Imperial College London

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Department of Electrical and Electronic Engineering

Final Year Project Interim Report

Observability of Modes in Power Systems Through Signal Injection

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Contents

1 Project Specification

The first section in this report outlines this final year project (completed as part of the requirement for the MEng Electrical and Electronic Engineering degree at Imperial College London) in terms of its motivations, main goals, and expected deliverables.

1.1 Description

Inverter-based resources (IBRs) are quickly replacing classical synchronous machines in power grids around the world. As IBRs have been introduced, new unstable modes that can be a big danger to the operation of a power grid have been discovered. Therefore, a need to identify those modes easily and quickly is needed. One proposition is to use signal injection - injecting currents of various magnitudes and frequencies at specific points on the grid to build an impedance model that can then be used to identify those modes. The main advantage of this method is that it does not require a shutdown of the grid, a very crucial feature in a world that is entirely dependent on a steady supply of electricity.

This project aims to quantify the signals needed, develop a method of performing these injections, and describe how they can be used for identifying unstable modes (see section 1.2 for a full list of goals). The project uses SimScape [1] (part of MATLAB) to create models of power systems and IBRs. The models are modified versions of those created in the Control & Power Research Group, heavily relying on the work done by Yue Zhu as part of their PhD [2] (reused in this project under the Creative Commons license CC BY-NC 4.0 `https://creativecommons.org/licenses/by-nc/4.0/`) and Yitong Li, Yunjie Gu, and Yue Zhu on development of the Simplus Grid Tool.

1.2 Aims

The main aim of this project is to test whether modes on a IBR-dominated grid can be detected on a model of a national-scale power system by signal injection at different points. In order to complete that, the following minor aims are identified:

1. become familiar with simulation of a power system including IBRs in SimScape based on the models provided
2. create a model of a signal injection device (SID)
3. develop and add a model of measurement noise
4. plot the impedance spectrum between pairs of nodes and identify modes
5. assess how many injection and measurement nodes are required to observe the principal modes of the entire system
6. quantify the signals to be injected in terms of current and frequency
7. based on the SimScape model, identify the physical characteristics of a SID

The project also has extension aims. These, while not required for the completion of the main aim, should be completed (if time permits) as they are useful addons to the work and would result in a more fleshed-out project. These are:

A. develop a top-level design of a SID that is portable and as compact as possible, including a method of connection to the grid at points of injection and measurement

B. investigate commercial availability of components for such a device

The design for the SID should be as easy to use as possible. Ideally, a grid technician should be able to use it, gathering data at different points that can be then relayed back to the grid operator for analysis. The SID should also be versatile, meaning that it can be used both in the context of an isolated grid (e.g. a single wind farm) and for analysis on a national scale.

1.3 Deliverables

The main deliverable for this project will be the project report, detailing all work done and its results. Since the project is simulation-based, there will be no physical hardware. Other deliverables include:

- signal injection device model and documentation (including methods to analyse and produce results)
- measurement noise model and documentation
- modified power grid simulation files
- top-level diagrams of a physical signal injection device
- (extension) review of commercial products available to build a signal injection device

The SID documentation, at the very least, should be a Simulink model that is extensively documented, code that is able to analyse and visualise the results, and a plan on how it could be implemented on a physical device.

2 Background

This section details the background reading done and summarises key findings. The nature of this project is very theoretical, focusing a lot on background research. This was the main focus of the first stages hence there is little implementation to document other than the models already provided. Aim 1 (understanding the models) proved to be a much more challenging task than anticipated.

2.1 General Motivations

In recent years, many grids around the world have seen a sharp turn away from traditional generating methods to renewables for energy generation in part due to increased pressures to curb the effects of climate change. Wind farms in particular often incorporate variable-speed systems like the one described in [3], especially ones located offshore (one large DC link is built between an offshore substation connected to each turbine and a receiving substation on land) which necessitates the use of inverters at the grid interface.

The basic working principles of controllers in synchronous generators are very well-known as they have existed since the late 1800's, first in mechanical form and now as solid-state devices. Modern devices are very advanced and push the boundaries of current research. Nevertheless, they still rely on components like governors and excitation current controllers for setting the generator's reactive and active power respectively [4]. This was also the starting technology around which today's power grids have been designed, meaning that their interactions have been studied extensively, even as part of accident investigations, and are well understood.

