**Midterm Report** (Undergraduate Creative Independent Study in Electrical & Electronic Engineering)

Name: Dela Rosa, Joshua Gabriel (조슈아)
Student ID: 2019142208

Major: Electrical and Electronic Engineering
Date: 2023/10/13

Advisory Professor: Hur, Kyeon (허견) _______(signature)
Advisory graduate student: Lee, Insung (이인성)_______(signature)

## Classification of the Undergraduate Creative Independent Study

| | |
|---|---|
| H/W Implementation | ☐ |
| S/W Implementation | ☐ |
| Theory and Survey | ■ |

.

# Harmonizing Grid Frequency Stability: Investigating the Optimal Mix of Grid-Forming and Grid-Following Inverters in High Penetration Grids

## Current Progress

The student had been studying the theory and working mechanisms behind voltage-controlled converters (VSC) that are used to interface renewable sources such as wind power plants and photovoltaics based on the book [1]. During the summer break, simulations and implementation of control diagrams for these systems using PSCAD are conducted to help better understand the inner workings of these converters.

VSCs study included the basics of the half-bridge converter, different control frames (*abc*-, *αβ*-, *dq-frames),* differentiating the difference between the controller designs for each of the frames, differentiating grid-imposed frequency VSC and controlled-frequency VSC control. The study included weekly meetings with the TAs where the student is reporting about the theory and work done during that week. The report always includes theoretical discussions and simulation of the theory involved using PSCAD or extending the example problems on the book to a different required parameter etc.

The VSC study focused heavily on the grid following (GFL) and grid forming (GFM) basics theory and control. Figure 1 below shows the basic grid-imposed frequency VSC in *dq-frame*. This in itself the is main building block for GFLs. The controller design also considers possible changes in power delivered by the renewable source hence a DC-voltage compensation technique is also employed. Figure 2 shows the GFM control model in *dq-frame* which is the main building block for GFMs. All of the problems encountered in GFL studies were also considered in the GFM studies. However, simulations were only conducted on the GFL inverters as the student will be using a pre-existing model for GFMs. For brevity, this report will only include the major simulations and studies regarding theory and would not include simulations on how to use PSCAD.

.

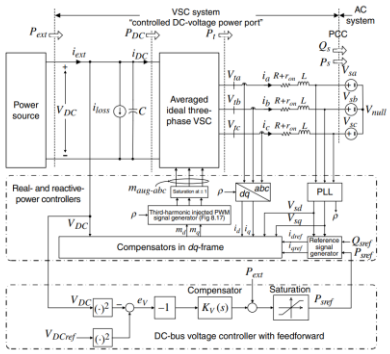


Figure 1: Basic GFL Control Diagram

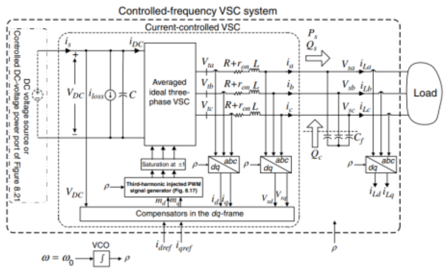


Figure 2: Basic GFM Control Diagram

The GFL controller is composed of a phase-locked-loop (PLL) to synchronize itself with the grid. The PLL controller designed on PSCAD is shown below in figure 3 following the design on [1]. The simulation is conducted with changing the voltage on the line as a disturbance and verifying that the frequency returns back to its nominal value. The results are shown in figure 4, wherein at 0.25s a fault arises but the frequency remains at its nominal value of 60Hz.

