ELEC3875 Individual Engineering Project
Centralised control algorithms for Smart Grid operation
(Interim Report)

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1. Motivation

The motivation for doing this project contains a vision of restructuring and sustainability of energy in the future.

1.1. Problems

A. Energy Crisis

The energy crisis is one of the most essential and critical crises in the 21st century.

Nowadays, non-renewable resource still consists of a large proportion in the energy system. Non-renewable resource, or finite resource, is depleting. Although we might not meet the complete depletion of non-renewable resources in the future 50 years, based on Hotelling's "Economics of Exhaustible Resources", David Ricardo proposed that [1] as the historical production stock accumulates, higher grade ores get depleted and the producer resorts to lower grade ores, sustaining greater extraction costs. It means, the extraction costs will rise, and the price of the products based on ores will rise. Thus, we can assume that the price of most of the non-renewable resources, like oil, coal and gas, will rise since these have similar properties with ores.

B. Climate Change

According to the paper from Nature [2], climate does change in the past 70 years. Climate change has already had effects on the environment around us. Glaciers have shrunk and ice on lakes and rivers is breaking up earlier. Most climate scientists agree that [3] the human expansion causes the current global warming trend. As we know, carbon dioxide (CO_2) is a significant component of the atmosphere. [3] Atmospheric CO_2 concentration has been increased by more than a third since the Industrial Revolution began. But most importantly, atmospheric carbon dioxide has been beyond the highest value of the last 400,000 years.

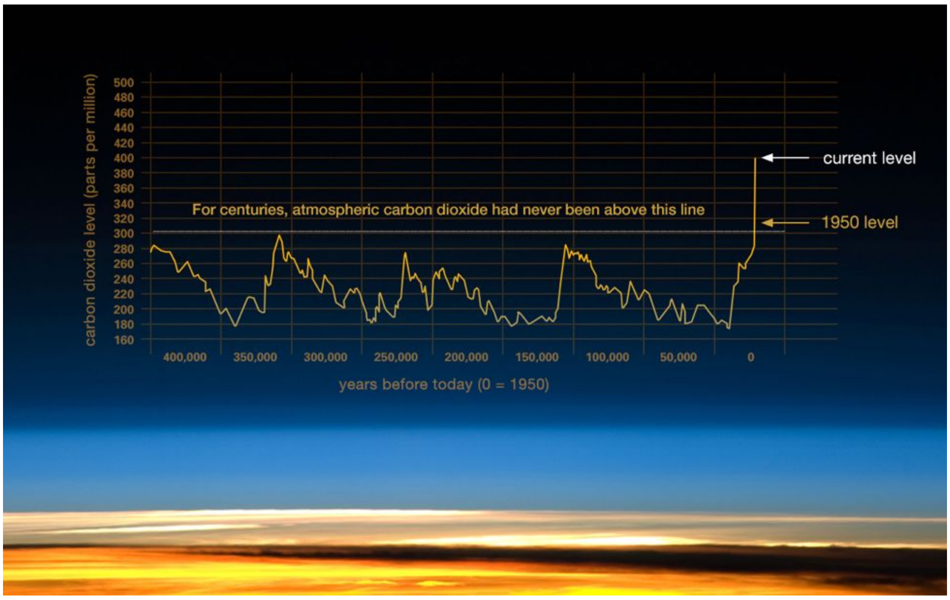


Figure1: This graph provides evidence that atmospheric CO2 has increased since the Industrial Revolution began.

C. Conflicts And Wars

Other than these two main reasons, an unbalanced energy distribution causes conflicts and wars. The wars, like the Gulf War, are more or less derived from energy issues since WW2.

D. Power Interruption

With the use of unreliable electrical grids, power interruption occurs when natural disasters, such as typhoon, earthquake, and wildfire, happen. Smart Grid is more reliable than the traditional electrical grid. It's possible to be built with the dynamic technologies, like secondary frequency control, that grid operators need. Self-healing is possible when the storms hit, or physical attacks occur. Therefore, the consumer will not encounter power interruptions.

