were considered as secondary implementations which were nice to have, but still lack some information needed to correctly model them.

- For the reactive power constraints, the grid model will have to include the parametrized equation for their generation curves to be able to obtain the analytic derivatives necessary to include in the gradients and Hessians of the optimization problem.

- For the DC links, the model will need a better implementation of the converters that connect the ends of the line, which will require adequate modelling of the control that they follow, the losses of the link and the power flow equations that are used to calculate the power transfer. It is possible that a full AC/DC solver would be needed to correctly model the power flow of the link.

- The addition of relaxations to the problem is also a possibility if there is a need to solve a great amount of cases for planning purposes, as this approach would increase the speed of the solver. It would come at the cost of precision, but for some cases it could be a good trade-off.

- Time-series studies could be considered by introducing new constraints and elements that have to be modelled considering a time variable, such as batteries and its state of charge, flexibility of loads, generation forecasting for renewable energies...

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