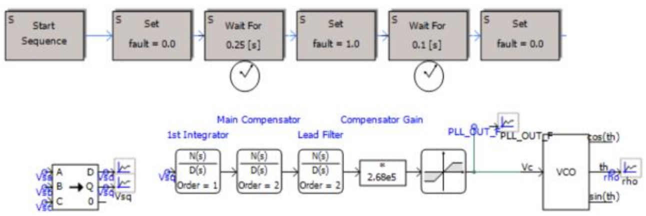


Figure 3: Basic PLL Control Diagram

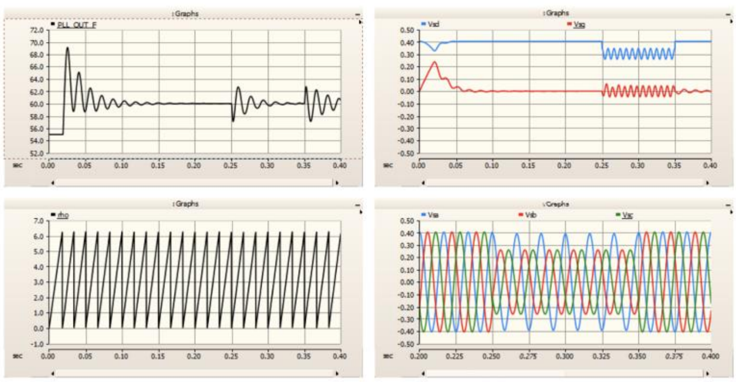

Figure 4: Results of PLL Simulation

.

Figure 5 below shows the GFL controller designed on PSCAD. The controller is tested to verify that GFLs can follow the input command given to it and follow the grid voltage as it injects power to the grid. The results in figure 6 and figure 7 show that the GFL does indeed inject the input power as commanded.

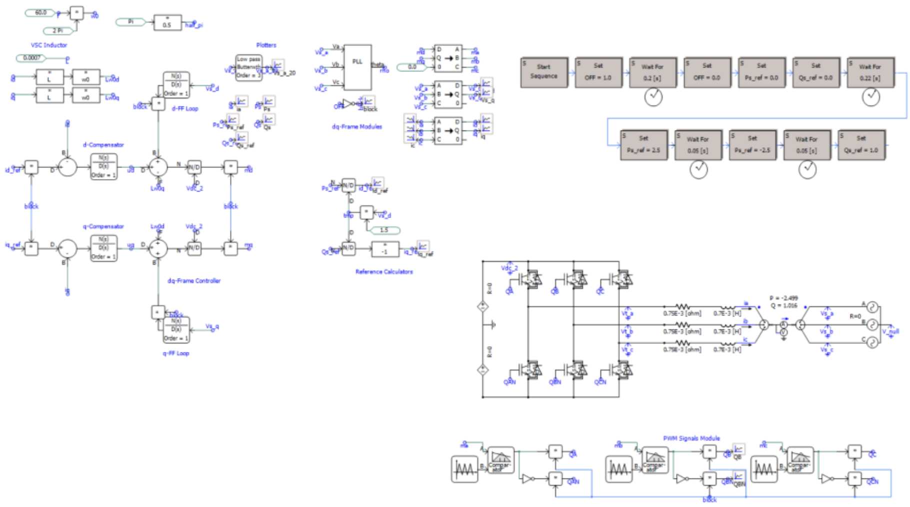

Figure 5: GFL Controller

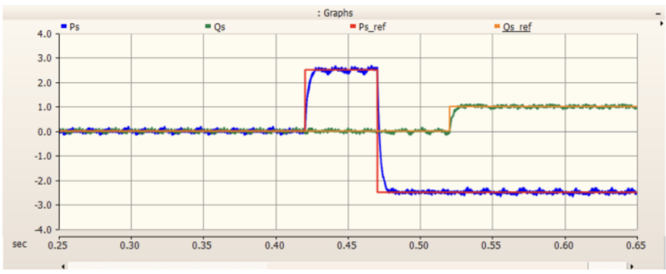


Figure 6: GFL Power Command Result

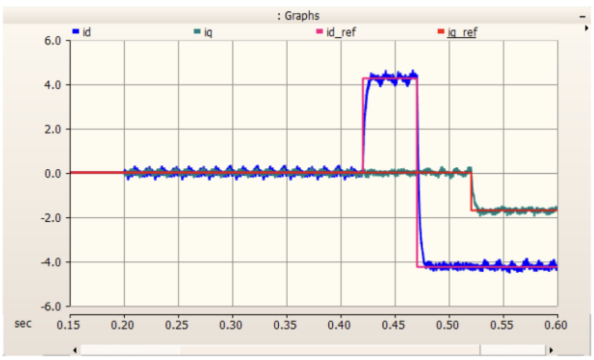


Figure 7: GFL Current Command Result

.

