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**ELEC5870M**

Interim Progress Report

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| **Accurate Estimation of Inertia for Power Systems with High Penetration of Renewable Energy Sources During Loss of Generation Event** |
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| SID: 201386924 | Project No. 27 |
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**ELEC5870M MEng Individual Project**

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# Abstract

Historically, a network or power system consisted of synchronous generators, converting mechanical energy into electrical energy [1]. This was done by rotating large masses. These rotating masses, as a byproduct of their use, store energy in the form of Inertia. Inertia, “the tendency of an object in motion to remain in motion” [1], could then be tapped to provide stability to a power system. The large rotating masses across a power system provided a soft buffer in the case of a generator (Loss of Generation or LoG event) or other system failure [1][2][3][4]. However, power sources, such as Solar energy harvested by Photovoltaic cells, are decoupled from the Alternating Current (AC) networks [2], and do not provide any Inertia to the system. With the penetration of Renewable Energy Sources (RES) increasing or replacing synchronous sources in power systems, low levels of Inertia make frequency stability and compensation more difficult. [4]

Large power systems’ frequency response to a LoG event can be modelled by the Swing Equation, and a Low-Order System Frequency Response (SFR) model [4][5] if the loss of generation is known. Problems arise with power systems as corrective measures in the case of a LoG event, are dependent on knowing the value of Inertia (and other variables). This is due to Inertia’s impact on the rate of change of frequency (RoCoF), the depth of the frequency nadirs, and the size of the transient frequency dip [6][7]. Estimating Inertia accurately is thus a valuable pursuit. This project aims to investigate and improve the accuracy of Inertia estimations. The findings should improve the accuracy of the corrective measures for minimizing the magnitude of the transient frequency and the depth of the frequency nadir.

# Index of Terms

FFR – Fast Frequency Response

H – Inertia

CoI – Center of Inertia

RoCoF – Rate of Change of Frequency

SFR – System Frequency Response

LoG – Loss of Generation

AC – Alternating Current

RES – Renewable Energy Sources

PFR – Primary Frequency Response

# Introduction

## I: Inertia

Inertia, “the tendency of an object in motion to remain in motion” [1] is a form of energy. It can be calculated for a rotating mass, using angular velocity and mass. This is relevant for power systems due to how synchronous generators produce power. Historically, power generation is achieved by rotating a turbine, using either steam or water. This turbine has a mass and inertia. In the case of a LoG event, the inertial energy of the rotating mass of these turbines can be tapped to slow down the RoCoF of the power system [1]. Inertia, in a power system, resists changes in frequency by temporarily making up for any lost generation of power, providing crucial time for systems to compensate and rebalance the network [1][2][3][4]. Inertia provides a buffer or time to respond.

The effects of Inertia on the RoCoF of a system after a LoG event can be seen in [4]. Changes in Inertia impact the depth of the frequency nadir, the time it takes the system’s frequency to drop to the frequency nadir (the point of greatest frequency change), and the magnitude of the transient frequency dip [1][4][6][7]. Inertia, however, has no impact on the frequency the system settles at, in response to the LoG event. [4][7][8][10]

Calculating inertia is simple, for singular generators. As a function of mass and angular velocity, inertia can be found for simple synchronous power systems by calculating the inertia of each individual generator and finding the sum. Problems arise when the power system expands in size, or generators with variable inertia are introduced. Calculating inertia for the entire power system accurately becomes more difficult.

## II: Impact of RES

As outside forces incentivize the increasing penetration of RES, either to meet new demand or to replace traditional synchronous generators, the ratio of inertia to total power in power systems is decreasing. This steadily decreases the availability of inertia to assist in network frequency stability. As can be seen in [4] and [7], the effect of a decrease in inertia, on the SFR model during a LoG event is an increase in the transient frequency dip, a deeper frequency nadir, and a greater RoCoF. Large changes in frequency across a power system can cause cascading faults. This is because of mechanical problems involving torque when a generator’s turbine spins at frequencies they are not designed for, which can result in damage to the generators, triggering cascading faults, or brown outs [10].

As the frequency nadir represents the largest deviation in frequency in the power system, it is important to appropriately compensate for the effects of low inertia on the depth of the frequency nadir.

