Power electronic load impacts on regional power system stability

Simon Anthony Julien

Office of Science, Science Undergraduate Laboratory Internship Program

University of Colorado, Boulder, CO

National Renewable Energy Laboratory

Golden, Colorado

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Participant: ____________________
Author

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ABSTRACT

Through mathematical modeling and simulation, this study investigates the exact impact power electronic loads (such as electric vehicles) will have on the stability and reliability of a renewable power system. The paper reviews some fundamental concepts of power systems, load modeling, and dynamics before demonstrating these concepts in a small scale load model and flow simulation. Our results outlined voltage and frequency instabilities caused solely by power electronic loads and a simple contingency. As the study progresses, the scope of our project will be expanded to simulate projected data of the entire US Western Interconnection grid using a 2023 Heavy Summer (HS) load case [1]. This study will continue past SULI and will eventually be published, so this paper serves as a progress report of the project and my introduction to electrical and power engineering as the primary author.

I. INTRODUCTION

Modern day America relies heavily on power resources and technology. In the United States, the average human consumes over 43,000 kWh of energy a year on everyday appliances ranging from transportation, to air conditioning, and even charging our cellphones. It would take about 200 fit workers, turning a generator 40 hours a week, all 365 days per year, to supply enough energy for one American. That means that the entire US would need an average of 403 million power generating workers, and in the highest peak of energy consumption: 2 billion workers. Fortunately, we have functioning electric transmission grids and power generators to supply this energy. However, global alarm for climate safety is surging while fossil resources are depleting. Renewable energy is emerging as the next era of power generation, and converting our grid to renewables comes with new obstacles.

Much research in industry and at institutions like the National Renewable Energy Laboratory is spent transforming the grid into a system that is resilient to the undependable and geographically scattered nature of solar and wind resources. However, resilience to the changing demographics of technologies that are consuming power from the grid (*loads*), is frequently overlooked. Power electronic loads (e.g. cell phones, computers, TV's, batteries, and electric vehicles) are rapidly increasing in numbers and in how much power they are demanding from the grid. The grid is expected to jump from providing 0.02% of its power to electric vehicles (EV's), to 25%. Power electronic loads always demand a constant amount of power regardless of the health and current state of the grid. Our purpose is to study how this behavior can escalate small failures on the grid into major instabilities and even blackouts. This paper will review power systems concepts and study power electronics through modelling and dynamic simulations.

II. FUNDAMENTALS OF POWER SYSTEMS & DYNAMICS

A. Components of the Grid

The United States (and Quebec) national grid system, NERC, is split into four, mostly separate regions. The *Western Interconnection* [1] is the region that spans the entire US north to south and ranges from Colorado to California. In any power system like the Western Interconnection, there are three main stages of delivering power to the people. First, power is harnessed at the *generators*. Coal and natural gas plants are examples of fossil fuel generators, and solar and wind farms are considered renewable generators. *Transmission* lines then take the electricity from the generators to cities, neighborhoods, large commercial buildings, etc. Lastly, the electricity is consumed at the *loads*.

Loads represent technology that connects to the grid for power (commonly by wall outlet). Loads can be categorized by their compositions and how they consume power. For example, incandescent lamps are considered *resistive* loads, yet refrigerators are labeled as *inductive* (motor driven) loads. Cell phones, computers, TV's, batteries, and EV's are ***power electronics***. As mentioned in the introduction, these loads are very unforgiving to a temporarily unstable grid, whereas other load types naturally reduce their overall power consumption to ease stress on the grid.

The intersection point of any two of these three stages of power delivery (or the intersection point of two transmission lines) is referred to as a *bus*. When modeling and simulating a power system, busses are used as nodes that store all data and changing variables in the system [9].

B. Power Flow

The power flow, also known as *load flow*, of an electrical system describes exactly how power is moving from generation to the loads. The following analogy [11] compares electricity to water and is particularly useful for understanding difficult concepts of power flow.

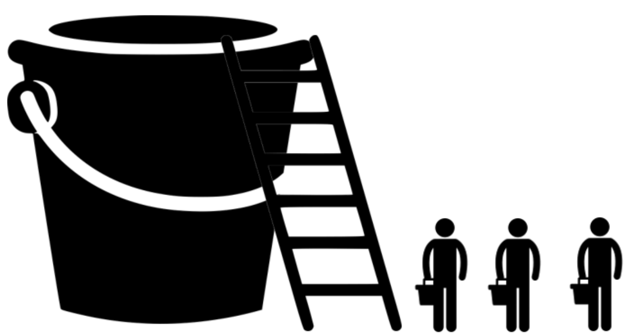


Figure 1: **Basic power flow analogy**

In Figure 1 three people are trying to fill a large bin with water, but they only have small, personal buckets and a ladder. To fill the large bin, they must fill their individual buckets with water, climb up the ladder, pour their water into the bin, climb back down, and repeat. After some time, the three people figure out that they can stagger their tasks perfectly so that someone is always pouring water into the large bin (i.e. there is a constant flow of water into the bin).