E. Equal Rights to Use Natural Power

Besides, everyone should have his/her right to use his/her natural resources equally. However, in most of the countries, the fact is that a few big companies predominate public funds and then a monopoly market is formed. By using their centralised power, entrepreneurs restrict consumers' right to have different opinions.

However, the technologies should start with the customer. It's connected with intelligent devices that always communicate with each other. The system creates and stores energy throughout the day and any extra energy flows back onto the grid to power neighbours and businesses. Those smart energy buildings then power entire communities. It's distributed, clean, and more cost-effective.

1.2. Clean Energy

Using clean energy from renewable resource could be one of the ways to solve these problems! In fact, recently, California Assembly passed a bill requiring 100 percent of the state's electricity to come from carbon-free sources by the end of 2045. The east of China has more and more wind turbines and solar panels. The public is accepting the idea of using electric cars instead of fuel cars.

1.3. New Issues From Electrical Grid

However, these renewable energy sources interfaced with national or state power systems will introduce new issues on stability, resilience, and reliability. Thus, power networks are under modification.

For countries like Switzerland, where 62% of electricity comes from renewable sources, it's another situation. Although it's really friendly to the environment, energy instability has also increased. Sun doesn't always shine, wind doesn't always blow, and water doesn't always flow.

1.4. Solution ---- Secondary Frequency Control

As these highly variable sources come to represent a growing portion of the grid, it becomes more and more important to develop accurate and validated models to represent these units in the computational tools used to analyse the ancillary services of Smart Grids.

Smart Grid will power the modern city, and Secondary Frequency Control is one of the most important tools available in Smart Grids to ensure energy security of the electricity system and allow to increase renewable energy penetration.

Secondary Frequency Control ensures that the frequency of the electricity network is always restored to its nominal value when disturbances occur in the system. The frequency is one of the key "health" indicators of Smart Grids, and actively monitoring and controlling it ensures system security. This is done by remotely controlling the power output of generating units (both conventional and renewables) through a communication network.

2. Theory And Objectives

2.1. Theory

Every country has its nominal frequency of the oscillations of alternating current in an electric power grid transmitted from a power station to the end-user. For instance, the nominal value is 50Hz in the UK [22] while it's 60Hz in USA [23].

However, [4] if a load is suddenly connected or disconnected to the system, or if the protection equipment suddenly disconnects a generating, there will be a distortion in the power balance between that delivered by the turbines and that consumed by the loads.

This imbalance is initially covered from [4] the kinetic energy of rotating rotors of turbines, generators and motors and, as a result, the frequency in the system will change. If there is a mismatch between the generation and the demand, for instance, due to the outage of one generating unit, then the frequency starts to drop down. If no control is applied, the frequency largely deviates and then reaches a meagre and steady-state value, due to which the electrical grid is shut down.

The mechanism of primary frequency control is to restore the active power balance in a power system. After primary control takes place, the power balance is restored at a lower or higher frequency. However, the frequency does not go back to its nominal value and remains at a steady-state value below or above the nominal one.