The student did not conduct any simulations for GFM inverters by building it block by block. Instead, the student used the Kenyon models which not only included the controller studied in theory but also included high level control blocks such as droop-controller, current limiter, AGC, etc. The student simulated them on the IEEE 9 bus system in PSCAD as shown in figure 8. The grid is simulated for frequency stability in response to changes in GFL input powers (from 1s to 2s), load changes (at 3s and 3.5s), and a line trip (at 4s). Figure 9 shows the simple simulation results.

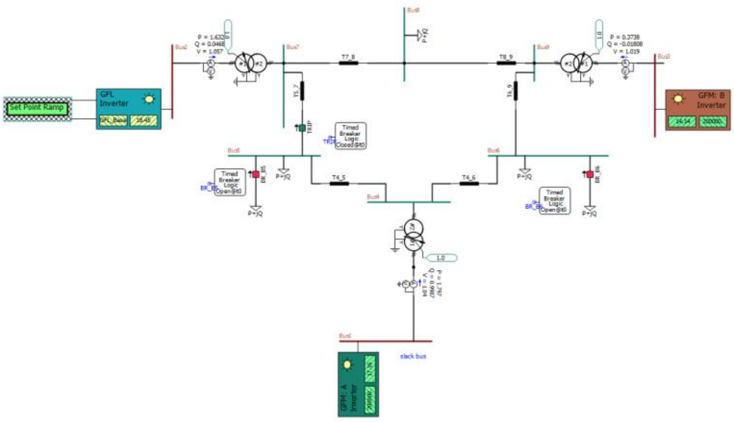


Figure 8: Simple IEEE 9-Bus Grid Simulation Grid

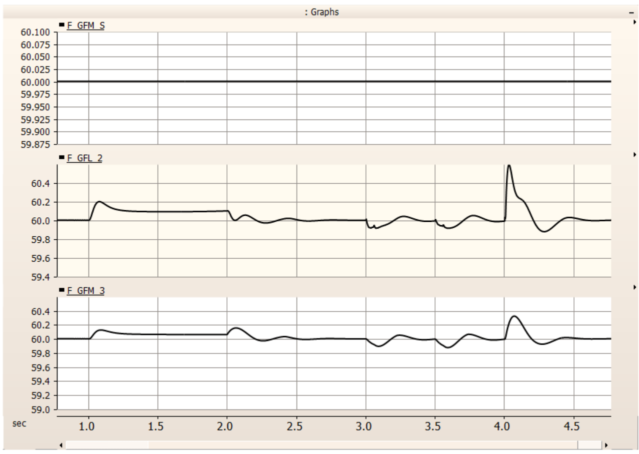


Figure 9: Simulation Results (Inverter Output Frequency)

While studying the theory behind VSCs, GFLs, and GFMs, the student was also given a handful of research papers that extend VSCs to power converters that connect renewable energy sources to the grid as well as understanding the theory behind grid frequency stability. The student had also reviewed novel research papers [2], [3], [4], [5] as well as a related document from the U.S. Department

.

of Energy [6] which discusses the need for grid forming, the dynamics of grid frequency stability, the difference between grid-forming and grid-following, and the different proposed solutions to help solve the challenge of maintaining grid frequency stability with increasing penetration of renewables.

Graduate level discussion with the TAs where also made. In these discussions, the TAs present their study materials used in their graduate courses or study to the student where he is able to learn about the current status of the research study. One such discussion included extensive review of [2] by one of the TAs. These graduate level discussions were done after finishing the review and study of VSCs.