1. Real vs. Reactive Power

In this analogy, real power would be the water actually delivered to the large bin, and reactive power would be the power it took for the men to climb up and down the ladder. In reality, real power is the power someone pays for when they charge their EV or pay their electric bill. Reactive power is oscillating power required to deliver real power, and it has no price. In the analogy, all three people started and finished the process on the ground, so their was no real gain in "reactive power". This is also true on the power grid. Loads may consume reactive power, but they immediately give it back to the grid resulting in no gain of reactive power. The frequency of these reactive power oscillations (waves) on the grid typically occur at 60 Hz.

2. Phasors

In the analogy of Figure 1, the three people stagger their tasks so that water is constantly being poured into the large bin. If you have noticed power lines on the side of the road, the grid transmits power through three separate lines that act similarly to the three people in the analogy. One of the three lines is referenced as the *zero sequence*, and the other two stagger their reactive power oscillations to lead and trail the zero sequence as the *positive sequence* and *negative sequence* respectively. The measurement of how staggered the reactive power oscillations are is called the *phase angle*, which can be seen in equations 4 & 5. By this method of *symmetrical components*, power is constantly being delivered to the loads.

C. **Per-Unit Metric**

In 2015 the Western Interconnection delivered around 883 TWh of energy with an instantaneous peak of 150,700MW of power. The Per-Unit metric was created because these numbers are so large, but a small fluctuations still result in massive amounts of power lost and stability issues.

Per-Unit (p.u.) [1] is a relative unit. A reference measurement is taken (for example a reference power of 100 MW) and given a p.u. value of 1. All the other values of the same unit are then scaled onto the relative per-unit metric (90MW would be 0.9 p.u. and 110MW would be 1.1p.u.).

1. The Swing-Bus

The swing bus [3, 9] can be thought of as the "reference" bus. There is only one active swing bus in an entire power system, and the characteristic values of the swing bus are often used to create the per-unit reference values.

D. **Surge Impedance Loading**

1. Impedance

In a circuit like the grid, *resistance* (R) is the measure of how difficult it is for the current to flow through a wire, and *reactance* (X) represents how much the wire resists changes in AC (reactive power) frequency. Together these values form the complex value *impedance* (Z) in the equation

$$Z = R + jX. \tag{1}$$

Impedance is the total amount of difficulty electricity faces when traveling through a wire. The simulation performed in this study organizes data using an *admittance* matrix (Y) [9] at the buses. Admittance is simply the reciprocal of impedance $Y = \frac{1}{Z}$. Conceptually, admittance is then how easily current flows through the system.

2. Surge Impedance (SI)

Just as loads do, transmission lines consume reactive power through *inductive reactance* (X_L), which actually creates a magnetic field. Lines also produce reactive power, as do loads, through their natural *capacitive reactance* (X_C). At the *surge impedance* power produced in the wire equals the power consumed. The expression for SI is found in equation 7.

3. Surge Impedance Loading (SIL)

The SIL [14] of a transmission line is the amount of impedance in the line needed to balance this reactive power consumption and production at SI. Typically, this impedance is modeled as load attached to the end of a loss-less (ideal) transmission line. In this project, SIL is used as the per-unit basis for the power consumed at the loads. The relationship between SIL and SI is shown in equation 8.

E. **Dynamics and Stability**

1. Contingencies

A power system contingency [1] is a broad term for any type of error that could occur on the grid. Specifically, a contingency usually involves either a short circuit, faults in generation, losses of transmission lines, or sudden changes in loads consuming the power. These events are very unpredictable and can be caused by falling trees, forest fires, maintenance mistakes, etc. In this study we caused generation faults and load spikes to investigate the resiliency of different systems.

2. Frequency Response

AC on the Western Interconnect has a stable frequency of 60 Hz. Before any contingencies, this number remains mostly constant. Once a contingency occurs, the grid will adjust to accommodate for its failed components [4, 7, 11]. Figure 2 is an example plot that illustrates a possible shape of a frequency response curve.

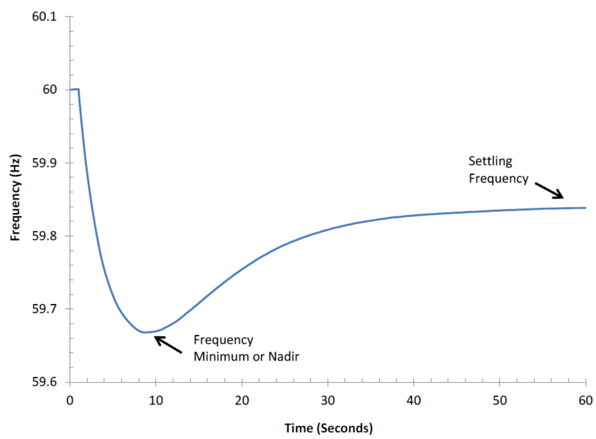


Figure 2: Example frequency response triggered by load increase or a tripped line. [1]

3. (Low) Rotational Inertia

Fossil fuel generation plants provide plenty *rotational inertia* [4,7]. In the plants, a heavy motor is spinning very fast, and after a contingency the spinning motor will have enough momentum to keep spinning at nearly the same rate. This was very useful for the stability of the grid system because contingencies would not cause such large drops in frequency (generators regulate the system frequency). Contingencies on a renewable grid do not have the same physical advantage. During contingency on a renewable grid, all generation at the failed location stops entirely. Therefore, solutions for quicker settling frequencies and stabilization techniques are crucial for a successful renewable grid.