As the penetration of wind and solar energy increases, more and more control systems are installed onto those grids. The controllers in many modern inverter units are far more advanced than those in synchronous machines and their detailed design remains a trade secret for manufacturers. This poses an issue - while their individual behaviour is sufficiently described for designing power plants, the interactions between inverter units are often not easy to predict based on this data. Connecting the units together into a power grid may result in unexpected unstable modes when looking at the grid as a large controlled system. The biggest issue with that is, since these modes are not identified, a power grid may suddenly enter one during normal operating conditions which leads to oscillations. It's not difficult to imagine why an unstable power grid is catastrophic news for a grid operator. With a relatively low penetration of wind and solar, conventional stabilising methods using mechanical generators have been used, however, new methods need to be developed as more and more of these machines are decommissioned.

2.2 Inverter-Based Resources (IBRs)

Inverter-based resources (IBRs) is an umbrella term for any power generation method that connects to the grid via DC-to-AC converters, known as inverters. The most common examples of these are wind, solar, and battery storage. IBRs do not include all renewables as hydroelectric, geothermal, and biomass power stations operate using classical synchronous machines.

IBRs can be divided into two categories: grid following (GFL) and grid forming (GFR). Grid following IBRs track the grid frequency and use it as a basis for power export. Without a grid to synchronise to, these IBRs cannot function. On the other hand, grid forming IBRs export power by holding their voltage phasor constant, even during fault events on the outside grid. This allows them to create virtual mechanical inertia that can be used to decrease the rate of change of frequency (RoCoF) during a fault, effectively mimicing the behaviour of a synchronous generator [5]. A lower RoCoF means the system is easier to control - more time for a response before frequency falls too low or rises too high.

2.3 Unexpected Oscillation Events

Many sources of instability exist in a grid with IBRs. While instability caused by interactions between synchronous generators is well understood and controlled, oscillations caused by IBRs are still not fully explored. Many papers about this topic refer to subsynchronous oscillations (SSO), subsynchronous resonance (SSR) or subsynchronous control interactions (SSCI or SSI) [6]. Broadly speaking, these happen at frequencies below 50 Hz (as their names suggest) and differ in the exact mechanism that is thought to cause them.

Oscillations leading to instability have been observed on grids with significant wind generation capacity and have been the subject of extensive research in recent years. One of the first happened in October 2009 in Texas. An interaction between a doubly-fed asynchronous generator in the wind turbines and the series compensation capacitors on a transmission line (caused by a lot of power being shunted through one link due to an outage) led to unstable oscillations. Within 400 ms, currents and voltages on the line exceeded 300% which led to serious damage of the wind turbines [7].

Since 2014, the grid in China's Xinjiang Province (a region with a high density of wind farms and DC links) observed numerous oscillation events. One severe case led to the tripping of all generators at a power station. Research into these oscillations showed that the mechanism by which they happened could not be explained using previous validated theories [6].

The most significant event for the context of this project occurred on 9th August 2019 when parts of the United Kingdom experienced a blackout. An investigation revealed the major cause - a lightning strike at Hornsea 1 wind farm. The strike caused a fault on a 400kV line which led to a loss of about 150 MW. This disconnection caused unstable behaviour in the control system of Hornsea 1, resulting in the wind farm dropping from supplying 799 MW to just 62 MW in less than a second. The regulator's report [8] states that, combined with an unexpected loss of more generation (1,500 MW in total at one point), the outage led to a blackout in parts of the country.

2.4 Tackling Oscillations

All of the events described in section 2.3 have prompted many studies. Research surrounding the use inverters in power grids is progressing fast with new methods for evaluating grid stability [9], understanding the mechanisms by which these oscillations happen (such as in [10]), and developing control methods to minimise or eliminate the oscillations [11], [12]. Most of these are recent developments and are changing rapidly, but for the context of this project, it is sufficient to simply mention them to justify motivations.

3 Implementation Plan

This section describes the technical background that is specific for the work done in this project. In the final report, it will also include simulation results and explanations of Simulink models created.

3.1 Basic IBR Models

As with most electrical components, there are many ways to represent an IBR. In GFR mode, the IBR tries to keep its voltage phasor constant, acting in a similar way to a lab bench power supply. It can therefore be respresented as a voltage source with some sort of output impedance. In GFL mode, the IBR is injecting some current to the grid, synchronising to its frequency and voltage. It is best represented as a current source with some output admittance in parallel with the source [2], [13].