Finally, the student and the TAs had been in close contact throughout the whole procedure on possible novel ideas to propose in response to grid frequency stability. Based on the current discussion, the student and TAs proposed studying the implications of using both grid-forming and grid-following inverters in supporting grid frequency stability during faults, line trips, and changes in the load. Moreover, a proposal to study the optimal mix through observation and practicality were also discussed. This enthused the student to read more about these proposals through numerous research papers searched on IEEE's website or academic journals.

As per the current discussion, the student will be studying how the grid frequency behaves based on the N-1 contingency analysis of high penetration grids. Using the IEEE 39 bus system as shown in figure 10, the 10 generators on the grid would be replaced by GFM and GFLs in 2:8, 4:6, 6:4, and 8:2 ratios respectively. Each case would be subjected to one contingency at a time – a line trip on the line with the most power flow, changes on the load value by a significant amount, and a fault near a generator.

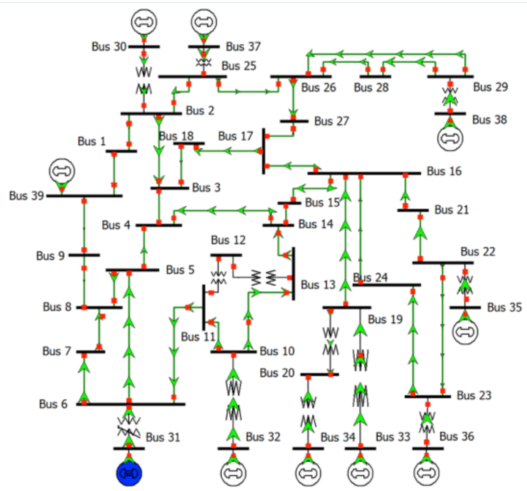


Figure 10: IEEE 39 Bus Model

.

## Schedules

Table 1 below shows the tentative schedule of the capstone project during and after the midterm report submission.

Table 1: Schedule

| **Date** | **Activity** |
|---|---|
| Oct. 6 – Oct. 12 | Post-midterm schedule discussion, finalization of experiments to be conducted, submission of midterm report. |
| Oct. 13 – Oct. 19 | Kenyon GFL GFM Model study and simulations |
| Oct. 20 – Oct. 26 | IEEE 9 bus and 39 bus reference study and simulations |
| Oct. 27 – Nov. 2 | Frequency stability study on IEEE 39 bus model and simulations on line trips and load changes |
| Nov. 3 – Nov. 8 | Fault study and simulation |
| Nov. 9 – Nov. 15 | Results tabulation, discussion, analysis |
| Nov. 16 – Nov. 22 | Final presentation and draft of final report writing |
| Nov. 23 – Nov. 29 | Discussion and consultations about final report |
| Nov. 30 ~ | Final report preparation |

## References


[1] A. Yazdani, R. Iravani. *Voltage-Sourced Converters in Power Systems: Modelling, Control, and Applications*. Toronto: IEEE Press, 2010.

[2] D.B. Rathnayake, et. al. "Grid Forming Inverter Modelling, Control, and Applications", *IEEE Power & Energy Society Section*, vol. 9, pp 114781-114807, Jul. 2021

[3] W. Qiu, et. al. "A Grid Forming/Following Sequence Switching Control Strategy for Supporting Frequency Stability of Isolated Power Grids," in *2023 The 5$^{th}$ Asia Energy and Electrical Engineering Symposium, AEEES 2023, Chengdu, China, March 23-26, 2023.*

[4] B.K. Poola, D. Groβ, and F. Dörfler. "Placement and Implementation of Grid-Forming and Grid-following Virtual Inertia and Fast Frequency Response", IEEE Trans. Power Syst., vol. 34, no. 4, pp.

.

3035-3046, Jul. 2019.

[5] Y. Li, Y. Gu, T.C. Green. “Revisiting Grid-Forming and Grid-Following Inverters: A Duality Theory,” *IEEE Trans. Power. Syst.*, vol. 37, no. 6, pp. 4541-4554, Nov. 2022.

[6] P. Denholm et. al. “Inertia and the Power Grid: A Guide without the Spin,” National Renewable Energy Laboratory, Golden, CO, Tech. Rep. NLEL/TP-6A20-73856.

.