The induced stress from power electronics coupled with a low rotational inertia renewable grid is the underlying concern of our research. As a solution to this problem, plenty of other research addresses energy storage techniques that could supplement temporary losses of generation. Equation 13 shows the frequency swing equation that is used to simulate the frequency response of the system.

4. Transient Stability

Transient stability [4, 7, 11] is an effective method for the system to fluently transition from normal operating conditions to another stable solution. With scattered generators of renewables and fossil fuels, and the increasing low-inertia of the system, this is an important setup for the resilience of the grid. Figure 3 illustrates transient response through a mechanical analogy.

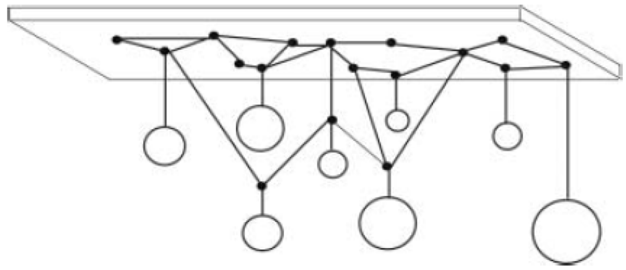


Figure 3: Ball and string transient stability analogy. [1]

In this analogy, if one of the strings was cut, all the other balls would fall and the system would readjust to compensate for the slack in the strings. Recall that our simulation investigates the impacts of **power electronics** not following this *transient response*, and not adjusting to accommodate any contingencies on the grid. Newton-Raphson is the computational method used to calculate the new equilibrium positions as described in the mathematical formulation section.

F. Mathematical Formulation

The important relation between voltage (V), current (I), and impedance (Z) is

$$V = I * Z. \tag{2}$$

1. Power Flow

Because of the harmonic nature of the power system [9], also seen in equation 1, V is a complex value. The *magnitude* of power (P) throughout the system can be shown using equation 2.

$$P = \bar{I}\bar{V} = \frac{V^2}{\bar{Z}} = I^2\bar{Z} \tag{3}$$

Here $\bar{I}, \bar{V}$, and $\bar{Z}$ are magnitudes. From equation 3 it is clear how power electronics, that demand constant power, increase current ($\bar{I}$) when contingencies drop voltage ($\bar{V}$). High current levels endanger transmission lines.

Total power (S) is the complex sum of the magnitude of power (real power) P on the real axis and reactive power Q on the imaginary axis.

$$S = P + jQ$$

This complex value introduces harmonics and a wave-like function. Using equation 3, we can find the total power delivered by averaging the power over one oscillation period. Voltage and current include their phase angles in the following [8, 9]:

$$V(t) = \bar{V}\cos(wt + \theta_v) = \bar{V}\angle\theta_v \tag{4}$$

$$I(t) = \bar{I}\cos(wt + \theta_i) = \bar{I}\angle\theta_i \tag{5}$$

The mean power over one period (T) is

$$S(t) = \frac{1}{T}\int_0^T \big[\bar{V}\cos(wt+\theta_v) \times \bar{I}\cos(wt+\theta_i)\big]\,dt.$$

Solving for the result using angle addition and double angle formulas we find

$$\begin{aligned} S &= \frac{\bar{V}\bar{I}}{T}\int_0^T \big[\cos(wt+\theta_v) \times \cos(wt+\theta_i)\big]\,dt \\ &= \frac{\bar{V}\bar{I}}{T}\int_0^T \big[\cos(\theta_v-\theta_i) + \cos(2wt+\theta_v+\theta_i)\big]\,dt \end{aligned}$$

Substituting period with frequency $w = \frac{2\pi}{T}$...

$$\begin{aligned} S &= \frac{\bar{V}\bar{I}}{T}\int_0^T \big[\cos(\theta_v-\theta_i) + \cos(\frac{4t}{T}+\theta_v+\theta_i)\big]\,dt \\ &= \bar{V}\bar{I}\big[\cos(\theta_v-\theta_i) + j\sin(\theta_v-\theta_i))\big] \\ &= \bar{V}\angle\theta_v \times \bar{I}\angle(-\theta_i) \\ &= V \times I^* \end{aligned}$$

Therefore we finish with the power flow equation:

$$\boxed{S = VI^* = P + jQ}. \tag{6}$$

2. Surge Impedance Loading

At the surge impedance [14] of a wire, *power consumed* = *power produced*. Therefore, using X_L ($2\pi fL$) and X_C ($\frac{1}{2\pi fC}$) defined in section 2. with equation 3,

$$\begin{aligned} P_{\text{consumed}} &= P_{\text{produced}} \\ I^2 X_L &= \frac{V^2}{X_C} \\ X_L X_C &= \frac{V^2}{I^2} \\ \sqrt{\frac{2\pi fL}{2\pi fC}} &= \sqrt{\frac{V^2}{I^2}} \end{aligned}$$

$$\frac{V}{I} = \boxed{\text{Surge Impedance} = \sqrt{\frac{L}{C}}} \tag{7}$$

To solve for the SI equivalent load to a loss-less line (SIL), we follow the equation 3 relationship between power (P), voltage (V), and impedance (Z) to create equation 8.