3.2 Grid Model

The grid used for this project is a modified version of the standard IEEE 14-bus network used for common simulations [14]. Three additional GFL IBRs were added. The overall system diagram can be seen in fig. 1. This is a three-phase system and so more advanced IBR models than those described in section 3.1 were used. This is the model that will be used for testing the SID in the future.

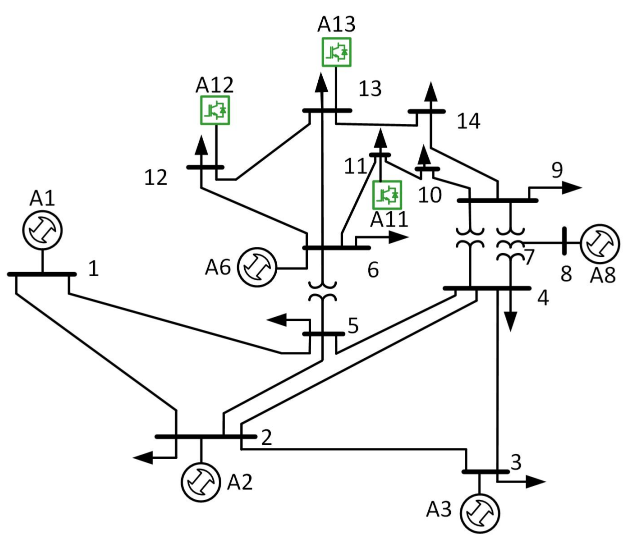
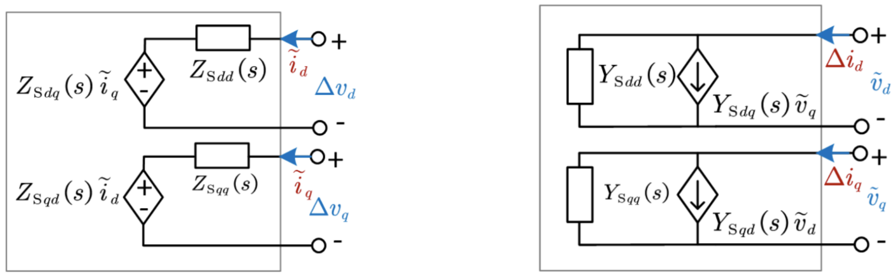


Figure 1: Grid diagram [2]

3.3 Advanced IBR Models

Since the grid model is a three-phase system, the IBR models used are also more advanced than the ones described in section 3.1. The main principles still stand though. To make the model simpler to control, it is transformed from the stationary phasor frame of reference (the a-b-c phase phasors rotate with a set frequency in the complex plane) to the direct-quadrature-zero, or dq0, frame (the axes rotate with the same speed, meaning the phasors remain stationary in relation to the axes) [15]. This simplifies the system from a control point of view, going from time-varying state variables (voltages) even in steady state to fixed phasors in steady state.

In the dq0 frame, the three-phase IBR can be modelled as a two-port-pair block. Figure 2b shows the new model for a GFR IBR and fig. 2a shows the model for a GFL IBR. These are represented as Simulink objects in MATLAB together with relevant controller modelling. The details of the derivation of the models can be found in [2].



(a) GFR IBR model

(b) GFL IBR model

Figure 2: Electrical models for GFR and GFL inverters used in simulation [2]

Models like these can be formed and used for simulation if the exact control methods of the IBRs are known. As mentioned in section 2.1, this is not the case for commercial devices, the inner workings of which are a closely guarded secret. Models provided by manufacturers are often binary files and have been used for simulations, but based on the oscillation events observed, they are often not detailed enough or omit some dynamics [2]. It is also impossible to correct those dynamics based on experimental data without rebuilding the model from scratch.

3.4 Impedance Measurement

The stability of a grid can be analysed by developing an impedance model. This is easily done for theoretical networks or ones where all parameters are well known. In real networks, these have to be developed by direct measurement as not all parameters are known.

Impedance measurement relies on one of the most common equations in electrical engineering - the definition of impedance as the voltage and current ratio. By injecting a known current (voltage), the voltage (current) caused by the injection can be measured. A model of a whole network can be built by connecting to each node and measuring the impedances either side, i.e. of the IBR as seen by the grid and of the grid as seen by the IBR. Using a sufficiently small signal avoids disturbing online equipment and means the derived value is more accurate (an inherent property of small-signal approximations). In real life, the impact of measurement noise can be significant though which is discussed in section 4.2.