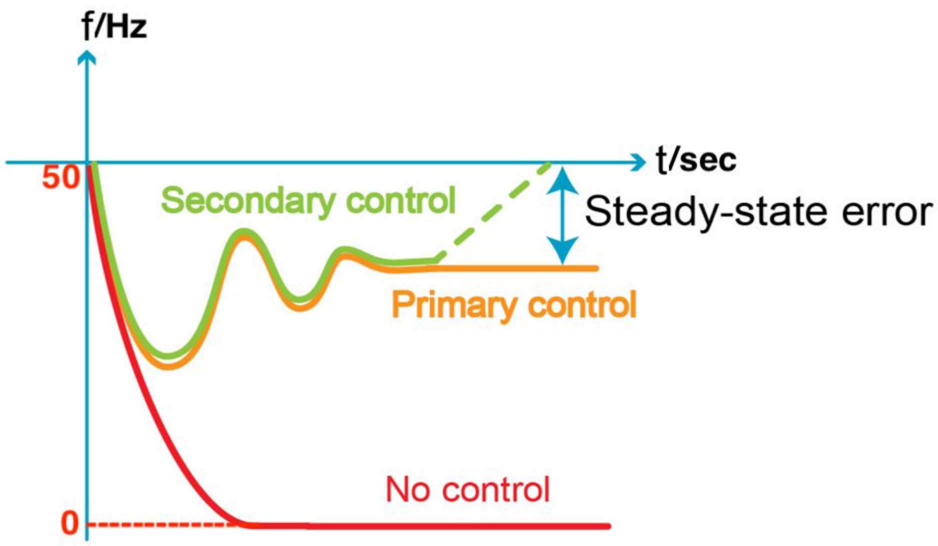


Figure 2: The f-t relationship (in British Standard) when there is no control or there is primary and secondary frequency control after a mismatch between generation and demand due to the outage of one generating unit.

To avoid damages to equipment and loads, we need secondary frequency control to [4] restore the frequency balance to its nominal value or to eliminate the steady-state error/frequency error.

Secondary frequency control, or load frequency control (LFC), or automatic generation control (AGC), is an automatic control that [4] restores the frequency back to its nominal value in a centralised way. It's implemented that is activated after the primary frequency control. Typically, it takes 1 minute to several minutes.

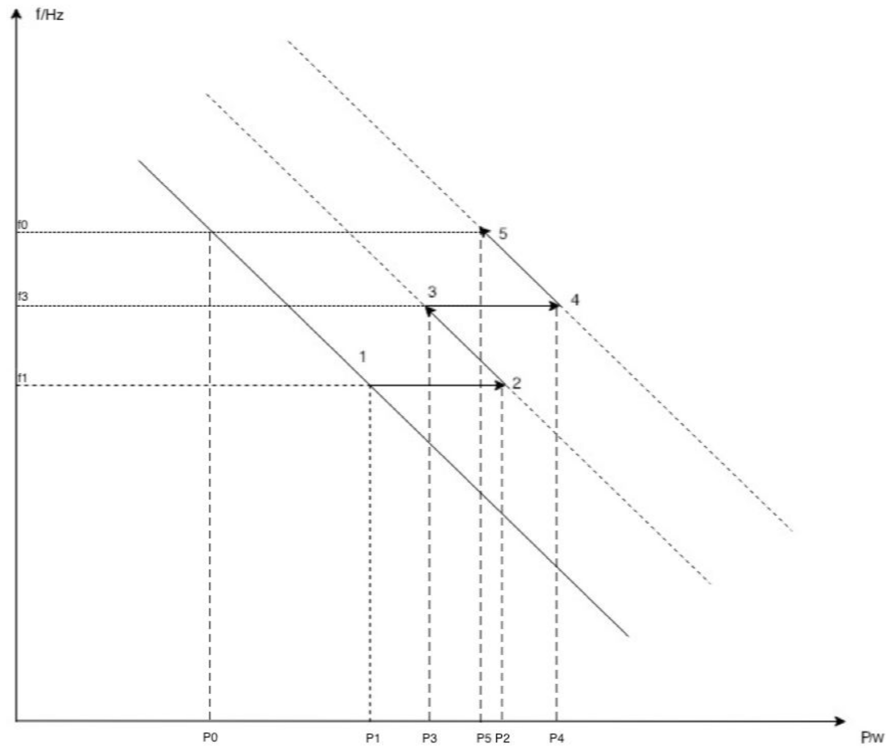


Figure 3: Equilibrium points for an increase in the power demand.