$$\text{SIL} = \frac{V^2_{\text{transmission line}}}{\text{Surge Impedance}} \tag{8}$$

3. Newton-Raphson Method

Our simulation method is an iterative method that approximates simultaneous, nonlinear equations into linear equations through Taylor series and solves for the equilibrium (stable solution) of the system. In our system, the "equations" are formed in the admittance matrix (Y) mentioned in section 1. Knowing $Y = \frac{1}{Z}$, and using equation 2 we find

$$I = Y * V \tag{9}$$

Y is a matrix containing data information from every bus in the system. Therefore

$$I = \sum_{n=1}^{n=N} \bar{Y}\bar{V}$$

Integrating phase angles (Θ) and incremental change (δ), a few steps later we have the power equations

$$\begin{aligned} P_i &= \sum_{n=1}^{n=N} \bar{V_i}\bar{V_j}\bar{Y_{ij}} \cos(\Theta_{ij} - \delta_i + \delta_j) \\ Q_i &= \sum_{n=1}^{n=N} \bar{V_i}\bar{V_j}\bar{Y_{ij}} \sin(\Theta_{ij} - \delta_i + \delta_j). \end{aligned} \tag{10}$$

Jacobian elements are formed from partial derivatives of equation 10, but in short the computer is working with the solution [3]

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta \bar{V} \end{bmatrix} \tag{11}$$

These changes in power and solutions to readjusting $\bar{V}$ and δ are solutions for one iteration. This process continuously repeats until the equilibrium is found or the system diverges [8–10].

4. Frequency Swing

Frequency [7] is modeled as if there is a physically spinning generator that exists only in fossil fuel generation. The energy (E) in the spinning generator is shown with

$$E = \frac{1}{2} J (2\pi f)^2$$

where J is the moment of inertia and f is frequency. The following *swing equation* can be derived with time:

$$\frac{\delta E}{\delta t} = J(2\pi)^2 f * f^2 = \frac{2E}{f} = P_{\text{generated}} - P_{\text{demanded}} \tag{12}$$

The *aggregated swing* differential equation, with damping constant k soon follows:

$$\boxed{\frac{\delta f}{\delta t} = -\frac{k f_0}{2E} f + \frac{f_0}{2E}(P_{\text{generated}} - P_{\text{load}} - P_{\text{loss}})} \tag{13}$$

This is how our simulation is able to track the frequency of the system with $f_0 = 60\text{Hz}$.

III. **LOAD MODELING**

Load modeling is a method of mathematically approximating the relationship between power and voltage at a load bus. In this project, we created a static load model that was then added to a dynamic simulation. This means that the load composition does not change over time in our simulation, which is an appropriate approximation because our project intends to mimic an extreme, heavy summer case instance worst-case results.

A. **Exponential Model**

The exponential model [2,8] is a very simple way to model the load relationship between power and voltage.

$$\begin{aligned} P &= P_0 \left(\frac{V}{V_0}\right)^{\alpha} \\ Q &= Q_0 \left(\frac{V}{V_0}\right)^{\beta} \end{aligned} \tag{14}$$

In equation 14, V_0, P_0, and Q_0 are taken as values of the initial operating conditions, while α and β are constants that depend on the type of load (constant impedance, constant current, or constant power). In fact, the voltage dependent relationships outlined in equation 3 lead to the conclusion that:

$$Z : \alpha = \beta = 2 \rightarrow \text{constant impedance load}$$

$$I : \alpha = \beta = 1 \rightarrow \text{constant current load}$$

$$P : \alpha = \beta = 0 \rightarrow \text{constant power load.}$$

B. **The ZIP Model**

The ZIP model [2, 5, 6, 8] is an aggregation of the constant impedance (Z), constant current (I), and constant power (P) based on exponential models. This allows the ZIP model to more accurately model a load because it does not make the assumption that each load only fits into one of the three (Z.I.P.) categories. Instead, a polynomial model is formed that can include all three load types as shown in equation 15.

$$\begin{aligned} P &= P_0 \left[\alpha_p \left(\frac{V}{V_0}\right)^2 + \beta_p \left(\frac{V}{V_0}\right) + c_p\right] \\ Q &= Q_0 \left[\alpha_q \left(\frac{V}{V_0}\right)^2 + \beta_q \left(\frac{V}{V_0}\right) + c_q\right] \end{aligned} \tag{15}$$

α_p, β_p, c_p, α_q, β_q, and c_q are all scalar values whose value corresponds to a percentage of the total load that is of each ZIP type. Table 1 shows some example residential appliances and how they would fit into the model. Notice that $\alpha_p + \beta_p + c_p = 1$ for each load because each load must consume real power.