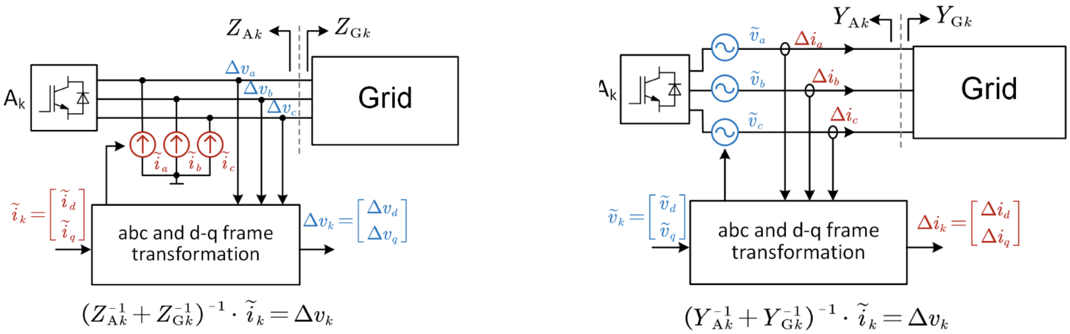
4 Signal Injection Device

This section describes preliminary research into and ideas for a signal injection device, including some of the functions it should fulfil.

4.1 Topology

The signal injection device can have multiple layouts depending on the method of measurement. Figure 3 shows two candidate topologies for a signal injection device (SID).

Both of these topologies have their advantages and disadvantages. The current-source-based SID should require fewer connections to the grid (only 2 on each phase) and these connections are only points that do not need disconnects. Voltage measurement with a known current has the potential to yield a more accurate impedance as it is generally 'simpler'. Current injection can also be limited more easily to maintain a steady value. Using a voltage-source-based SID would have to involve bypassing the connection between the IBR and the grid which could be hard to do while keeping it operational (e.g. connect the SID bypass in parallel to the line connecting the IBR and grid, energise the bypass and deenergise the line, disconnect the line, perform measurement, connect the line, energise the line and deenergise the bypass, disconnect SID). However, current sources are generally harder to build.



(a) SID based on voltage sources

(b) SID based on current sources

Figure 3: Candidate SID topologies [2]

4.2 Measurement Noise

Noise is inherently a random quantity and so is often difficult to model. Analytical methods for dealing with it accept a certain model that best captures the noise at the expense of accuracy. Taking noise as a white Gaussian noise (WGN) works for designing protections against it, as in general, most systems should be able to reject a wide band of noise. In the real world however, noise is often not just WGN, especially for an electrical system. Extra frequencies are added around 50 Hz and its harmonics including others that are harder to predict. This is not unexpected - the grid operates at 50 Hz so instruments close to the IBR that are not connected to the grid can affect measurement.

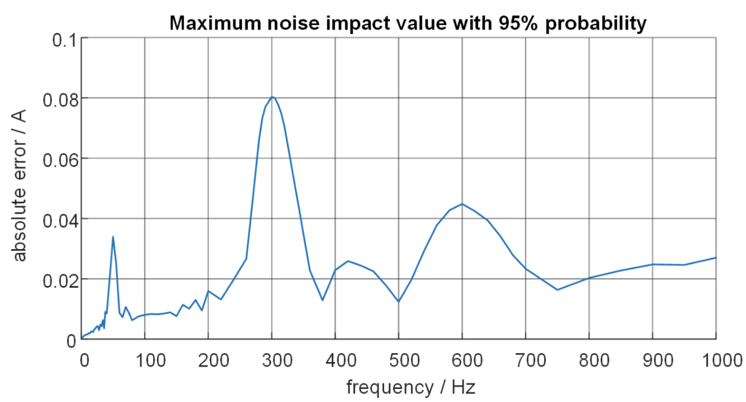


Figure 4: Example of predicted absolute error in current measurement due to noise with 95% confidence [2]

In [2], the author analyses the sources of noise in depth and provides methods to measure it in situ. The result is a curve of absolute error in measurement (the paper uses the fig. 3a topology hence current is the quantity being measured). A physical SID would incorporate measuring this noise first before taking impedance readings. Based on this data, it could calculate the amplitude of current or voltage to be injected given a desired signal-to-noise ratio. It could then make a prediction of the error like the one shown in fig. 4 and correct the impedance measurement depending on how much processing power it has.