## III: The Goals/Motivations of the Project

J. Sanchez Cortes, alongside Dr. S. Azizi, has proposed a novel approach to compensating the transient section of the SFR model, for any LoG event. The paper, [7], suggests using a triangular injection of power, to optimally remove the transient dip, either partially or entirely. This also decreases the depth of the frequency nadir.

The proposed solution depends on the General SFR model, which includes the inertia of a power system in its calculations. Therefore, to properly compensate for the transient dip and reduce the frequency nadir, an accurate representation of inertia for the entire power system is required.

## IV: Project Objectives

* To investigate the effects of the Margin of Error specific to each average variable on the SFR model
* To investigate the Probabilistic Envelope of Frequency Responses output from the SFR model.
* To investigate the frequency responses when attempting to compensate for the transient frequency dip.
* Relate the results to the transfer function in [7], evaluating the effects of the estimation on the suggested power injection.
* Use the swing equation, and a known Delta P, to improve accuracy when estimating Inertia of a system.

# Background Literature

## I: SFR Model

### I.a: Purpose

The SFR model, in specific, the Low-Order System Frequency Response Model, is a model constructed for “estimating the frequency behavior of a large power system …. To sudden load disturbances” [4].

The SFR model attempts to simplify larger, more complex power systems, as a single equivalent generator. To achieve this, a set of assumptions are made. This creates a model that is not entirely accurate, but to quote George Box and Norman Draper in [2]: “All models are wrong, but some are useful.” The first of such assumptions is that nonlinearities can be neglected [4][12].

The second, is that all but largest time constants can also be neglected, leaving the generating unit inertia and reheat time constants as the predominant forces in the system average frequency response [4].

The third assumption is that the singular equivalent generator is suitably large enough, and the power disturbance is small enough compared to it, that it can absorb the power disturbance [4]. This results in a model that represents the average system dynamics, with the intermachine oscillations entirely removed.

### I.b: Variables to Investigate

It is important for the project to have an in-depth understanding of the SFR. Specifically, how it functions and the effects of the variables governing the model. Ignoring Inertia, which will be expanded on individually, the following will define each variable, and where they come from in the scope of a power system. Borrowing from [4], [7] and [12], the 6 governing variables, which can be used to derive all other required variables, are:

* Pstep = A step function representing the power disturbance (per unit)
* H = Inertia constant (seconds)
* FH = Fraction of power generated
* TR = Reheat time constant (seconds)
* D = Damping Factor (pu/Hz)
* Km = Mechanical Power Gain Factor
* R = Governor Droop

**Pstep** is the power disturbance, represented as a step function, and mimics a loss of power

loss through a fault in the network or a generator failure.

**FH** is the fraction of power generated by the singular representative generator.

**TR** is the reheat time constant, measured in seconds, of the prime mover, which is the representative generator.

**D** is the damping factor, which is the rate at which oscillations decay over time

**Km** is the Mechanical Power Gain Factor of the generator and system.

**R** is the governor droop, which is the percent change is speed from no load to full load of a generator [13].

## II: Swing Equation

The swing equation quantifies the relationship between Inertia, damping factor, a Function of Frequency and Delta P. “which is a non-linear second order differential equation that describes the swing of the rotor of synchronous machine” [14]. Different sources have different representations of the swing equation, however they are all similar. For example, figure 1 comes from [14], and clearly uses a different set of variables than figure 2, or 3, from [7] and [15].

A white board with black text

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Figure 1: The Swing Equation



Figure 2: Swing equation per paper [7] by Jesus Cortes et al

A math equations with numbers

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Figure 3: Swing Equation per paper [15] by Colin ADAMSON et al

These are slightly different representations of the same equation, for example, M is the Inertia Constant, and is equivalent to 2H [16]. It can be easily inferred that Pd is equivalent to the damping factor. The existence of multiple conventional swing equations is suggested in [17]. It is also based on several assumptions, making it another inaccurate but useful model, like the SFR model. For this project, the one featured in Figure 2 will be used.

## III: Inertia

Inertia, as explained above, is the tendency for objects to remain in motion. This can be used to provide extra power in the case of a generation loss. It provides a buffer of time, to allow relevant stakeholders to address the problem that has occurred. In the Swing Equation and the SFR model, the value for Inertia used is often an ‘expected’ value for the inertia of the system, not an exact one. This leaves a Margin of Error, which this project will explore. The Margin of Error is predicted to create an envelope of possible frequency responses in the SFR model, which would create a probabilistic representation of the actual frequency response of a system.