Table 1: Electrical Appliance Constant Values in ZIP Model [2]

Load	α_p	β_p	c_p	α_q	β_q	c_q
Air Conditioner	1.6	-2.69	2.09	12.53	-21.1	9.58
CFL bulb	-0.63	1.66	-0.03	-0.34	1.4	-0.06
Elevator	2.36	-4.15	2.79	11.7	-19.5	8.81
Incandescent light	0.54	0.05	-0.04	0.46	0.51	0.03
LED Light	0.69	0.92	-0.61	1.84	-0.91	0.07
Microwave	-0.27	1.16	0.11	15.64	-27.7	13.1
PC	0.18	-0.26	1.08	-0.19	0.96	0.23
Resistive Heater	0.92	0.1	-0.02	0.15	0.86	-0.01
Refrigerator	1.19	-0.26	0.07	0.59	0.65	-0.24
Battery Charger	3.51	-3.94	1.43	5.8	-7.3	2.46
Advanced Washing Machine	0.05	0.31	0.63	-0.56	2.2	-0.65
Microwave	-2.78	6.06	-2.28	0	0	0
Oven	0.99	0	0	0	0	0
CRT Monitor	0	0	1	0	0	0.15
LCD Monitor	0	0	1	0	0	0.15

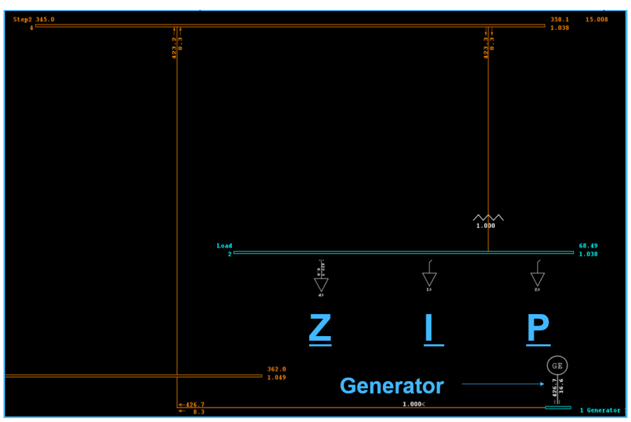


Figure 4: Screen shot from the static PSLF model used in power flow simulations. This load model only chooses *one* ZIP type to be active in a simulation to directly associate each transient response with its corresponding load type. In the bottom right is the only generator of the system and the arrows above it represent each type of load (ZIP). The generator bus and load bus are connected by two transformers and a high voltage transmission line (far left).

C. Other Load Models

[2] and [6] are extensive reviews of other load models and their advantages. This project will be using a composite LV load model for the Western Interconnection model.

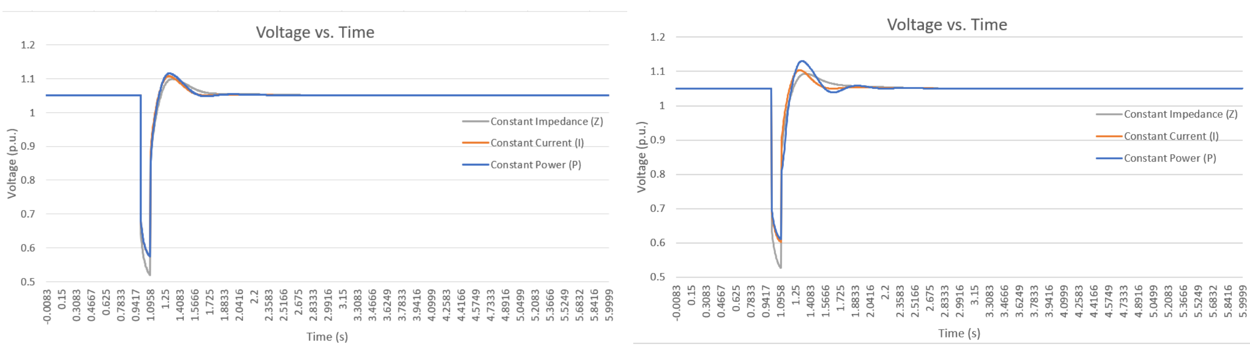
IV. **SIMULATION**

The purpose of these simulations is to perform a sensitivity analysis in order to quantify the impacts of power electronic load (P), versus other load types (Z & I), on a the small-scale power system model in figure 4. Positive Sequence Load Flow (PSLF) by GE was the software used to build the power system model and preform these simulations. As contingencies, a fault was enacted on the generator bus or a load demand jump occurred at 1 second. At 1.1 seconds, the fault was removed and the system was allowed to stabilize at equilibrium (load jump remained at the increased value). A stable solution is iteratively calculated as simulation time progresses by a Newton-Raphson algorithm.

A. **Results**

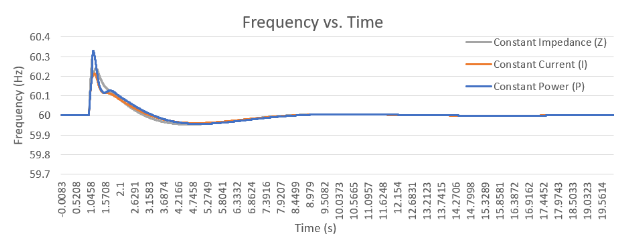
This section focuses primarily on relevant results outlining significant power electronic impact are displayed. Please see the appendix for plots of non-referenced results or sensitivity trend progressions.