5 Project Plan

This section describes project planning and the provisional times allocated for completing work. Section 5.3 summarises this plan using a Gantt chart that shows all tasks and their deadlines.

5.1 Provisional Deadlines

Table 1 shows the soft deadlines by which the key aims or deliverables should be completed. This is of course just an estimate at this stage, but they should be followed for a timely completion of the work. The last deadline for establishing injected signal parameters must be stuck to as that is a key aim for the project's success. These deadlines expect around 3 hours of project work to be done per working day (a minimum of 14 hours a week).

Aim or Deliverable	Due Date
Signal injection device (SID) model	6th March
Measurement noise model	19th March
Impedance spectrum measurement implementation	9th April
Injected signal parameters established	11th June

Table 1: Provisional deadlines for key aims and deliverables

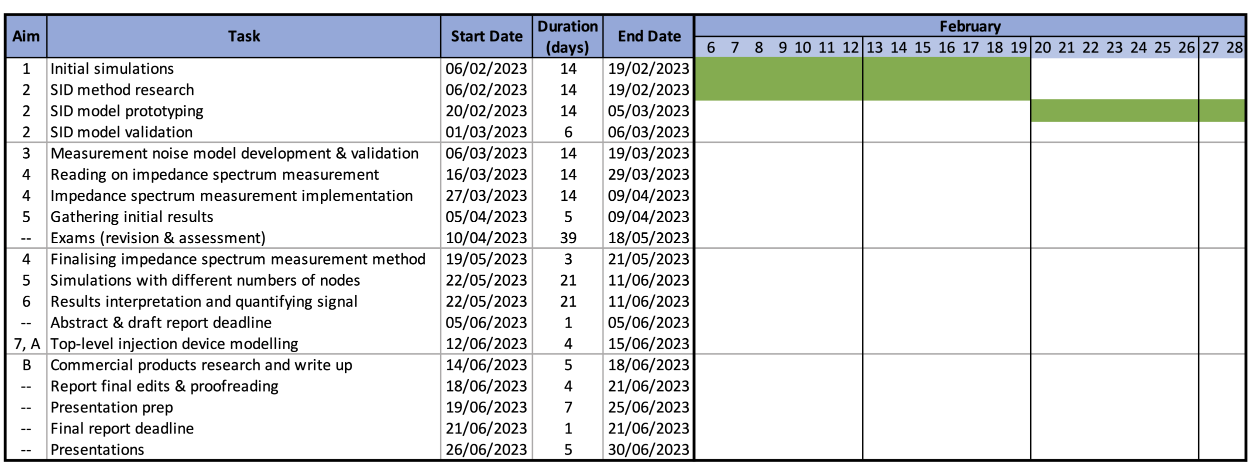
5.2 Fall-backs

In the case that the deadlines outlined in section 5.1 are missed, more time will be allocated which will eat into the extra week of contingency time in June left for extension work (see fig. 8). All deadlines after that will shift accordingly (with the exception of the last one). If the entire week is used up before the start of the exam revision period, project work and exam revision will be balanced to bring the project back on track.

With all that said, the project plan is fairly lenient, which is a design feature. It is highly unlikely that the work outlined will not be completed by the deadlines.

5.3 Gantt Chart

The Gannt chart for this project is quite long. To ease readability, it has been broken down into multiple sections: fig. 5 shows the tasks and times allocated for February, fig. 6 shows March, fig. 7 shows April and May (the red dotted line is a break since the exam revision period is not shown as it is over 5 and a half weeks long), and fig. 8 shows June.