According to Figure 3, frequency value will rise as reference power rises. Assumed that point 1 is the situation after primary frequency control happens and point 5 has the nominal value of frequency. When trying to raise the reference power a little bit, point 1 will shift to point 2. Due to the power rise, the frequency of the system will rise, so point 2 will move to point 3. Changing more reference power of individual governors will move the overall generation characteristic of the system upwards. Eventually, this will lead to the restoration of the rated frequency (f_0).

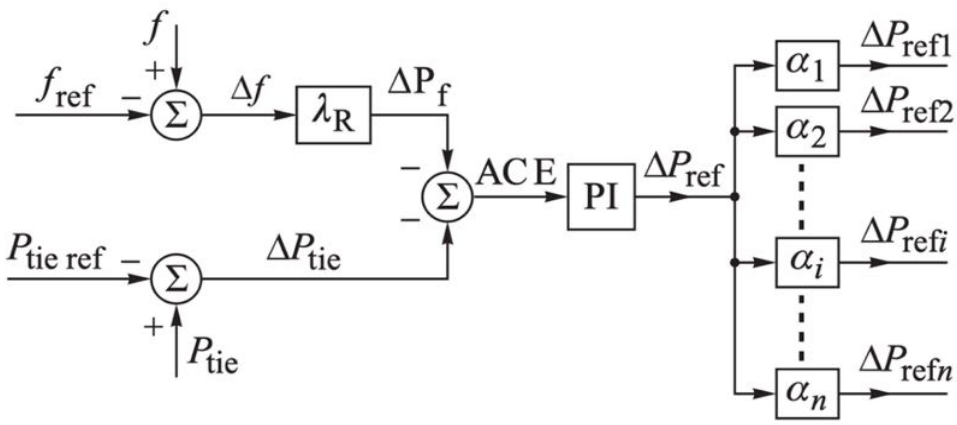


Figure 4: Functional diagram of a central regulator.

As seen in Figure 4, the frequency (f) will be measured in the local network and compared with the reference frequency to produce an amplified signal (ΔP_f) that is proportional to the frequency deviation (Δf). For instance, if the frequency is smaller the reference frequency, then the signal ΔP_f will be negative. Thus, input signal ACE is positive according to the functional diagram. Therefore, output signal ΔP_{ref} is positive and it will adjust the system by raising the reference value of the power. Then the system will have a new frequency value (f_{new}) that will go through the functional diagram again to compare the difference with the value of the reference frequency. ACE won't be zero and the frequency won't be stopped adding until we remove any error.

In this standard case, which ignores the existence of tie-line interchange error, the only condition to remove errors is the frequency deviation (Δf) equals to zero.

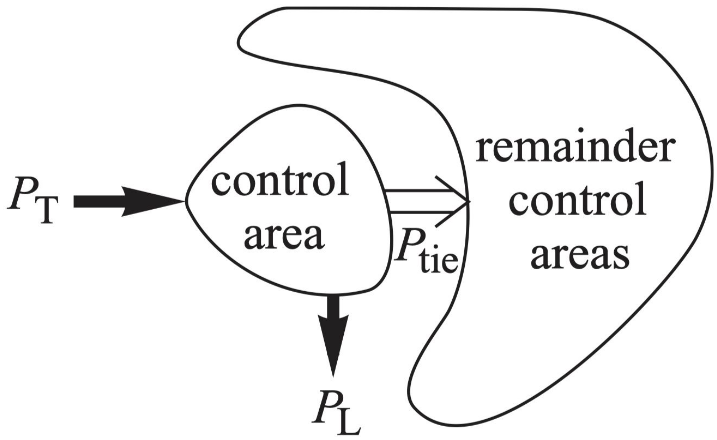


Figure 5: Power balance of a control area.