1. SIL Sensitivity

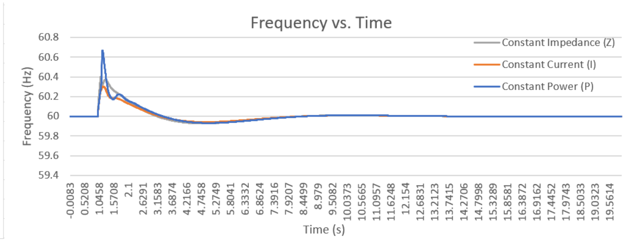


(a) Voltage: SIL=1 (b) Voltage: SIL=1.5

Figure 5: Surge Impedance Loading (SIL) sensitivity analysis of fault response (X=0.00125 Ω). Plotted is Voltage vs. Time results for all three load types of the ZIP model, comparing 1 and 1.5 SIL. Power electronics are represented by the blue line.



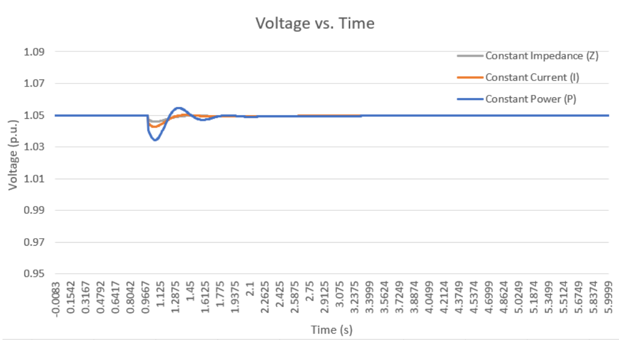
(a) Frequency: SIL=1



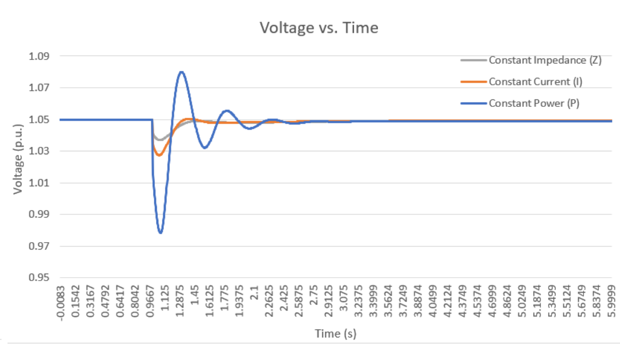
(b) Frequency: SIL=1.5

Figure 6: Surge Impedance Loading (SIL) sensitivity analysis of fault response (X=0.00125 Ω). Plotted is Frequency vs. Time results for all three load types of the ZIP model, comparing 1 and 1.5 SIL. Power electronics are represented by the blue line.

2. Load Jump Sensitivity

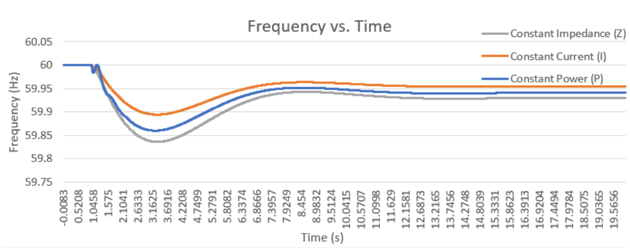


(a) Voltage: Load +4%

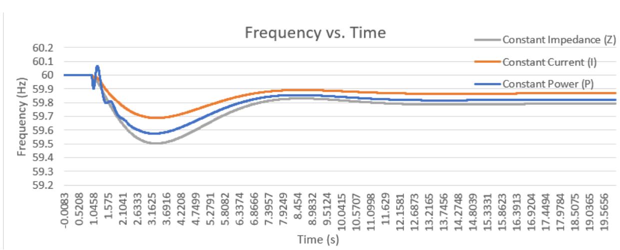


(b) Voltage: Load +12%

Figure 7: Sensitivity analysis of voltage response to percentage load jump (starting at 1.5 SIL) comparing a 4% increase to a 12% increase. Plots include responses from all three load types of the ZIP model with power electronics in blue.



(a) Frequency: Load +4%



(b) Frequency: Load +12%

Figure 8: Sensitivity analysis of frequency response to percentage load jump (starting at 1.5 SIL) comparing a 4% increase to a 12% increase. Plots include responses from all three load types of the ZIP model with power electronics in blue.

B. **Discussion**

When looking at the load bus voltage responses in figures 5 & 7, it is important to recall how power electronics demand constant power and therefore, by equation 3, power electronic currents will have inversely extreme swings. Too much current can cascade into overloading line failures, and the blue power electronic line has the most extreme voltage swings in these figures. If either Z or I had the largest swings in voltage, there would be much less concern because current traveling through the lines wouldn't overcompensate. It is also clear from figures 5 & 7 that higher loading corresponds to much more power electronic induced instability, particularly in figure 7b.