## IV: UFLS

Mentioned during an initial meeting, Under Frequency Load Shedding (UFLS) schemes are defined as “emergency mechanisms that are designed to mitigate the risk of power system collapse following multiple Non-Credible Contingency Events.” [18] UFLS is a compromise between linear control and a predefined set of loads to drop in the case of a disparity between demand and supply [19][21]. It acts as a pseudo injection of power to a system, from the perspective of its effect on the frequency response of the system [19][20].

It was quickly realized that in-depth knowledge of UFLS schemes will not be required for this project. It represents an avenue to create the Optimal Power Injection but is not to be explored in detail.

## V: Optimal Frequency Containment

Optimal frequency containment refers to "a mechanism used by transmission system operators (TSO) to keep the electricity grid stable and reliable." [22] In the case of this project, the frequency that will be focused on is the Transient Frequency dip that occurs during a LoG event. This transient frequency, alongside the frequency nadir, represents the worst-case scenario of the frequency response to a LoG event. The length, depth, and area of this region are all important to mitigate as the mechanical damage to generators it causes is accumulative. Damage is sustained only from the depth of the Frequency Nadir.

# Work Done

## I: Background research

As evident above, a portion of the project’s first half was spent doing in-depth research into the aspects of the project mentioned by Dr. Azizi during meetings. This involved making notes during meetings on topics brought up during meetings, finding papers on those concepts or variables, and reading them in addition to any papers acquired from Dr. Azizi. This was deemed important, as the project’s scope and topics were unknown to me. As an Electronics and Computer Engineering student, I did not cover any of these concepts in the Control Systems module the school provides. This was a deficit that was identified as valuable to overcome.

## II: Matlab and Simulink

The first few weeks of the project, while working on other aspects such as modelling, were spent relearning Matlab, as it had not been used since first year, and not to the capacity expected of this project. This was done using Matlab’s excellent onboarding curriculum. Matlab’s coding language and structure were quick to reacquire, thus the majority of those weeks were spent finding and learning relevant libraries and classes/variables that could be useful, such as symbolic functions and the transfer function.

Simulink, a subset of Matlab, was also never used prior to this project. This is due to, again, not taking the Control Systems module, which resulted in needing to go through a similar onboarding process for Simulink. Simulink has been and will continue to be used extensively during this project. It has and will be used for models. As the project progresses, understanding on how to use Simulink will be expanded beyond the foundation acquired during the first semester.

## III: Modelling Papers

Another major portion of this semester’s work was spent modelling papers, provided by Dr. Azizi. Specifically, Papers [4] and [7]. This was done alongside the learning of Simulink, thus paper [4], “A Low-Order Frequency Response Model” was modelled in Simulink. This model was relatively simple, as it is well defined in the paper. The results can be seen in figure 4. The Simulink was later modified to make Pd, which represents Pstep a variable which could be provided by a Matlab Script.

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Figure 4: Simulink Model of a General SFR Model and Frequency Response Generated

For paper [7], “Targeted Fast Frequency Response by Decomposing Frequency into Transient and Steady-State Deviations” by Jesus Cortes et al, was modelled in Matlab using a LiveScript. This focused on working through [7], recreating the functions and equations that Cortes used to create his Optimal Power Injection findings. This was modelled as a LiveScript instead of a Simulink Model being run by Matlab code due to a miscommunication during a meeting, where it was suggested to make the model with symbolic functions, which Simulink does not support. However, it successfully models Jesus Cortes paper. The results, the code, and the commentary were then compiled into a report.

The LiveScript model will act as a foundation for the Simulink model that needs to be constructed to achieve the project’s objectives.

## VI: Extras

It was suggested by the professor to read through his Google Scholar page. Relevant papers from this source were identified and read. Notes taken in One Note to make them available for referencing during any future meetings, and to also broaden the general understanding of the field and the topic.

# Reflection

## I: Progress

In terms of project progress, I am not entirely satisfied with the rate of progress over the past semester. More specifically, the lack of consistent progress. I feel I have made burst of progress, and then stalled, only to have another burst later. This comes down to time management, which I will expand on, but also my understanding of the project. It took until the last week of term time in December, to “get” the aim and purpose of my project.

There were compounding reasons for this, including not having done the Control Systems module, thus having zero grasp of Simulink and a weaker grasp of MatLab, compared to the average EEE student. I was not worried about learning either, due to being a 50% computer science student, but it did slow my progress down.