However, it would be more difficult if consider the situation of tie-line interchange error. In interconnected power systems, AGC is implemented in a way where each subsystem has its own regulator. As shown in Figure 5, the power system is in equilibrium if the total power generation (P_T), the total power demand (P_L) and the net tie-line interchange power (P_{tie}) satisfy the condition in each subsystem:

$$P_T - (P_L + P_{tie}) = 0.$$

[4] The objective of each regulator of the subsystem is to maintain frequency at the nominal level and to maintain net tie-line interchanges from the given area at the scheduled values. If there is a disturbance in one subsystem, then regulators in each subsystem should try to restore the frequency and net tie-line interchanges. Each subsystem regulator should enforce an increased generation covering its own area power imbalance and maintain planned net tie-line interchanges.

As shown in Figure 4, to obtain a signal proportional to the tie-line interchange error (ΔP_{tie}), [4] the information on power flows in the tie-lines is sent via telecommunication lines to the central regulator which compares it with the reference value. Then the signal (ΔP_f) is added to the net tie-line interchange error (ΔP_{tie}) so that ACE is:

$$ACE = -\Delta P_f - \Delta P_{tie}.$$

The situation here is similar to the situation above, where we ignore tie-line interchange error, except for the condition to remove errors. In this book [4], it shows us zeroing of errors can be achieved in two ways: zeroing of both errors (P_{tie} = 0 and f = 0) and achieving a compromise between the errors ($\Delta P_f + P_{tie} = 0$ or $P_f = -\Delta P_{tie}$).

2.2. Objectives

The objective of my project is to design a centralised and communication-based secondary frequency control, to implement it in Python using RAMSES, and to analyse its performance against two variants.

3. Literature Review

3.1. Integral control

The standard Secondary Frequency Control only uses integral control. [6] used the standard integral control, where the integrator is 1/s, and they proposed that Integral Controller is required to stabilize the frequency by properly selecting control parameters of the dual mode controller. Large integral gains can degrade system performance or result in larger system oscillations or even instability.

3.2. PID And Its Variants

3.2.2. PID Control

The difficulty in using PID control in load frequency control is that the power system model is high-order under-damped, and most of the existing PID tuning methods focus on the overdamping process. [8] implemented an area load frequency control using fuzzy PI gain. It can guarantee zero steady state time error and inadvertent interchange. [9] introduced another PID controller that is a resistant differential control against load disturbance. This control method can eliminate the effect of this kind of disturbance and decrease the power transfer between control areas.

3.2.1. PI Control

[4] used proportional–Integral control, whose functional diagram can be seen as Figure 4. The output signal is:

$$\Delta P_{ref} = \beta_R (ACE) + \frac{1}{T_R}\int_0^t (ACE)dt$$

where β_R and T_R are the regulator parameters. However, it cannot always remove both errors Δf and ΔP_{tie}. In this case, zeroing ACE can be achieved in two ways: zeroing both errors or achieving a compromise between the errors $\Delta P_f + P_{tie} = 0$ or $P_f = -\Delta P_{tie}$.

Pan and Liaw [7] used a PI (proportional-integral) adaptation to implement an adaptive controller to satisfy one kind of stability condition (hyperstability) for processing the changes of parameter in the power system. They confirmed that It has good control performance and is sensitive to the changes of parameter. Furthermore, the control is still effective in the condition where the generation rate constraints.

3.3. Artificial Neural Network

[5] introduced that "Artificial Neural Network (ANN) is a black box which connects the non-linear relationship between input and output without information of system structure". Because of non-linearities in the system components and alternators, it's difficult for controllers to control the frequency efficiently and quickly. [10] found the GNN controller is suitable for controlling the plant dynamics in a short time. Each neural network controller receives only local frequency. This kind of architecture decentralises the control of the system and reduces the amount of exchanged information between different modes of the power grid.