Figures 6 & 8 display frequency responses of the generator bus. In figure 6 it is very clear that higher loadings of power electronics impact frequency stability as well. Figure 6b approximately doubles the deviation from 60Hz that figure 6a does, while the other load types keep very similar curves between SILs. In figure 6, frequency of the generator bus rises because the fault removes generator loading responsibilities. In figure 8 more load is being added to the system, immediately slowing down the frequency. Figure 8 does show interesting early oscillations from power electronics, but does not express increased settling instability due to power electronics.

Figure 9 in the appendix shows our analysis of how fault reactance magnitude would influence voltage, angle, and frequency stability. These plots show similar trends as the figures above. In all cases, phase angle swings did not outline power electronics as a particular issue, but angle plots can still be informative about the "struggle" the grid is managing. See all plots in the appendix.

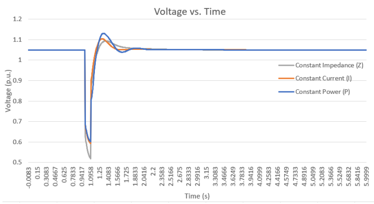
V. **CONCLUSIONS & CONTINUING WORK**

From progress in this project thus far, we have gathered useful intuition that power electronics fundamentally affect a power system through our simple model and dynamic simulations. In the near future we will be applying these methods and algorithms to study power electronics on the US Western Interconnection using a 2023 High Summer projection data case provided by [1]. Using our results on a theoretical system, outlined in this paper, we now have a strong direction and "educated hypothesis" for what trends we might see in our published product concerning the Western Interconnection.

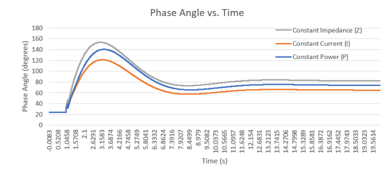
VI. **ACKNOWLEDGMENTS**

This work was supported in part by the U.S. Department of Energy, Office of Science, Office of Workforce Development for Teachers and Scientists (WDTS) under the Science Undergraduate Laboratory Internships Program (SULI).

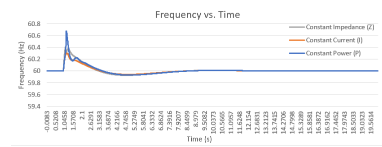
VII. APPENDIX



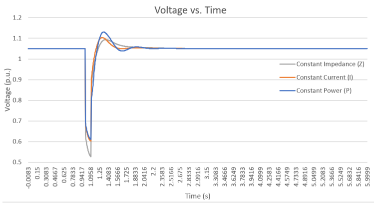
(a) Voltage: X=0



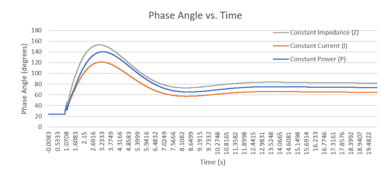
(b) Angle: X=0



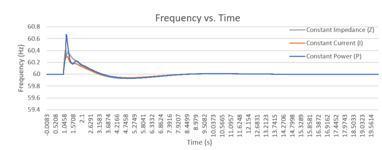
(c) Frequency: X=0



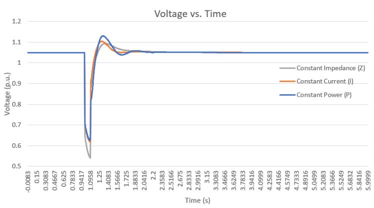
(d) Voltage: X=0.00125



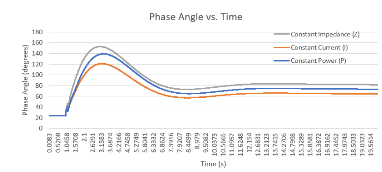
(e) Angle: X=0.00125



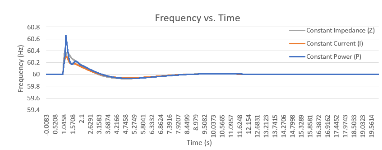
(f) Frequency: X=0.00125



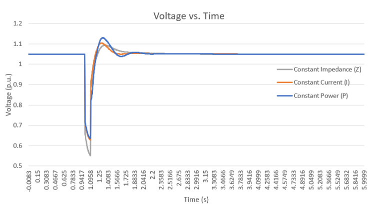
(g) Voltage: X=0.00325



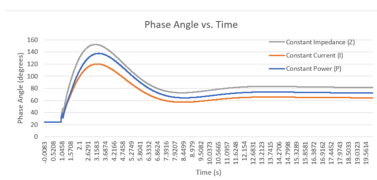
(h) Angle: X=0.00325



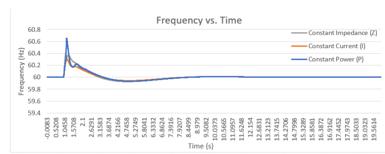
(i) Frequency: X=0.00325



(j) Voltage: X=0.005

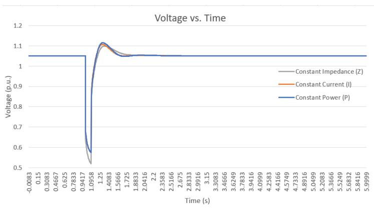


(k) Angle: X=0.005

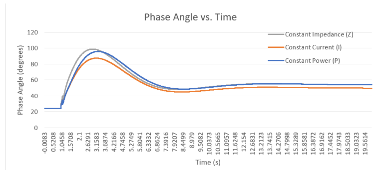


(l) Frequency: X=0.005

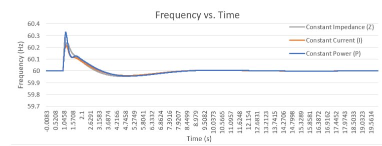
Figure 9: Fault Reactance (X) Sensitivity