Aim	Task	Start Date	Duration (days)	End Date
1	Initial simulations	06/02/2023	14	19/02/2023
2	SID method research	06/02/2023	14	19/02/2023
2	SID model prototyping	20/02/2023	14	05/03/2023
2	SID model validation	01/03/2023	6	06/03/2023
3	Measurement noise model development & validation	06/03/2023	14	19/03/2023
4	Reading on impedance spectrum measurement	16/03/2023	14	29/03/2023
4	Impedance spectrum measurement implementation	27/03/2023	14	09/04/2023
5	Gathering initial results	05/04/2023	5	09/04/2023
--	Exams (revision & assessment)	10/04/2023	39	18/05/2023
4	Finalising impedance spectrum measurement method	19/05/2023	3	21/05/2023
5	Simulations with different numbers of nodes	22/05/2023	21	11/06/2023
6	Results interpretation and quantifying signal	22/05/2023	21	11/06/2023
--	Abstract & draft report deadline	05/06/2023	1	05/06/2023
7, A	Top-level injection device modelling	12/06/2023	4	15/06/2023
B	Commercial products research and write up	14/06/2023	5	18/06/2023
--	Report final edits & proofreading	18/06/2023	4	21/06/2023
--	Presentation prep	19/06/2023	7	25/06/2023
--	Final report deadline	21/06/2023	1	21/06/2023
--	Presentations	26/06/2023	5	30/06/2023

Figure 5: Gantt chart for February

Aim	Task	Start Date	Duration (days)	End Date
1	Initial simulations	06/02/2023	14	19/02/2023
2	SID method research	06/02/2023	14	19/02/2023
2	SID model prototyping	20/02/2023	14	05/03/2023
2	SID model validation	01/03/2023	6	06/03/2023
3	Measurement noise model development & validation	06/03/2023	14	19/03/2023
4	Reading on impedance spectrum measurement	16/03/2023	14	29/03/2023
4	Impedance spectrum measurement implementation	27/03/2023	14	09/04/2023
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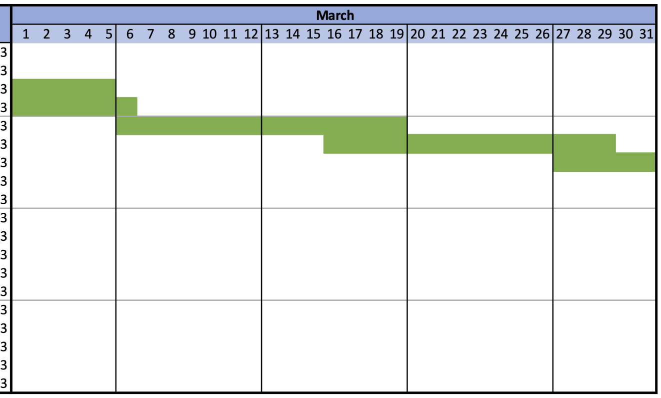

Figure 6: Gantt chart for March

Aim	Task	Start Date	Duration (days)	End Date
1	Initial simulations	06/02/2023	14	19/02/2023
2	SID method research	06/02/2023	14	19/02/2023
2	SID model prototyping	20/02/2023	14	05/03/2023
2	SID model validation	01/03/2023	6	06/03/2023
3	Measurement noise model development & validation	06/03/2023	14	19/03/2023
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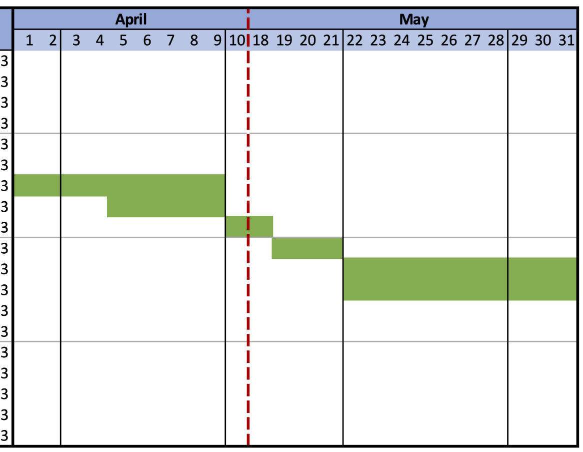

Figure 7: Gantt chart for April and May (red line represents a continuity break)