3.4. Genetic Algorithms

Genetic algorithms are an optimisation technique used to solve nonlinear or non-differentiable optimisation problems [5] based on the operation of natural genetics and Darwinian survival-of-the-fittest with randomly structured information exchange. [24] proposed a simple controller where genetic algorithms (GAs) optimize the PI controller parameters. The author of [24] said it had achieved a good robust performance. [13] proposed an intelligent control scheme using the robust search feature of GAs incorporating the basic idea of self-tuning regulators, where the selection mechanism of GAs employs the square of the difference between the actual and the estimated outputs as the fitness function. It was proved that it can provide good system characteristics.

3.5. Particle Swarm Optimisation (PSO) Algorithms

[14] Fixed gain controllers for automatic generation control are designed at nominal operating conditions and fail to provide the best control performance over a wide range of operating conditions. [5] Particle swarm optimisation is a population-based stochastic optimisation technique, inspired by social behaviour of bird flocking or fish schooling, to improve the performance of the controller by easing the design effort. [14] proposed a control scheme, which to optimise and update control gains in real-time according to load variations,

based on artificial neuro-fuzzy inference system (ANFIS). It has the same performance with NERC (North American Reliability Council) control performance standard.

3.6. Optimal Control

Optimal control theory deals with the problem of finding a control law for a given system such that a certain optimality criterion is achieved. It is an extension of the calculus of variations and is a mathematical optimisation method for deriving control policies. Optimal control can be seen as a control strategy in control theory. [15] used a state variable model and regulator problem of optimal control theory to develop new feedback control law for two-area interconnected non-reheat type thermal power system. [16] proposed that an algorithm for AGC of inter-connected power systems using the theory of variable-structure systems and linear optimal control theory. A systematic procedure for the selection of the switching hyperplane, which is of vital importance in the design of variable-structure controllers, is developed by minimising a performance index in the sliding mode operation. Its simulation results show that it has good performance.

3.7. Sub-optimal Control

In a complex and large system, the use of precise optimal control can result in excessive computational complexity or even impossible implementation due to the complexity of large systems, such as high dimensionality, nonlinearity, hierarchical, decentralised structure, and time lag. Therefore, simplified methods are needed, which cause the degradation of performance. In [17], [18], [19], they proposed an AGC controller based on sub-optimal control.

4. Future Work

4.1. Important Past Work

I have done lots work during the first semester, including setting up the software environment like academic simulation software RAMSES [20], [21] understanding the theory behind Secondary Frequency Control, and knowing the goal of my project.

Especially, I have simulated the situation of Primary Frequency Control in Nordic System, based on which I will design my own secondary frequency control system of Great Britain in the following semester.