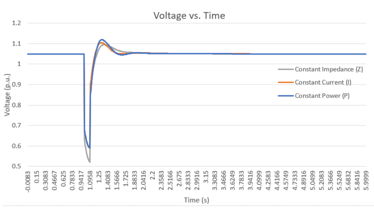
(a) Voltage: SIL=1



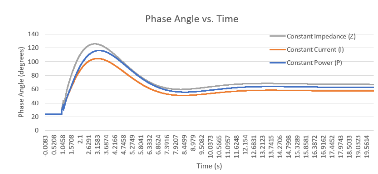
(b) Angle: SIL=1



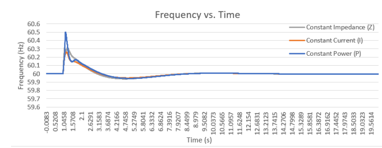
(c) Frequency: SIL=1



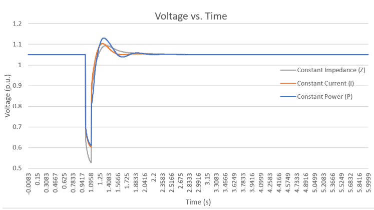
(d) Voltage: SIL=1.25



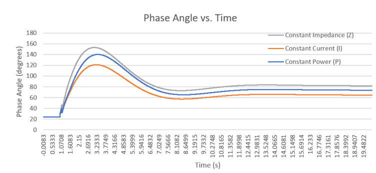
(e) Angle: SIL=1.25



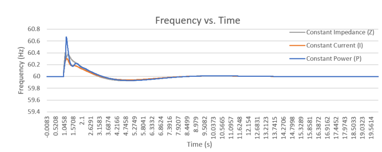
(f) Frequency: SIL=1.25



(g) Voltage: SIL=1.5

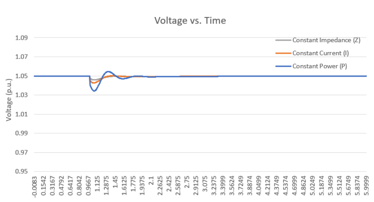


(h) Angle: SIL=1.5

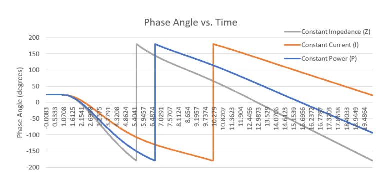


(i) Frequency: SIL=1.5

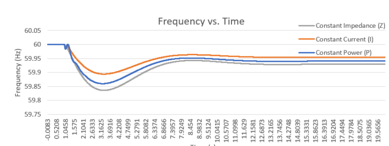
Figure 10: SIL Sensitivity



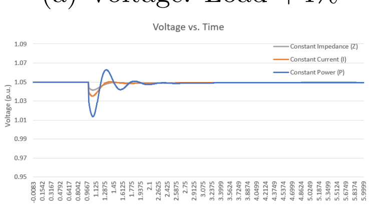
(a) Voltage: Load +4%



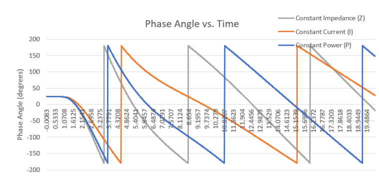
(b) Angle: Load +4%



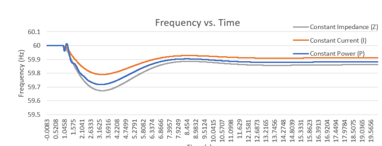
(c) Frequency: Load +4%



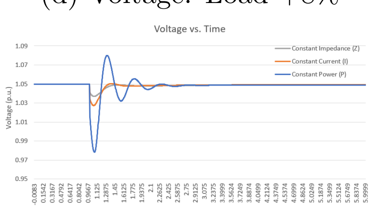
(d) Voltage: Load +8%



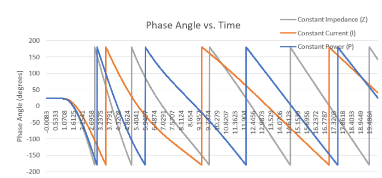
(e) Angle: Load +8%



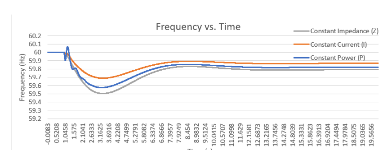
(f) Frequency: Load +8%



(g) Voltage: Load +12%



(h) Angle: Load +12%



(i) Frequency: Load +12%

Figure 11: Load Jump Sensitivity

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