Aim	Task	Start Date	Duration (days)	End Date
1	Initial simulations	06/02/2023	14	19/02/2023
2	SID method research	06/02/2023	14	19/02/2023
2	SID model prototyping	20/02/2023	14	05/03/2023
2	SID model validation	01/03/2023	6	06/03/2023
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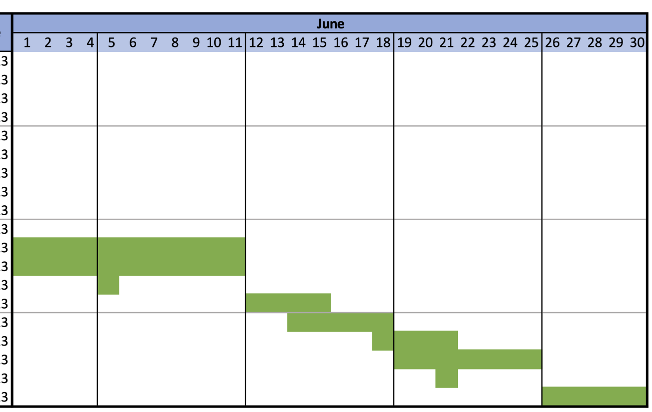

Figure 8: Gantt chart for June

6 Project Evaluation

One way of measuring the success of this project is to look at the quality of the deliverables, mainly the project report and the signal injection device. Even if the SID is not fully completed, a thorough documentation will be done so that it can be developed easily in the future, including calculations and reasoning behind design choices. The degree of success can be broken down as follows based on the SID:

- **high** - The SID is able to identify modes on its own through simply plugging it in at the right points. It can also output raw data for further analysis and can be used by a grid technician in the field with little to no prior training. Most data analysis is done by the SID so little processing is needed.

- **intermediate** - The SID can visualise data and help with analysis, but is too complex to be operated without moderate training. Some post-measurement data analysis has to be done before conclusions are drawn.

- **low** - The SID collects only raw data with no processing. It cannot be operated without in-depth knowledge requiring specialist personnel. Noise model is not automatically developed.

These goals directly relate to the extension aims A and B. Should there be no time left to design a physical system, the success can still be measured by ignoring ease-of-use considerations and focusing only on the simulated behaviour.

Another way of evaluating success is to look at the versatility of the SID. Can it analyse any grid, not just the example used in the project? Provided Simulink models of different grids are available, this should be easy to verify. It can also be judged analytically by more experienced researchers and engineers - if the inner workings of the device can be easily translated into the real world or other simulation software, the design is successful. This would be tedious to verify for sure (building the device exactly as designed in real life or finding new software for grid simulation and translating the model) so for the purposes of evaluating success, the opinion of a few experts in the field of grid stability, power electronics, and power systems and limited testing in the lab (if possible, see section 7) would suffice.

7 Ethical, Legal and Safety Aspects

This project is of a very technical nature so the standard ethical and legal concerns apply. No work is being conducted on a live electrical grid, but the project's results may lead to such work in the future. In this case, it's important to consider that the grid is always online and any work conducted should minimise the impact on consumers (ideally none). A lot of key infrastructure depends on the constant supply of electricity such as communications, healthcare, defense, public order, and food distribution to name a few. Maintaining grid stability while tests are being conducted is therefore both an ethical and legal (grid operators may be fined or penalised by regulatory organisations if tests cause disruptions) requirement. This is however, a significant tangent from the work conducted for the project itself as no work on a real power grid will be conducted. Nevertheless, it is important to note.

The bulk of the project is entirely simulation based, hence there are no physical (electric shocks, mechanical hazards, bio-hazards etc) safety concerns. No surveys on the general public will be conducted. The only safety considerations that apply are those for the person conducting the work - a lot of time spent behind a desk in front of a computer screen. The negative effects of this can be mitigated by following well-established guidance (proper posture, regular breaks etc).

Should there be enough time, a basic SID implementation could be tested in the power lab on level 1 (using a similar setup to the one described in [2]). This would obviously be done under close supervision and with sufficient training due to the relatively high-power equipment present. In this case, electrocution would be a major hazard. In order to do these experiments, the risk assessment for the area and relevant safety procedures must be adhered to. My previous experience working around high power equipment and formal training I received during an industrial placement would be useful for this. This will be discussed in depth with the project supervisor and lab staff if it looks like there is sufficient time. The final report will be supplemented with these considerations.

The last issue to consider is intellectual property (IP). Since this project is authored by one student with help from a supervisor, College policy dictates that the student has full ownership of the IP and retains copyright.

8 Current and Future Work

After conducting a literature review, the immediate next step is to move to building a simulation model of a SID. Getting basic functionality should be fairly straightforward. After that, the difficult part will be refining the SID and adding more features. A bottom-up approach will be taken, first making a device that simply gathers data, then adding analysis functionality to it.

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