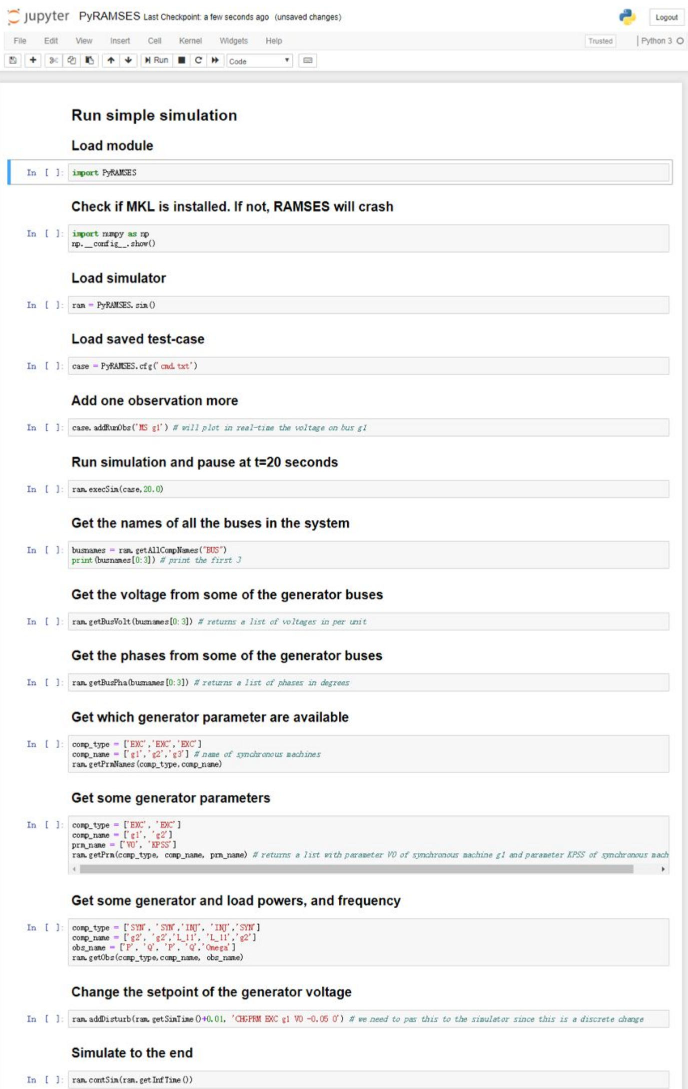


Figure 6: Nordic Test System source code in Jupyter.

Add one observation more

```
In [5]: case.addRunObs('MS g1') # will plot in real-time the voltage on bus g1
```

Run simulation and pause at t=20 seconds

```
In [6]: ram.execSim(case, 20.0)
Out[6]: 0
```

Figure 7: Run the simulation of Nordic System (0~20 seconds).

As shown in Figure 7, I used Jupyter Notebook to run the source code of Primary Frequency Control in Nordic System.

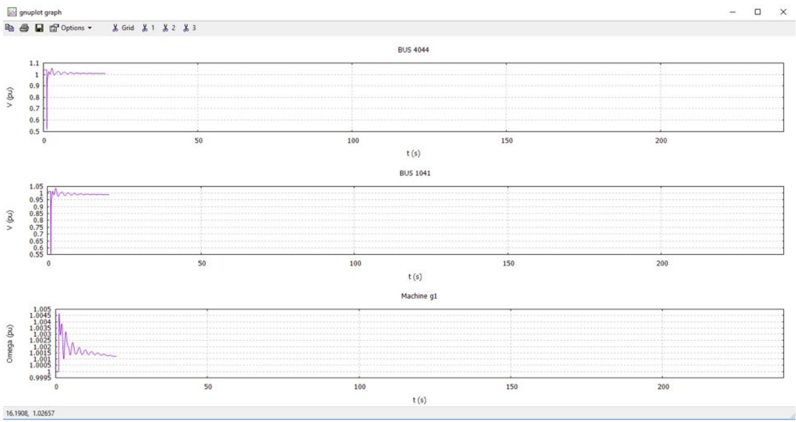
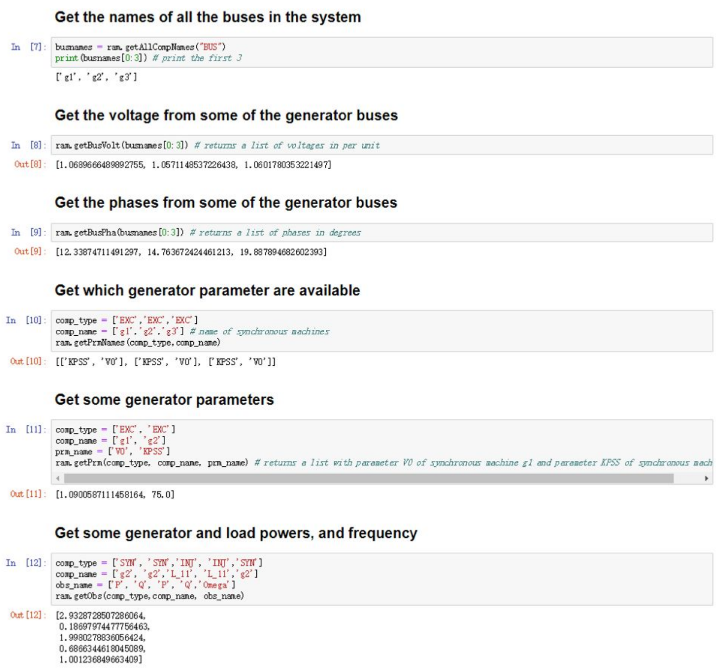


Figure 8: The simulation result of the Nordic System in Gnuplot (0~20 seconds).