Another reason for what felt like stages of progress was the slow approach taken in lowering me into the depths of the project. As a worker, I prefer being given a larger set of targets. Reducing the temptation to finish 1 thing and then wait until the next meeting.

I was also originally confused about the project. The paper written by Kush Lohana finally triggered a moment of understanding. This paper was provided in December. This was because of a communication issue between Dr. Azizi and I which resulted in a period where I felt confused by the project’s objectives. I know have a better understanding of what is wanted from me in the second portion of this project.

I am looking forward to making sizable progress in this second semester. I understand what I am pursuing, if not how I am going to achieve those results or what I will discover.

## II: Project Management

As mentioned earlier, I feel like I was making sporadic instead of consistent progress. I did work in sporadic chunks, as I waited for the next meeting. I do feel I achieved the 15 hours of work per week, per the handbook’s recommendation, but as an average across the total number of weeks.

This comes down to not adjusting to university life postindustrial year. Put simply, for the past 13 months prior to September, I have been working consistently, for 40 hours per week, with a very structured separation of “work time” and “my time”. If I was at home, at my computer, it was not time to work, and this became engrained. University works differently, and in essence, for a student, any time of day can, and should, be “university time”. This meant I struggled to initiate work at home. When I did manage, I would work for 8-10 hours straight, to make up for the lost time.

Solutions exist, for example, separating home life and work, by going to university to do work. I considered this, but my laptop is not as powerful, and handles Matlab poorly. Working on university computers is an option I want to investigate. I will continue to persist and find ways to improve that work life balance.

It is also worth mentioning that I was unable to get any work down over the winter break, which is an optimal time to do work (no other coursework). I became bed bound with a high fever (40C) and migraines for the span of 2 weeks and suffered lasting aftereffects. This was due to an influenza A outbreak and was an unexpected barrier during a time when I had intended on working.

My plans for mitigating and improving time management will be further explained in the “Next Steps” section of this report.

# Next Steps

## I: Plans for the Entire Semester

The main portion of the project, which will develop new information and insights, is the estimation of Inertia, using the swing equation, and evaluating the effects of its accuracy on the SFR model and the Optimal Power Injection. This is the focus for the next semester, and will involve a little more research, but mostly working with Simulink and Matlab. This will involve models and then running a Monte Carlo Simulation to record and measure the output, then investigating the resulting Probabilistic Envelope of Frequency Responses. If possible, this will then be applied to the Optimal Power Injection research done by others.

I will also be implementing a solution for the issue with my time management. While I did achieve the total number of hours recommended, I feel it would be more conducive to a good project, if I could stabilize that time spent. Avoiding sporadic bursts, so my meetings with Dr. Azizi moving forward can be more beneficial to my work, with more to share with him per meeting. To solve this problem, I will try reintroducing that separation of my day, as I had while working in industry. It may be less fluid for me, as working on Matlab on a school computer is not always smooth, and my laptop is not as efficient as my desktop computer. However, I believe, overall, the benefits of separating the time in my mind will result in distraction less work, and a higher quality of focus, as well as a much more consistent progress per week.

## II: Next steps in the short term

Besides having a meeting with Dr. Azizi as soon as possible, I want to remake the model of Jesus Cortes’ paper, [7], as a Simulink model which is run by a Matlab LiveScript. This was not done originally because of miscommunication and mistaken understanding. Instead, a LiveScript only model was made. However, I need a model that I can feed a known Step function, the representation of power loss, and some sort of Power Injection, to observe the outputs. This would be easier with a Simulink model, which can be run from a Matlab script with input variables, many times, and then all the outputs compared.

Another SimuLink model will be created to investigate the effect of using nonmatching or arbitrarily chosen values of t, for [7]’s equation. This will then be fed a set of t, and a lookup table constructed of the results. This should expand our understanding of why the optimal injection of power found in [7] looks as it does.

Lastly, a model needs to be constructed to begin investigating the effects of each Margin of Error, compounding and not, for the Averages used for variables in the SFR Model. This will enable looking at the effect on the resulting frequency response of the SFR model, as this is one of the main objectives of the project.

I also feel that a better understanding of the Damping Factor in the Swing Equation will assist me in the rest of this project, so some time will be spent on this very soon.

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