Get the names of all the buses in the system

```
In [7]: busnames = ram.getAllCompNames("BUS")
        print(busnames[0:3]) # print the first 3
        ['g1', 'g2', 'g3']
```

Get the voltage from some of the generator buses

```
In [8]: ram.getBusVolt(busnames[0:3]) # returns a list of voltages in per unit
Out[8]: [1.0689666489892755, 1.0571148537226438, 1.0601780353221497]
```

Get the phases from some of the generator buses

```
In [9]: ram.getBusPha(busnames[0:3]) # returns a list of phases in degrees
Out[9]: [12.33874711491297, 14.763672424461213, 19.887894682602393]
```

Get which generator parameter are available

```
In [10]: comp_type = ['EXC','EXC','EXC']
         comp_name = ['g1','g2','g3'] # name of synchronous machines
         ram.getPrmNames(comp_type,comp_name)
Out[10]: [['KPSS', 'V0'], ['KPSS', 'V0'], ['KPSS', 'V0']]
```

Get some generator parameters

```
In [11]: comp_type = ['EXC', 'EXC']
         comp_name = ['g1', 'g2']
         prm_name = ['V0', 'KPSS']
         ram.getPrm(comp_type, comp_name, prm_name) # returns a list with parameter V0 of synchronous machine g1 and parameter KPSS of synchronous mach
Out[11]: [1.0900587111458164, 75.0]
```

Get some generator and load powers, and frequency

```
In [12]: comp_type = ['SYN', 'SYN','INJ', 'INJ','SYN']
         comp_name = ['g2', 'g2','L_11', 'L_11','g2']
         obs_name = ['P', 'Q', 'P', 'Q','Omega']
         ram.getObs(comp_type,comp_name, obs_name)
Out[12]: [2.9328728507286064,
          0.18697974477756463,
          1.9980278836056424,
          0.6866344618045089,
          1.001236849663409]
```

Figure 9: Get parameters of Nordic System.

The function of the code above includes run the simulation in a specific time (Figure 7), activate Gnuplot to show simulation's result (Figure 8), and get parameters (Figure 9).

4.2. Semester Two's Plan

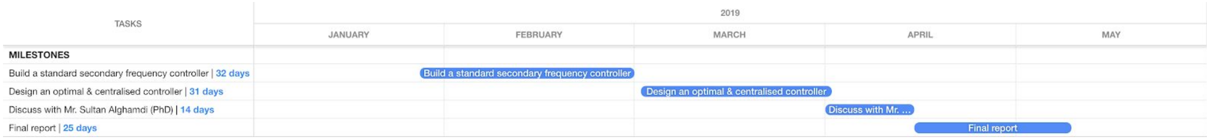


Chart 1: Gantt Chart of next semester's plan on Individual Engineering Project.

As shown in Chart 1, in the first month (Jan 28 - Feb 28, 2019) of Semester two, I will build a standard secondary frequency controller that will be written with Python at Jupyter Notebook. I will find a supporting package, like pypl, to help me to design my standard controller that will be an integral controller at first. Then, I believe, there will be problems, like large integral gains, coming out according to my feedback of literary readings. I will collect and analyse these problems for my next design.

Then, in March, I will design and build an optimal and centralised controller for congestion/voltage alleviation.

In April, I will discuss with Doctor candidate Mr. Sultan Alghamdi on other complex questions, such as multi-area models, centralised and decentralised models, and multi-level models.

Finally, I will write my final report and submit it on May 9.

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